Simulation Modelling of Complex Human Policy Issues: Towards a Broad Interdisciplinarity

David C. Crane

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Acknowlegements

This thesis has benefited greatly from my interactions with many individuals and organisations before and during the time I spent writing it.

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Declaration of Ownership of the Thesis

This thesis has been composed by myself, and all the work presented herein is original and my own. The computer models used to develop the case studies were all created either solely by me, or by myself and others as part of a research programme, as indicated below.

The work presented in this thesis has been undertaken over four years, following a previous two years of research engaged in developing simulation models, and the ECCO model in particular. The ideas that developed into this thesis have their roots in those two years of work, and have also been fuelled partly by the consultancy work I have undertaken for the CSIRO Resource Futures Program (see Chapter 5) and EC-funded Sustainable Europe Project whilst registered for this thesis. The case studies chosen to illustrate the topics here draws partly upon these other works, and partly from the intellectual freedom that the thesis scholarship provided.

A large part of the work of this thesis involved coding simulation models as part of the case study. It is important to state here which models were developed explicitly as a part of the thesis content, and which were available as case study tools through other work that I had been involved in.

- The UK ECCO model used to provide case studies for Chapter 4 was developed between 1993-94, prior to my beginning the thesis. I was one of a team of four developers. The case studies results were developed specifically for the thesis using a copy of this model.
- The OzEcco model described in Chapter 5 was developed as a consultancy project for the CSIRO Resource Futures Project, with intermittent pieces of work ongoing from 1995 to the present. The first piece of work (20 person-days) was undertaken jointly by myself and Professor Malcolm Slesser in May-June 1995, with the principal design and implementation of the model

being undertaken by myself. Barney Foran of the CSIRO assisted us a great deal with the collection of data. Subsequent work (over 50 person-days) was undertaken solely by me on a consultancy basis, with the intent that the model be used as the principal ECCO case study in this thesis. The case studies presented in Chapter 5 were developed exclusively for the thesis.

- The CarteSim model (Chapter 6) and IPSO model (Chapter 8) were developed exclusively for this thesis, and their design and implementation for the purpose of testing the broad interdisciplinarity method should be considered a part of the work of this thesis.

Source code listings for the OzEcco, CarteSim and IPSO models are presented in the appendices.

[redacted]

David Crane, August 1999

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Abstract

Computer simulation models are being used increasingly as decision support tools for policy-making regarding many complex human-related policy issues. It is important to know how to apply modelling to the issues appropriately, that is, to properly understand the relationship between the real situation and the model of the situation.

Starting with a review of current thinking in the philosophy of (physical) science and other literatures dealing with the methodology of economics and with metaphor, the concept of a model is expanded to include the informal assumptions upon which formal structures are founded. Two types of interdisciplinarity are identified; the 'broad', which establishes dialogue between the non-formal foundations, and the 'narrow', which does not. These ideas are then applied specifically to the case of systems modelling (including system dynamics, complex systems and quasi-formal systems) of human-related issues.

These debate between a mainstream and 'ecological' economics is introduced. A broad interdisciplinary reading suggests that the division between these two schools is at best useful in only some circumstances, and hides a number of other important divisions within the field. The polarisation between ecological pessimists and technological optimists is seen to have less to do with the intellectual content of the theories than with the social, ideological, personal and political context of those participating.

Three case studies of policy-relevant models are introduced, both as an illustration of the practise of broad interdisciplinary thinking and as a way of advancing the debate between mainstream and ecological economics. The ECCO model represents national and regional sustainability options in the biophysical context using conventional system dynamics. The CarteSim model represents changes in spatial land-use patterns at the regional and urban level using complex system dynamics. The IPSO model is a hybrid

of ECCO and CarteSim, using complex dynamic representations of the interaction between physical capital and technology options.

The case studies are, collectively, an exploration of the possibility of stepping beyond the polarity of the economic growth debate by using a broad interdisciplinary approach.

Hypothesis

Intellectual theories about human activity cannot adequately be treated as purely objective or rational. These theories can only be understood by taking account of the broader context in which they are developed.

Discussion about economic growth can be divided into two polarised positions, with one side emphasising the limits imposed by natural resources and the other emphasising the freedom from such limits offered by technological change. The debate cannot be resolved by determining which position is 'correct'. It is possible to encompass both positions by looking at the context in which the debate occurs, even within an exercise as apparently mechanical as computer modelling.

The first part of the thesis is aimed at addressing the first statement by looking at modes of academic debate in general, and the economic growth debate in particular.

It is taken as given that the economic debate is polarised. The possibility of stepping beyond this polarity is addressed using a series of case studies in simulation modelling, each of which offers a different perspective on economic growth issues. While much of the content of the second and third part of the thesis is aimed at presenting these case studies, a final chapter will return to this hypothesis and offer a test of its validity.

Introduction

This thesis covers two topics. At one level, it is a presentation of a series of exercises in dynamic modelling. These exercises are linked together as a discussion about the causes of economic growth. At another level, the set of simulations and attendant discussion is taken as a case study of how to conduct interdisciplinary research.

The thesis is divided into three Parts. Part 1 outlines a comprehensive approach to approaching interdisciplinary work, and discusses the limitations inherent in a purely scientific stance to the analysis of contentious issues. From this, a prescription for a 'broad interdisciplinarity' (Chapter 1) is formulated, in which the concept of dialogue in the modelling process is emphasised, allowing the modeller to see beyond the formal structures that they develop. The concepts developed here are applied in a general way to the tools of systems theory (Chapter 2) and subject of economics (Chapter 3) before embarking upon the case studies.

Broad Interdisciplinarity

The broad interdisciplinarity that is developed here describes a 'hybridisation' process whereby the formal contradictions between sets of models are used to develop new complementary models that fill in some of the gaps in the discussion that their 'parents' cannot access. The three models presented as case studies in this thesis provide an example of this hybridisation process.

Part 2 of the thesis presents results from each of the 'parent' models, ECCO (Chapters 4 & 5) and CarteSim (Chapter 6), and examines them using the concepts developed in part 1 in order to establish the extent to which they can usefully engage in a dialogue. A number of points of contact are identified at the formal and content level (Chapter 7).

Part 3 of the thesis describes the process of developing a hybrid model, IPSO, from the two 'parent' models (Chapter 8). The limitations and strengths of IPSO in relation to its parents are also discussed.

The Growth Debate

The 'growth debate' to which the simulation models presented throughout this thesis are addressed has its origins in the development of economic theory (Chapter 3), arguably originating with Malthus' formulation of impending food scarcity. In its modern form, the debate is essentially conducted between two broad positions, on the one hand the 'ecologists' stressing the limitations imposed by resources (e.g. Ehrlich, 1968), the earth's pollution-absorption capacity (e.g. Rees & Wackernagel, 1994) or the uncertainty associated with intervention in ecosystems (e.g. Funtowicz & Ravetz, 1991). On the other side of the debate, the 'technological optimists' stress the failure of previous predictions of disaster (e.g. Simon, 1998; see also Watt, 1994, for a good overview, although he personally leans more to the ecological side), and the role of technology in surpassing perceived limits in unpredictable ways (Ausabel, 1996; Isaacson, 1998).

Both sides conduct their arguments in isolation from the other, and relatively little attempt has been made by either to listen to syntheses of both sides. The specific debates conducted between Khazzoum & Lovins in 'The Energy Journal' (Khazzoum, 1980; 1987; 1989; Lovins, 1988) or Daly & Young in 'The Journal of Environmental Economics & Management (Young, 1991; Daly, 1992b) are typical of the general pattern.

Syntheses are scarce; some of the work of Marchetti & colleagues (Marchetti, 1994, 1983; Marchetti et al., 1978; Grubler et al., 1993), Allen (1994a, 1994b, 1992; Allen & McGlade, 1987) or Watt (1994) might be considered as drawing upon both positions.

The simulation models presented here are all designed to act as decision support systems in practical policy-making. The content of the three models is discussed in terms of the ongoing debate regarding the causes of economic growth. ECCO, as a strongly bio-physical representation of the economy, stresses the importance of resource constraints, and of the ability to supply sufficient physical infrastructure to the economy. Within the mainstream of economics, a significant part of the discussion focuses on acquisition of knowledge and the role of technology in determining growth. The CarteSim model presented in Chapter 6 is much more closely associated with this way of looking at things, given its emphasis on innovative and adaptable behaviour. Resource scarcity and technological innovations, are often presented as exclusive viewpoints. The IPSO model of Chapter 8 attempts to draw upon the strengths of both approaches, and to borrow ideas from both ECCO and CarteSim, in order to encapsulate both viewpoints within a holistic framework, and so inform the debate. Chapter 9 summarises the entire debate and the model hybridisation process, and begins a dialogue between IPSO and it's parent models, suggesting further avenues of inquiry.

Glossary

The thesis uses a number of words and phrases in a specialist way, as defined by one or more of the disciplines or research communities working on the topic. Sometimes different groups will use the same term in different ways, adding to the confusion. The only terms defined specifically for this thesis are the 'broad interdisciplinarity' and 'narrow interdisciplinarity', as defined in Chapter 1.

The glossary below lists key specialist terms which might require clarification during the reading of the thesis, and indicates the sense in which they are generally used within this work.

Broad Interdisciplinarity

An interdisciplinary approach that requires communication of the assumptions, world-views and intellectual foundations of each discipline. See section 1.4.3

Complex Adaptive System

A complex system capable of altering the rules by which it operates in response to its environment. Compared to system dynamics models, a complex adaptive system model has a greater ability to represent innovation and discontinuous change. Some authors, e.g. Allen (1994), draw fine distinctions between systems, adaptive and evolutionary models, but others use the terms synonymously. Within this thesis, the term *Complex Adaptive System* is used to refer to any system composed of interdependent actors which is capable of generating emergent macro-level behaviour. See section 2.3.

Complex System

A system composed of a population of interdependent actors, possibly with heterogeneous characteristics. The macro-behaviour of a model of such a system is not hard-coded into the rules defining the model, but will emerge from the hard-coded lower-level rules. See section 2.3.

Ecological Economics

Economic thinking that draws its worldview or inspiration from the popular ecology movement and its tradition of holistic thinking. This theory is 'ecological' in the sense that its primary focus is on the interactions between entities rather than on the entities themselves. It is often concerned with environmental impacts of human activity, but this, or any other direct link to wildlife ecology, need not be a defining characteristic. See sections 3.2 and 3.4.

Industrial Ecology

Holistic or systems-based study of industrial systems aimed at understanding the interactions between different production units, industrial sectors, etc. Models and concepts from wildlife ecology, such as food webs, may be drawn upon, but the boundary of study need not incorporate any genuine biological or natural systems. See section 8.1.

Narrow Interdisciplinarity

An interdisciplinary approach in which the communication between disciplines happens only at a surface level. The underlying assumptions of each discipline are not communicated to the other disciplines. See section 1.4.2.

System Dynamics

A modelling technique for representing systems undergoing change. System components are represented explicitly as model variables, and rules defining interactions between them are defined. The values of variables are computed using discrete-interval approximations to continuous differential equations. Developed as a method for analysing systems in a holistic or systems-based fashion. See section 2.1.1.

Chapter 1 Models and Theories

Hypothesis: Complex human policy issues can only be addressed by drawing upon a range of disciplines, whose models are reconciled not by merging the logical structures, but by establishing a dialogue between the informal structures that underlie the models.

This chapter is concerned with laying down the basic concepts to be used in the discussions that follow in this thesis. Specifically, the aim is to discuss the meaning of the term 'model' in relation to the development of theory, and the role of models within scientific (and other scholarly) thinking. Section 1 of this chapter reviews recent developments in the philosophy of science that may be useful here. Other sources of ideas are considered in the second section.

1.1 Philosophy of Science Topics

Scientific methodology is not the only way of addressing economics as a discipline, and is not the primary approach taken in this thesis. Nevertheless, economic methodologists often use the philosophy of science as an "epistemological touchstone" (Barnes, 1989), and a discussion of economic methodology would be incomplete without addressing this topic. The following section summarises the influence of the Philosophy of Science upon economic thinking. Alternative approaches and their relative merits are introduced in the remainder of the chapter.

1.1.1 History of the Philosophy of Science

Canterbery & Burkhardt (1983) have noted that science only became a "self-conscious" activity in the early part of this century, with the emergence of the logical positivist school of philosophy (although, as we shall see in Chapter 2, the physical sciences represented an ideal to which other disciplines sought to aspire at a much earlier date). The logical positivists developed explicit criteria for evaluation of theories, most notably Carnap's *verifiability* (Schilpp, 1963) and Popper's *falsifiability* (Popper, 1963). Use of these criteria supposedly provides a rigorous means of advancing the state of knowledge within a discipline, and of distinguishing between science and other bodies of knowledge. (In particular, Popper's work was driven partly by a desire to formalise his misgivings about the practice of psychoanalysis which arose in Vienna in the early part of this century). The purpose of logical positivist theory can be seen as two-fold:

1. as a means of assessing the merits of existing programmes of knowledge
2. as a prescription of an *ideal* method for 'scientific' research

Later developments (e.g. Kuhn, 1962; Feyerabend, 1975; Lakatos, 1976) introduced a third element; the actual practice of disciplines that are described as scientific. Popper's main criticisms were levelled at 'fringe' disciplines aiming to imitate the rational approach of physics and mathematics. A large part of Kuhn's work involved identification of what could be termed the 'social' practices of those working within the scientific disciplines, although Kuhn himself did not conduct detailed sociological studies of laboratory practice. The concept of continual progress developed by the logical-positivist model of science was challenged by alternative explanations, such as Kuhn's 'paradigm' and, to a lesser extent, by Lakatos' concept of a 'research program', which allowed for a greater degree of relativism and plurality.

According to these 'sociological' explanations of scientific activity, a number of interpretations of phenomena can be developed, and the choice between possible interpretations is not made primarily on 'scientific' or 'rational' merit. Kuhn introduces the idea that different interpretations may be incompatible, or *incommensurate*, with one another, and therefore incapable of being combined or reconciled. Under such a scheme, conflict between interpretations is to be expected, and the notion of regular accumulation of technique replaced with a disjointed progress incorporating setbacks and sudden changes (his much-(mis)quoted 'paradigm shifts'). Later developments of the sociological school of thought, such as the Edinburgh "Sociology of Scientific Knowledge" school (Barnes, 1985; Barnes & Edge, 1982; Bloor, 1992 a.o.), have placed even greater emphasis on the role of society in shaping scientific ideas and practice, and emphasising the subjectivity and context-dependence of science.

The purpose of this brief historical sketch is to note the following:

1. there was (and is) debate as to the nature of good scientific practice
2. the broader study of science extends well beyond the debate described in 1. covering sociological analysis of actual and historical working practices in addition to the abstract treatment of purely logical thought

3. a considerable amount of the literature is therefore concerned with what, under some definitions at least, would be considered as 'unscientific'. The literature therefore contains concepts that are useful in discussing a wider range of academic activity than those readily classifiable as science. If, as Canterbery & Burkhardt (1983) argue, economics is "a pre-positivist 'system of organised cognition' " (p.22) rather than a science, the ideas presented here may still shed light upon the discipline.

This breadth is desirable given the range of reasons for which the term 'scientific' is sought in society. It is certainly incontestable in a very general sense that logical, structured, demonstrably self-consistent thought is a powerful analytical tool in many situations. It is also true, however, that "scientific" is a term that attracts unreflexive kudos and respect in some circles (and, equally, unreflexive hostility in others).

1.1.2 Models & Realism

The term 'model' can be applied to a number of classes of entities, as noted by Hacking (1983: pp.216-8). These include:

- physical models (such as rod-and-ball constructions of molecules),
- formal logical representations of reality, including those using the language of mathematics; formal logical models may themselves be simply recorded as text of some sort, or may be implemented on a computer, allowing automatic manipulation of the rules.
- one may expand the definition to include the category of 'mental models', covering informal abstract representations of reality, typically expressed in a 'natural language' such as English. This thesis is concerned primarily with the development and use of mathematical models, but it is useful initially to consider the broader class.

Following Hesse (1963), a model is said to relate to some part of reality, termed the "explicandum". The purpose of the model is an explanation of this part of reality. Obviously, a model will rarely, if ever, be a one-to-one representation of it's explicandum, and will contain both positive and negative correspondences ('analogies' in Hesse's terminology). Hence a model (or theory) can offer only a partial explanation.

Hesse describes the relationship between model and explicandum[1] as consisting of three parts:

1. a positive analogy, describing the properties of the model known to belong to the explicandum
2. a negative analogy, describing the properties of the model known not to belong to the explicandum
3. a neutral analogy, describing properties of the model about which the relationship to the explicandum is unclear.

Models are based upon theories (see below). We can presume that any foundational theory will contain at least some negative or neutral analogies, that is, it will be an incomplete representation of the explicandum, an approximation to reality. Cartwright (1983) notes this fact, and its bearing upon the theory-model approximation. Given two models of a phenomenon, the more approximate will not necessarily give a poorer account of phenomena. Following this, the validity of an approximation is context-, or application-dependent. This point is central to Cartwright's "simulacrum" account of explanation, a simulacrum being:

> *"something having merely the form or appearance of a certain thing, without possessing its substance or proper qualities" (OED, quoted Cartwright p.15).*

The simulacrum serves as an intermediary between the theory and reality, interpreting observable phenomena in a coherent but disposable framework. In many ways, Cartwright's simulacra is similar to a model, in that the key reason for its existence is its tractability, rather than a direct claim to the truth.

This challenges the conventional "covering law" account, which presupposes the existence of 'fundamental' laws which theory attempts to express. The hierarchy of fundamental or theoretical laws over phenomenological laws is reversed in Cartwright's scheme, with any supposedly 'fundamental' law relegated to the status of a convenient approximation that holds for certain circumstances or purposes. Only the low-level causal explanation offered by phenomenological laws are true of reality. Fundamental laws

[1] More correctly, Hesse refers to theory-explicandum relationships. Her ideas have been transferred to the model-explicandum relationship here.

govern only the objects in the simulacra or model.

1.1.3 Models, Theories & Experiments: Role of Models in the Scientific Process

In this section, the role of a model within a broader framework of knowledge (whether scientific or not) will be considered. Again, the primary emphasis will be on concepts drawn from the philosophy of science, with the caveat that many of these concepts can be applied to non-scientific knowledge systems too.

The classical description of scientific analysis follows a two-way division between theory on the one hand and experiment on the other, that can be traced back to Francis Bacon. Models, it is suggested, serve as intermediates between experiment and theory. Achinstein's (1968) characterisation of theoretical models provides a useful reference here. He lists five distinguishing characteristics of theoretical models as:

1. a model is a set of assumptions about some object or system
2. these assumptions attribute an inner structure, composition or mechanism which manifests itself in other properties observed in the explicandum
3. the assumptions are treated as simplified approximations useful for certain purposes
4. the model is proposed in the framework of some more basic theory
5. the model may display an analogy between explicandum and some other object/system

Redhead (1980) notes that the first of these also characterises theories themselves, as does the second in many cases. Point 4 merely indicates the hierarchical nature of the model-theory relationship, supported by point 3, in that the model is not considered to be true in any strong sense, merely useful. This echoes Cartwright's stance on explanation, in terms of the relationship between theory and approximation, if not the imputed degrees of realism. Point 5 seems a poor distinguishing characteristic, and can be said to be true of many theories as well as models, anyway.

A model, as an approximation to a theory, may be said to *impoverish* or *enrich* it (Redhead, 1980). In the case of impoverishment, the approximation is made purely to allow analytical solubility. Enrichment occurs where the model fills in 'gaps' in the theory, allowing application to a limited range of theoretical conditions. One may distinguish between these two types of model as *approximation* and *application* respectively.[2]

The key difference between a model and a theory rests, then, with the imputed degree of truth; models are usually explicitly recognised as approximate, whereas theories are often treated as being essentially true. Grice (see Cartwright, 1983: Essay 8), for example, coined the term 'properties of convenience' to describe the features of models included for mathematical or analytical solubility rather than as direct representations of real entities. Cartwright's own 'simulacrum' account acknowledges a similar lack of direct realism in models.

Hacking describes models as 'doubly models'. That is:

> *"they are models of the phenomena, and they are models of the theory...siphoning off some aspects of real phenomena, and connecting them, by simplifying mathematical structures, to the theories that govern the phenomena" (pp.216-7).*

This three-layer description of scientific procedure as experiment-modelling-theory is still somewhat idealised. Hacking (1983: Ch. 12) notes that many different 'levels' of theory exist, from speculated qualitative or semi-quantitative relationships through ad hoc mathematical representations to physical explanations within established bodies of theory.[3]

Hacking & Everitt (Hacking, 1983) propose a division of theorising into two activities, termed speculation and calculation. Speculation may be qualitative in nature (e.g. a relationship between A and B exists) or semi-quantitative (e.g. the relationship between A and B is probably exponential). Speculation is largely a creative process, an informed

[2] Note that the two types are not mutually exclusive; many application models will also contain impoverishing approximations.

[3] Hacking provides, as an example, an account of the development of electromagnetic theory, identifying six main stages of development, beginning with Michael Faraday's essentially metaphysical conviction that some connection between light and magnetism must exist. Although detailed histories of specific cases can be developed in this way, no regular pattern of development is evident (compare the historical accounts given in Chapter 2 of this thesis).

'playing with ideas'. Calculation involves more than simply mathematical encoding of a theory, but involves alteration of the theory in order to bring it "into resonance with the world", as Hacking puts it (p.214). Calculation is a fine-tuning process, arguably incorporating some aspects of model building.

The three-layer description of theory-model-experiment is a fuzzy one, then. Both theories and models come in a variety of forms, and a considerable degree of overlap exists. Models fulfil a number of roles, then, as illustrated by Redhead's distinction between impoverishing and enriching models. Real bodies of theory cannot be mapped 'automatically' onto the three-layer description, but nonetheless it can serve as a useful frame of reference.

1.1.4 Theory and Model Entry and Exit

As noted above, the distinction between models and theory is not clear cut, and that the two classes share many properties. The purpose of this section is to review the description of theory 'entry' expounded by Cartwright (1983), and subsequently apply it to the development and use of models.

1.1.4.1 Theory Entry

In broad terms, 'theory entry' refers to the process of abstracting from a situation some generalised description or explanation. Direct observation and recording of events is sometimes referred to as "pre-theoretical". Once underlying mechanisms or other explanations are advanced, a theory has been developed.

Cartwright (1983: Essay 7) describes two stages of theory entry. In the first stage, the pre-theoretical observations are "prepared", that is, presented in a way that is compatible with existing theory. This stage generates an informal prepared description in an essentially *ad hoc* fashion. Only in the second stage are the axioms and/or rules of the existing theory rigorously applied and the prepared description manipulated in order to fit the internal logic of the existing theory.

Cartwright's two-level description is amenable to further generic sub-division. Preparation of an informal model can be thought of as occurring in three stages:

1. acceptance of a metaphysical world-view, a 'cosmic map' describing the nature of relationships and properties of the world. Examples of such world-views are the atomist and energetist schools of thought in 19th Century physics (i.e. the world

composed of particles vs. the world composed of fields), and the General Systems Theory of von Bertallanffy (1968), Boulding (1985) a.o. (the world composed of interacting, hierarchically organised components). This stage is often so fundamental as to be overlooked as being a decision made by the theorist. In some cases, a theory may fit happily into more than one such metaphysical framework (e.g. it is of no relevance to a theory of human behaviour whether the world is composed of wave-like or discrete particles). Even this can be viewed as a design decision in itself. 'Fundamental' concepts need not reside at the sub-atomic scale; all axioms can be thought of as fitting this category. The assertion of 'methodological individualism' (the economist is not concerned with *why* people make the choices that they do: preferences are inherent) by certain neoclassical economists, for example, represents such a fundamental world-view.

2. a 'region' of the world as a whole is identified as being of interest. For example, a theory of forest ecosystems will treat open plains or aquatic ecosystems as exogenous (save for any relevant edge effects). Regions need not be spatially defined; subject matter, for instance, may also serve as a delimiter.
3. selected aspects of the 'region' of interest will be selected as being of interest. This will include both qualitative aspects (e.g. the mass of a body is relevant, whereas it's colour is not) and the level of hierarchical detail expressed (e.g. a map will only represent detail at a certain resolution or scale). Naturally, this latter point will be linked to the selection of the 'region' of interest.

All of these stages can be incorporated within Cartwright's stage 1 theory entry. That is, an informal theory will tend to specify a generic world-view, a region of interest and the aspects of that region to be examined. Indeed, for a purely informal theory, these stages of theory specification are sufficient.

In specifying an informal theory, then, a number of qualitative decisions must be made. A theory is an artefact, and, as such, has been designed. The specification process can be thought of as a series of design decisions, and, as Cartwright notes, there is no formal or repeatable methodology for performing this process.

In developing a formal (e.g. mathematical or logical) theory, the design stages described above must be reviewed. Each design decision has implications for the formal treatment of the theory. This includes the prescription of a world-view; formal representations of atomistic, field and systems universes differ considerably, with different mathematical techniques having been developed in each case.[4]

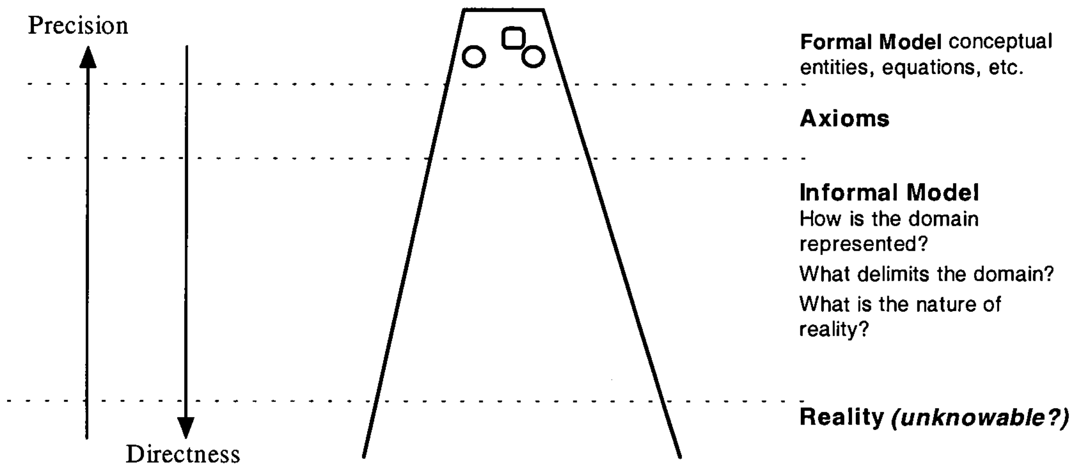

Figure 1.1: The layers underlying a theory or model: In addition to the well-structured, well-defined formal aspects of a theory or model, there are a number of intervening layers connecting it to 'reality'. From the bottom up, an informal model must be prepared first. The informal model is a relatively direct representation, and imprecise in terms of formal detail. It serves as a ground for construction of axioms, which, while more precise in content, are still expressed in natural language (and may serve as definitions for the more specialised language of the formal model). These intervening layers are less visible, and are often unacknowledged by users of the formal model.

When considering mathematical theories, the choice of numerical unit or numeraire can be seen to arise from the third set of design decisions, those concerned with assigning relevance to the various aspects of the system of interest. In many cases, the numeraire

[4] A clear illustration of the design element at this stage is that of the Hamiltonian equation used in quantum mechanical descriptions of sub-atomic particles. The wave-particle duality of matter must be explicitly recognised here, and the choice between Hamiltonian functions representing the particle as discrete or wave-like is often made on the strength of the problem to be solved.

chosen can be expressed using well-established conventions, such as the SI system of physical units. (A unit of measurement is more limited and technical than a numeraire, but a numeraire is usually expressible using a unit of some sort.)

In human systems, conventions are less clearly established, possibly owing to the greater number of aspects from which to choose in these more complex systems, and to the fact that people are closer to these phenomena in their everyday lives. This high level of complexity also tends to lead to a greater degree of ambiguity, as the need to simplify the representation may involve a semi-qualitative commensuration between essentially different things.[5]

The point here is to note again the subjective nature of model specification: based on a set of informal beliefs and conventions regarding the depiction of some system, the choice of formal representation is (incompletely) prescribed. It should be remembered, of course, that the formalisation itself may involve introduction of further subjective beliefs and conventions.

Note that the process of theory entry described above is applicable to the design of models, which are also artefacts. The development of a model from a theory is similar to the second stage of theory entry, with the theory acting as a 'prepared' description of reality from which the model is constructed. Even in the case of informal models, it is often the case that new conventions and beliefs will be invoked in abstracting model from theory, so that, while issues of numeraire and formal representation are unimportant, many aspects of the process are similar.

In practice, theories and the models that they produce will develop over time through repeated stages of theory entry as outlined above, and mature theories will exist on many 'levels'. This development will also (one would hope) involve references back to the 'unprepared' reality, as discussed below.

1.1.4.2 Theory Exit

As Rosen (see Casti, 1987) notes, the 'encoding' of a system into a formal model must be

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[5] For example, the use of money, and, at a more abstract level, utility and value, in economic theory compounds many commodities into a single numerical scalar. This specific case will be raised again in Chapter 3.

paralleled by the 'decoding' or 'interpretation' of the formal model, if the formalisation is to yield meaningful statements regarding the properties of observables. In keeping with Cartwright's terminology, it is proposed to discuss this process as ‘theory exit’. Theory exit can be described then, as the drawing out of understanding of 'unprepared' reality following manipulation of a 'prepared' description, i.e. a theory.

For theory exit to be successful, it is necessary to be aware of the design processes undertaken in theory entry. These design decisions will inevitably limit the scope of the theory, and therefore the domain of reality which it is qualified to represent. Successful theory exit should, then, identify the valid domain of a theory, and draw conclusions regarding the observables within that domain only.

Full specification of a valid domain will necessarily require several parts. Following the stages of theory entry outlined in the previous section, a valid domain will identify:

1. the aspects of the explicandum treated by the theory
2. the (hierarchical) level of detail of the treatment
3. the region of the explicandum treated by the theory
4. the metaphysical framework within which the theory is developed, and the axioms required to support the theory

In the case of formal theories and models it may be necessary to 'exit' the analytical frameworks more than once, moving backwards to an informal preparation and then to unprepared 'reality'. That is, one must consider the implications of the designs of both the formal model and the informal model upon which it is based.

The process of model or theory entry and exit is rarely so straightforward as suggested above, of course.

- It is relatively rare to begin from scratch in modelling a specific system and then working back to statements relating to the understanding of that system only. Most specific models will draw upon at least one established body of theory, and therefore upon more general set(s) of axioms.
- Generic conclusions may be drawn from a specific model's behaviour. Simple models may suggest (if not explain) powerful underlying mechanisms that are common to a wide range of real cases. These objections can be readily accommodated into the scheme of entry and exit however, by treating generalisations as additional design

decisions.

A more serious deviation from the ideal description occurs when one considers the inexact nature of subjective decisions, and the metaphorical nature of all modelling. The process of working backwards from a theory or model to identify a valid domain has been described above as a purely logical operation, which it is not. In practice, identification of all relevant design features of a model is unlikely to be straightforward or uncontentious. Where a theory has developed over the course of repeated entries and (partial) exits (i.e. extensions to the theory have been based on theoretical results corroborated by observation), deeply-held axioms may become embedded within the theory to the point of being 'invisible' (especially to those closely involved).

Subjective decisions are creative as well as rational. Model and theory development proceeds by a process of encoding and decoding of metaphors, which, unlike analogies, are imprecise and often highly evocative. This is not to say that rigour in science is impossible, but rather that it is a precarious process, dependent upon the personal qualities of the practitioners as well as the formal methodologies employed.

1.1.5 Metaphor

The theory of models draws upon the theory of analogy (Hesse, 1963: Chapters 3-4) within the mainstream of philosophy. Hesse's classification of positive, negative and neutral analogy has already been discussed. According to Newton's principia (see Cohen, 1995), the analogy is only one of four levels of 'discourse':

- identity - one to one correspondence, complete equivalence
- analogy - equivalence or likeness of function
- homology - equivalence or likeness of form
- metaphor - assigning value or property to that to which it doesn't rightly belong

Traditionally, metaphors have been treated as largely interchangeable with similes, in that the metaphorical statement "A is a B" conferred properties of B upon A in a rather mechanical, one-way transfer. In developing the interactive theory of metaphor, Max Black (1962) acknowledged the less precise cognitive powers of metaphor; upon pronouncing "A is a B", one's perception of B is altered. Having described a stock market as 'bullish', for example, one is prone to see aggressive exuberance the next time one sees a real bull, regardless of its actual behaviour. Similarly, rats, wolves and pigs evoke human emotions to us, as may inanimate objects such as clocks, cars and playing cards. Fox Keller and Lloyd (1992) express the ambiguity of language with some striking metaphors of their own, thus:

> *"[words] serve as conduits for unacknowledged, unbidden and often unwelcome traffic between worlds. ... Upon examination, their multiple shadows and memories can be seen to perform real conceptual work..." (p.2)*

Black's work applies primarily to literary use of metaphors, in which the ambiguity introduced is desirable and enriching. Some authors have sought to distinguish between scientific and literary use of metaphors. Klamer & Leonard (1995) suggest that in the scientific metaphor, the ambiguity is appropriate to a hypothesis, acting as a goad to further inquiry. Bicchieri (1988) ascribes a 'cognitive function' to scientific metaphors, although this seems to be just a more latinate way of saying that metaphor evokes non-rational thought in people.

Distinctions of this type are offered as defences of the special nature of science, as a rational activity separate from mundane or literary thinking. This defence is made in the spirit of the Modernist art-science split, and draws upon an outdated romantic ideal of literature and poetry,

> *"overstat[ing] the strangeness of poetry...[as] outside the routines of conversation"*

as McCloskey (1994:p. 45) puts it. Functional explanation and creativity are not isolated activities. Literature, like science, has a mundane explanatory role to fulfil, and science, like literature, is a creative activity. Science, and other academic disciplines, must make use of rational and creative thought in order to be effective. To admit that science uses metaphor is not to proclaim that it is irrational.

As Klamer & Leonard state, "the mere coinage of a metaphor...does not make science." Some metaphors are more suggestive, more stimulating than others ('fertile', in Menard's terminology: see Cohen, 1995). That is, by suggesting an extended analogical system, metaphor may lead to speculation around a subject. This speculation may then be applied usefully within the larger discourse, and be subjected to rational critique.

1.2 Beyond the Philosophy of Science

By viewing science as a creative *and* analytical activity, and by discarding the artificial 'two cultures' mentality separating the arts and sciences[6], we may move beyond the specialised philosophy of science. This section summarises some recent applications of such ideas to the human sciences, and attempts to synthesise the ideas presented thus far into a coherent whole.

1.2.1 Science and Social Science

The distinction between science and social science arises from the traditional logical positivist methodology of economics, with much of the debate centring around whether to treat social sciences as being on the 'genuinely' scientific side of the Modernist art:science split.

A number of commentators (Campbell & Cook, Eichner, 1983; Humphries, 1986) have noted that the division between science and social science is not necessarily the most useful one. A number of natural sciences, such as geology, astronomy, meteorology and wildlife ecology, deal with phenomena outside the scientists' control. Campbell and Cook note the distinction between controlled experiments and the random-sample statistical experimentation required in the latter cases. Further, in certain cases, e.g. wildlife ecology, the existence of underlying governing regularities (required by a deductive-nomological scheme of scientific practice) is far from established.

Similarly, some of the social sciences do fulfil some key positivist criteria. Behavioural psychology, for example, is highly suited to controlled experimentation. As Humphries (1986) suggests, then, economics' closest methodological relations may be to the complex natural sciences such as wildlife ecology, for which repeated controlled experimentation is not possible, and multiple (fallible) descriptions of governing regularities may be made.

This reasserts that, while clearly not scientific in the classical sense, economics and the human sciences may be usefully investigated using the concepts of the philosophy of

[6] at least for purposes of discussing the 'middle ground' of human sciences, the distinction between arts and sciences is unhelpful

science. It fails, however, to move beyond the concepts of (positivist) philosophy of science, and much of the debate is no more than a territorial dispute about the place of the 'borderline' disciplines within the Modernist/positivist categorisation of knowledge.[7] Inasmuch as type of methodology has served as the principle demarcation line, the 'sciences versus social sciences' debate, being framed in positivist language, has been unable to move with the philosophy of science literature beyond positivism.

1.2.2 Scientific Methodology and the Rhetoric of Economics

As noted already, the philosophy of science is not the only contending epistemological reference for studying economic methodology. An alternative framework developing over the last ten years or so is the treatment of economic literature as literature (e.g. McCloskey 1985, 1990, 1994; Klamer et al., 1988 a.o.). Economics can be viewed as a conversation between practitioners, in which appeals to fact, presentation and argument all play a role.

In comparison to the 'conventional' economic methodologists, the rhetorical approach has the appeal of a greater breadth of vision, and a greater ability to incorporate subjectivity. The ideas of this school are summarised briefly below.

Firstly, the nature of models and theories as simplifications are explicitly recognised. Theories are useful, but the real world is recognised as being too complex for any single theory to contain. As McCloskey (1994) remarks:

> *"The scientific conversation is not governed by rules convenient for a 3" x 5" card. It is a thick and complex and rhetorical matter, a practice, not a theory." p.107*

Dow (Backhouse, 1992) echoes these sentiments:

> *"no theory can be regarded as true in any absolute sense" p.72*

as does Toulmin (1972), taking the liberal argument to its extreme:

> *"Men demonstrate their rationality not by ordering their concepts and beliefs in tidy formal structures, but by their preparedness to respond to novel*

[7] The book titles "Why economics is a science" (Boulding, 1970) and "Why economics is not yet a science" (Eichner et. al, 1983) give an indication of the vociferous and inflexible nature of the debate.

situations with open minds."

To recognise the rhetorical nature of economics is not, then, to be merely rhetorical, but a recognition that discussion and exchange of ideas are necessities in addressing a subject too complicated to be narrowed down to one theory. Disagreement is encouraged, provided that each party is willing to listen to the viewpoints of the others.

To be successful, listening must be empathetic. In other words, the listener must attempt to shed, temporarily, any pre-conception of an issue, to look at it afresh. To adopt Cartwright's terminology, listening requires that the world in its unprepared state be considered first, rather than from the viewpoint of any habitual preparation. Needless to say, this is a difficult state of mind to achieve, but the benefits in defusing unnecessarily polarised debates can be considerable.

The rhetorical school, then, demonstrates a greater flexibility in incorporating the recent advances in the philosophy of science than the conventional methodology of social science. The rhetoric school also overlaps with the 'Sociology of Scientific Knowledge' programme of Science Studies, and Black's (1962) treatment of metaphor.

1.3 Formal models

In this section, the special case of formal models will be discussed, and the extent to which the use of formal techniques requires special treatment will be examined. 'Formal technique' refers to methods of explicitly expressing theory so that it becomes mechanically (i.e. reproducibly) manipulable. Obviously, in many situations, it is extremely useful to be able to do this, whether for purposes of prediction, analysis or as a surrogate for controlled experimentation. Within certain disciplines, notably economics, formalisation has at times also been pursued as an end-goal in itself.

The most common formal technique is mathematics, although other forms of logic may also be considered as similar. One can conduct an extremely narrow formal analysis without recourse to mathematics. As McCloskey (1994) notes on Schumpeter's 'Ricardian vice' (the use by economists of mathematics without adequate data to link the formal process to the real world):

"The Ricardian Vice has little or nothing to do with the use of ***mathematical*** *formalism. ... The physiocrats, a century before mathematics came to*

economics, were attempting to solve great social questions by manipulating definitions." p.146, original emphasis

The view that mathematics confers a special status upon those models that use it cannot be understood without an appreciation of the perceived status of mathematics within science and, more generally, within academia. Mathematics is often seen as an indicator of rigorous impartiality, particularly in disciplines uncertain of, and desiring, a 'scientific' standing within the positivist taxonomy. As Keuzenkamp and Magnus (1995) note, economists are more liable than physicists to validate their hypotheses by purely statistical means.

Porter (1995) makes a useful distinction between uses of mathematics in formalising theories. He distinguishes between quantification, a mainly empirical operation, and mathematisation, a more abstract process emphasising the ability to make further deductions from a set of encoded axiomatic statements. The intellectual values underlying each process may be considerably different; only mathematisation sets the formal method at the centre of the enquiry process.

Certainly, the use of mathematics or other formal languages (such as symbolic logic) does force a degree of rigour upon one's work, allowing *structured* inferences to be made. However, this rigour is entirely internal; that is, there is no way of checking the "correctness" of the axioms that one adopts as one's starting points from *within* the formal framework. The informal preparation must come first, and that cannot be checked by any formal method. Thus an examination of assumptions made from outside the formal framework must remain a key part of theory evaluation. As Hesse (1955) notes:

> *"A formal symbolic language can never be a substitute for thought because the application of a symbolic method to any empirical matter presupposes very careful analysis of the subject matter ... some necessary overtones of meaning are lost when a word is precisely and uniquely symbolised. The vagueness of living languages as compared with mathematics is the price they pay for their applicability to the world and their capacity for growth." (p.88)*

Similarly, Cairncross:

> *"As has often been remarked, logic can be a way of going wrong with confidence."* Cairncross (1992)

Because the mathematical model cannot be internally complete, one can view the process of expressing a model mathematically as the creation of a second model, with the formal model emerging from the informal one. Much of what has been said regarding the model-explicandum relationship already can be applied to the formal-informal model relationship. For example, any formalisation of a model will involve approximation, and no single approximation will be best suited to all purposes. That is, the formal model may contain positive, negative and neutral analogies with respect to the informal model.

Let one interesting property of this 'model within a model' view of formal modelling be noted here. The formal model has an existence of it's own, and may be transferred from one informal model to another. This phenomenon will be discussed in Chapter 2, in examining the exchange of ideas between physics and economics.

In surveying the positions regarding the use of mathematics within the social sciences, one encounters a broad range of opinions. It is tempting to polarise these positions into pro- and anti- camps, citing Debreu (1973) for instance, as valuing the mathematical content of his economic theory above its interpretation. Blatt (1983) implies a strong relationship between mathematics and science when he writes:

> *"until [opponents of the neo-classical synthesis adopt mathematics], economics is not yet a science" (p.185)*

Certainly, post-war mainstream economists tend to operate as mathematisers rather than quantifiers. Eichner (1983b) notes the "emphasis on technique for its own sake" (p.231) within the current academic economics profession, as does McCloskey's (1994) reference to the dominance in economics of "the intellectual values of the math department". As McCloskey himself would see it, mathematics is no more than one of a range of "rhetorical tropes" (1985) available to the economist for purposes of persuasion.

As already noted, 'rhetorical' here is not intended as an insult, although Barnes (1989) seems to read it this way. Similarly, Ruccio (1989) for example, accepts the usefulness *and* limitations of mathematical models:

> *"mathematical models are useful not because they bear a one-to-one correspondence to the world, but because they help us to understand, or teach, nonmathematical statements; they are just another way to frame or illuminate the issue."*

Barnes (1989) acknowledges the metaphorical nature of mathematics, and calls not for a rejection of mathematical modelling, but a critical awareness of the variety of models in existence, and a willingness to adopt or discard particular models as their usefulness dictates. Perhaps the most famous example of this is the wave/particle models used in subatomic physics. Both are essentially correct, and a physicist will use one or the other in a specific situation depending on the problem they are trying to solve.

In calling for this critical awareness, Barnes acknowledges that mathematical models are constructed rather than discovered (i.e. they are not arrived at solely by logical operations). Bloor (1983), following Wittgenstein, makes a similar point. Certainly when formal models are applied to the social sciences, pragmatism alone cannot dictate the construction of mathematical theory in economics. That is, the choice of mathematics as a tool is made on more than merely 'rational' grounds; a 'thick' reading of economics, as practiced by the rhetorical school, is necessary to understand the uses of mathematics in economics.

Moore (1995), for example, employs a feminist critique of the underlying power structures governing the construction of accounting data. Porter (ibid.) also suggests a strong cultural/institutional role for mathematics in the following passage:

> *"One is reminded of the role of abstract art in fin-de-siecle Vienna, which the authorities approved for monumental buildings precisely because it lacked content and historical meaning. ... Mathematical neoclassicism, while presupposing a broadly liberal individualist basis for economic order, was almost neutral with respect to the narrower but more numerous issues of policy that must lead to endemic conflict in a genuine political economy. The adoption of the mathematical foundations served not only to translate emotion-charged issues into a technical language, but even more to create a basis for agreements that could be viewed as deeper than mere applications. ... The abstract formalism of neoclassical mathematics has served admirably in preserving the unity of the economics discipline." p.160*

Formalisation is, then, a special case in modelling, as the modelling process is brought out in a much more explicit, concrete way than elsewhere. The fundamentals of the process are, however, unchanged; formalisation can only impose rigour from its starting points or axioms onwards into subsequent analysis. The derivation of axioms must be a pre-formal process at some point, and, in human systems, this will necessarily be a contentious process.

1.4 Conceptual Transfer, Novel ideas and Interdisciplinarity

In this final section, the general principles regarding the application of these ideas to complex human policy issues will be discussed. These principles will subsequently be drawn upon in the rest of part 1 in analysing the development of economics as a discipline, and in part 2 in application to the simulation modelling case studies.

As a starting point, a 'complex human policy issue' can be defined as an issue regarding the management of events or situations occurring as a response to, or stimulating, human activity. Such issues are practically significant, in that the way in which they are handled will have consequences for the lives and livelihoods of people. Such situations typically involve a wide range of interacting factors; social, cultural, physical, ecological, etc. An adequate framework for understanding, upon which an informed response can be based, must be interdisciplinary. No single discipline, with a single set of characterisable, agreed-upon theories and methods, can address the situation as a whole.

Another key feature of such issues is that they typically involve many participants, with different perspectives on the issue. Those seeking to respond on the 'advice' offered on the issue are one (or more) group of participants; there may be others. The modeller is engaged as a participant in the situation, rather than as an objective outsider, because no objective position from which to model will necessarily exist. Dialogue between participants is a necessary part of the acquisition of understanding.

Further, the aspects of the situation, as represented by the different disciplines that may be involved, interact to such an extent that they cannot be treated in isolation by the discreet disciplines on their own. More than one theory and/or model will be needed to address the situation as a whole, and dialogue between the participating modellers must be established.

Before going on to discuss interdisciplinarity in further detail, let us treat the related issue of conceptual transfer between disciplines.

1.4.1 Conceptual Transfer

The term 'conceptual transfer' refers to the passing of ideas between disciplines. Theories being what they are, many types of idea may be transferred, ranging from statements regarding the real world to purely formal techniques.

Thus conceptual transfer includes a number of general processes, all of which are of interest.

1. a theory yields a conceptual or qualitative insight, which is then applied to a different theory acting on a different domain. Transfers of these types may be quite implicit; the development of relativity theory, for example, undoubtedly had repercussions that filtered through to other disciplines. Such processes may also occur through popularisation, and hence into the non-specialist world-view of practitioners of other theories. In the 1980's, concepts from chaos theory and fractal geometry found popular expression in a range of fields, for example (often independently of the transfer of any formal representation).
2. a formalism utilised by one theory is transferred to another, where it is applied to a different domain. In transferring the formalism, all formal entities will ideally be mapped onto theoretical entities and thence to observables in the new domain. Alternatively, the original formalism may be altered by discarding formal terms or introducing new ones, or the new theory may retain theoretical entities for which no real-world analogue exists (i.e. properties of convenience). This was the case with the application of 19th Century energetics concepts to utilitarian economics; there was no suggestion that utility was really a kind of energy, rather the mathematics were adopted as a useful way of presenting and manipulating ideas.
3. the *modus operandum* used by one theory is transferred to another. Some economists and other social scientists have been keen to adopt the positivist methods attributed to the physical sciences, for example. The name 'regional science' differs from 'regional studies' in its appeal to the perceived rigour of the physical sciences.
4. two theories previously applied to separate domains may be linked together to create a unified theory covering either a larger or a more specific domain. Thermodynamics, for example, is 'larger' than its constituents energetics and

mechanics, whereas meteorology draws upon various branches of physics and chemistry in application to a specific domain. Both types essentially interdisciplinary studies, as discussed in more detail below.

Concepts of whatever type may become distorted during transfer. It is very rare that an exact identity between the use of a concept in two separate disciplines can be established. This may be taken as an argument against conceptual transfer, i.e. such transfers are inevitably 'flawed'. Menard (1988) has reversed this argument, suggesting that, for a "conceptual transfer" to be "fertile", the analogy from which it arises must "leave room for the decentralisation of the original idea" so as to "preserve an appreciation of the radical difference" between the two subjects.

For example, in thermodynamics, a collection of moving particles will, in the absence of external forces (i.e. in a closed system) achieve a dynamic equilibrium, in which the macroscopic properties of the system do not change over time, despite constant motion of the individual particles. Application of the same mathematical formalisms in utilitarian economic theory map individuals to particles, and the economy as a whole to the macroscopic physical system. The central concept of thermal equilibrium is partly decentralised by the economists assertion that 'motion' (i.e. activity) of the individuals in such a situation will lead to growth (i.e. a state of change). Either the utilitarian economist has failed to grasp the physical connection between equilibrium and rest, and has mis-translated, or the formalism has been distorted by the introduction of additional terms for which no energetic analogue exists (such as technological innovation).

1.4.2 Narrow Interdisciplinarity

One approach to establishing a dialogue between the disciplines required to address a complex human policy issue is to familiarise each participant with the models of the other disciplines, and then combine the formal models into a single formally closed structure. A prime example of this approach is the development of global circulation models (GCM's) of biosphere processes, in which 'sub-models' represent soil, ocean and atmospheric activities, and economic models are used to feed in data on anthropogenic emissions into each biosphere compartment. Figure 1.2 illustrates the structure of such a 'compartment' model in terms of the hierarchy described in Figure 1.1.

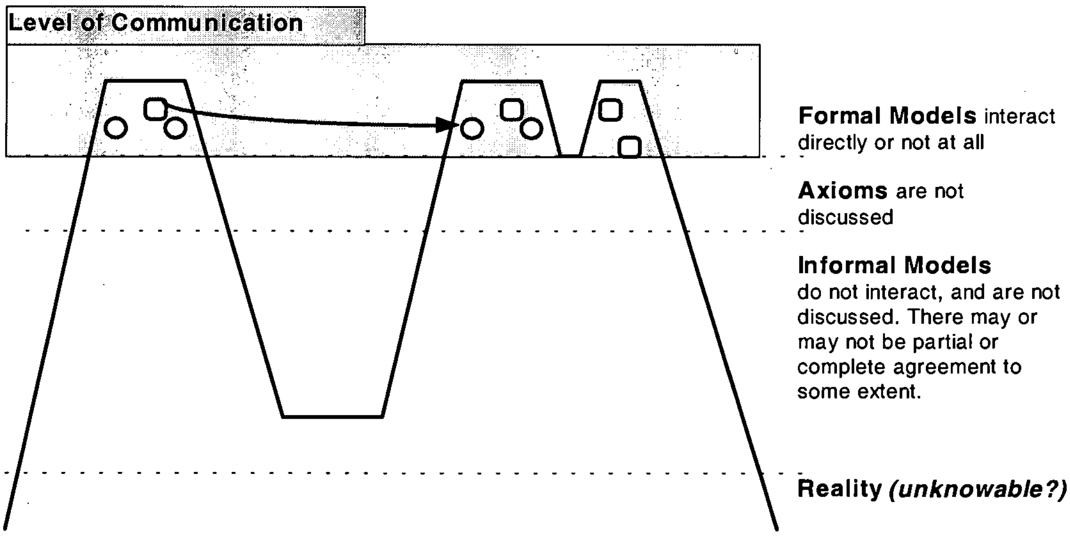


Figure 1.2: Narrow interdisciplinarity: A range of different theories or models, from different disciplines are drawn upon, but communication between disciplines only occurs directly between the formal models, in the form of sharing variables, for example. Differences in world-view (i.e. in the nature of the 'preparation of reality') preclude close interactions in those cases where the informal preparations differ widely, and may overlook informal arguments against the sharing of variables.

Under such a scheme, the pre-formal activities of each discipline require little contact with one another. In the case of the GCM, this does not necessarily create obvious problems, because the biospheric components all share a common pre-formal foundation in the applied physical sciences, and the economic component discusses concepts that are sufficiently dissimilar from the others that no overlap of subject matter occurs. (The economic model applies it's growth rate to calculating emission rates in units of mass/time, which the biophysical models can understand. The growth rate, the bridge between the economic and physical models, is dimensionless.)

This may overlook deeper-seated differences in approach. An atmospheric/meteorological compartment of the model may draw heavily on non-linear dynamics, whereas the economic model may follow a general equilibrium or linear programming approach. The world view offered by these two techniques is arguably quite different (see Prigogine & Stengers, 1985 or Kauffman, 1993 for explorations of the more comprehensive implications of complex dynamics. See also Chapter 2). Thus there is little scope or need for conceptual transfer between one discipline and another.

Practitioners may become familiar with one another's formal techniques, or, at the most, exchange ideas informally.

1.4.3 Broad Interdisciplinarity

In many cases, the different aspects of a situation may require reference to the same conceptual entities, and each discipline may prepare these entities in different ways. The entity most prone to such diverse characterisations is, of course, the human being. The behavioural automaton represented in mainstream economics bears little similarity to the interacting archetypes of Jungian psychology or the 'ego' of anthropological genealogy, but all are prepared descriptions of the same thing. Even within disciplines in the human sciences, there will be disagreement on how to best represent human beings. When discussing ourselves, objectivity is impossible to achieve.

In many complex human policy issues, the narrow interdisciplinarity described above may overlook certain problems associated with bringing together heterogeneous models. Because different formal methods are based upon different preparations of the same subject matter, they cannot be reconciled into a single logical framework (or, at least, not into one in which all viewpoints are fairly represented).

There is, though, scope for useful interdisciplinarity, if one can establish a dialogue that engages the pre-formal as well as the formal assumptions of each viewpoint. This requires that each participant is able to step back from their own formal techniques in order to access and question their own pre-formal frameworks. This is an unusual step to take; in daily practice of a discipline, the pre-formal preparation is rarely confronted directly, let alone challenged. It is a difficult step to take; as Belew and Mitchell (1996, p.19) note, "such conversations can often be unproductive and painful." Nonetheless, it can serve to establish a useful dialogue. Figure 1.3 illustrates this type of interdisciplinary interaction.

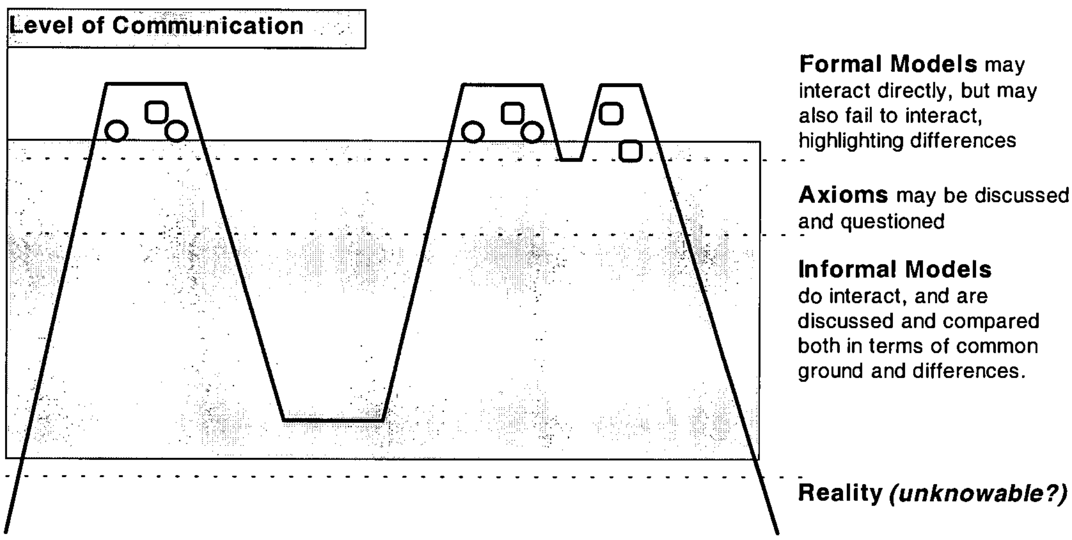


Figure 1.3: Broad interdisciplinarity: The emphasis on the shared work is moved from the development of formal models to discussion around informal foundations. Differences in underlying worldview are seen as an invitation to communicate. Formal models may not be able to link up directly because of differences in the way they have 'prepared' reality, but this can provide an opportunity for questioning axioms and seeing each discipline in a new light. New insights and methodologies may be developed as a result, and existing methodologies may be enriched by the dialogue.

Further, it can be argued that suspension of pre-formal assumptions is an enriching experience when returning to a main line of work. Confrontation does not necessarily imply rejection; indeed, it may lead to a better understanding of the functioning of the pre-formal framework within the discipline as a whole. Access to more than one conceptual framework allows for much broader cross-fertilisation of ideas, through what McCloskey (1995) calls 'toggling'. To 'toggle' between models is to alternate in viewing the world through each model. Neither model need be 'correct' at the other's expense, because (unprepared) reality is more correct than either.

It is important to note that subjectivism of the type that is proposed does not imply that all ideas are to be assigned equal weight. Such a situation would not allow for any development or clarification to occur.

This 'broad interdisciplinary' position does not, of course, sit 'above' the working of formal models, but alongside it. It is itself an articulation of intellectual values, favouring openness over closure, and, as such, is perhaps more closely allied to the opposing than the mainstream tradition. Nonetheless, it may be useful in allowing a more useful dialogue between the many schools of human policy-making to develop.

1.5 Conclusions

The formal (e.g. mathematical, computer-based) modelling approach most commonly conceived of as 'modelling' sits on top of a much more traditional process of deriving conceptual schema of a subject. Acceptance of this leads to a view of the role of formal models in the policy-making process rather different than the positivist/objectivist description which, while widely discredited in the academic literature, is still used implicitly in many policy modelling exercises. Specifically, recognition of the informal underlayer to any model requires that it too be drawn into the policy-making exercise, recasting the process as a discussion rather than a purely analytical task.

Chapter 2 Systems & Relativism

The models discussed in Part 2 (Chapters 4-6) of this thesis are systems models, and share a common ancestry in systems theory. Many other treatments of economics as a system of interactions have been made elsewhere. It is therefore useful here to outline some of the principle characteristics of the main types of systems theories before proceeding to the detailed case studies.

2.1 General Systems Theory

Systems theory is, at its broadest, a methodology for describing and explaining the behaviour of the observable world. It covers a broad range of ideas and outlooks, characterised by the treatment of reality as being shaped by the interdependence between things as much as by the discrete existence of the things themselves. It follows a long tradition in Western thought that can be traced back to Herodotus, for example, and Ovid's poetic vision as outlined in Metamorphoses. One can also find parallels in many non-Western traditions.

Systems theory under its current name has developed during the post-war years, under the influence of authors such as Ludwig von Bertalanffy (e.g. von Bertalanffy 1968), Kenneth Boulding (e.g. Boulding, 1970; 1985), James Miller (e.g. Miller, 1975), the posthumous publication of the works of Teilhard de Chardin (1959) a.o. Particularly under Boulding's influence, General Systems Theory developed as a combination of broad holistic thinking and narrow positivist science. His 'Spaceship Earth' concept (Boulding, 1985) for example, manages at once to convey the notion of the unity and fragility of the planet alongside a technical metaphor suggesting a large machine that can be manipulated intelligently (or 'steered') if one knows which 'levers' to 'pull'.

2.1.1 System Dynamics

The system dynamics methodology was initially developed (under the name of "systems" at least) in the late 1960's by Jay W. Forrester at MIT's Sloan School of Management (e.g. Forrester 1968; Forrester 1971; Meadows & Meadows, 1973; Meadows, 1975), as a numerical technique. System dynamics married the systems outlook to the emerging field of 'operations research', which developed out of military strategy research during the second world war. Numerical systems theory has continued to develop (e.g. Bossel, 1994, gives an up to date account of System Dynamics theory).

The systems description is centred around two generic types, called the *component* and the *interaction.* A component is a discrete part of the system. Components are connected via interactions. Interactions specify how one component is linked to another, and are *directional.* Interactions specify an influence that the *controlling* component has on the *controlled.*

The *structure* of a system is defined by the interactions existing between the system components. The structure of the system encodes information regarding the system's behaviour. The *state* of a system is defined by the values taken by each system component at a given time. Over time, the system may progress from one state to another. In many cases, however, the structure will impose *constraints,* and the number of potential states available will be a subset of N, or a fraction of the total possibility space. The concurrent adoption of certain states for different components may be *mutually exclusive.*

As a simple example, an ecological model may stipulate - either as an explicit rule, or through combination of other rules - that the number of predators cannot exceed a given fraction of the prey population. So while the system may in principle support a large predator population within its possibility space, it can only do so in combination with a larger predator population. A state comprising many predators and few prey is constrained from being reached.

2.1.2 Soft Systems

The concept of "soft systems" was introduced by Checkland (1981) as a reaction against what he saw as an increasingly technical perspective on systems. Checkland chose to stress the subjectivity of the process of conceptualisation of a situation as a 'system'. The 'rich picture' of reality cannot readily be condensed into a single formal representation, argues Checkland, and a consideration of a number of semi-formal representations is more suitable for analysing the range of viewpoints on a given situation. The insights that

Checkland has made available are valuable, but his complete rejection of formal and mathematical techniques seems extreme.

The relativistic approach has been taken by Robert Flood's 'Total Systems Intervention' (e.g. Flood 1995a; 1995b; Midgley, 1995), a method for selecting the relevance of a range of analytical tools to a particular organisational problem. Flood encourages the treatment of an organisational system as a whole, incorporating analyses of the power structures and 'culture' of an organisation in tandem with the more formal aspects of the system. Again, Flood's work is a mixture of holistic and compartmentalised outlooks: the methodology of TSI itself is laid out in very rigid detail as a series of sub-processes or 'modes' in a manner quite at odds with the spirit of the programme itself.

Another recent attempt to develop semi-quantitative systems models is that of Dohnal and colleagues (e.g. Dohnal & Kathrada, 1996), who have developed a formal representation of qualitative dynamics of systems that avoids actual numerical representations. The method purports to deliver the full insights of a 'hard' approach without the distraction of numbers. It is similar in some ways to the techniques developed by the Batelle group's BASICS cross-impact analysis (Luukkanen, 1994 pp.235-240).

2.1.3 Complex Systems Theory

A more recent development of systems theory has been the study of *evolutionary* systems, also referred to as *self-organising*, *dissipative*, *adaptive* and *emergent* (e.g. Kauffman, 1991; 1993; Prigogine & Stengers, 1980;). This field is developing simultaneously in a number of traditional academic fields such as biology (e.g. Dawkins, 1989; Holling, 1994; Nowak et al., 1994a, 1994b), physics (Prigogine & Stengers, 1980) economics (e.g. Arthur, 1989, 1990; Holland & Miller, 1991; Palmer et al., 1994; Sanglier et al., 1994) and sociology (Latane et al., 1994) at present, in addition to the creation of new disciplines such as "artificial life" studies (e.g. Ikegami & Kaneko, 1990; Langton, 1986, 1990). Hence, a comprehensive theory of evolutionary systems has not yet developed, although a number of attempts to impose a unified structure over the various strands have been, and are being, made (e.g. Farmer's (1990) "Rosetta Stone"; Kauffman, 1990, 1993). The roots of this approach can be found in the work of a number of innovators during the 1970's (e.g. Waddington, 1975).

Evolutionary systems, broadly stated, are those in which a feedback exists between the behaviour and the structure of a system. In other words, the set of components in the system, and the set of interactions between them, will change over time. This departs from the basic systems model of Forrester, for example, in which the structure is invariant to time.

One additional theoretical construct is necessary to develop a concept of an evolutionary system from a general system. One can define a component property of *reactivity* (*influence* in System Dynamics terminology) that determines the way in which a component will interact with other components in the system. In an evolutionary system, the reactivity of a component is assumed to be sensitive to its environment.

One can consider a system as a collection of such 'atomic' components. Perhaps the simplest example of such a system is John Conway's Game of Life (Berlekamp et al., 1982; Gardner, 1979), in which components are laid out on a regular rectangular grid. Each component possesses only two states, corresponding to "on" and "off", or "alive" and "dead". Time is simulated in discrete intervals and, at each interval, a component is switched "on" if it has between 3 and 6 "living" neighbours in the surrounding eight cells, and "off" in other cases. In the biological analogy from which the name gets its title, these upper and lower boundaries correspond to death by overcrowding and starvation/loneliness respectively.

Under the rules of the Game of Life, most possible arrangements are highly unstable, and will rapidly alter as (simulated) time progresses. Certain structures, however, are stable, and will, if undisturbed, persist indefinitely. Other structures are dynamically stable, operating in closed limit cycles. Yet others form repeating patterns that move across the grid, such as the simple "glider", an arrangement of between four and six cells. The highly complicated "puffa train" is a moving construct that leaves a stable trail in its wake, and generates a steady stream of "gliders" from one side. The work of Wolfram, Packard and others on the generic dynamics of cellular automata have characterised these different 'regimes' within specific rule sets and within groups of rules.

This behaviour of the Game of Life introduces the concept of a hierarchical system. The arrangements of cells such as "gliders" and "puffa trains" may be thought of as components in an interacting system themselves. This notional system operates at a "higher level" than the simple rules of the Game of Life themselves. The higher-level system can be fully understood by reference to the lower-level rules only, but description at the higher level provides a simpler way of looking at it. One need not know the rules of the game at a cellular level in order to describe the behaviour of gliders and puffa-trains adequately.

Having introduced a two-level hierarchy, it is easy to introduce further formal levels. Within the Game of Life, stable structures composed of a number of interactions between "gliders", "puffa trains" and similar components has been postulated. At the extreme, it has been proven mathematically (Berlekamp et al., 1982) that the Game rules allow for universal computation, i.e. they can generate structures that store and transmit information over infinite distances/times, and so can support a structure capable of performing computations.

The Game of Life allows for the existence of a huge number of hierarchical levels of organisation within a dynamically stable system. This concept of hierarchy arises inevitably from the feedback between fundamental component reactivity and environment. Such a system, when viewed from any hierarchical level, has the following properties:

- Every persistent component is dynamically stable within its current environment
- If the environment changes, it may lose its stability, and re-structure itself
- No component is therefore intrinsically stable or unstable
- Dynamic stability can be achieved under conditions which do not favour static stability
- Dynamic stability of a higher level component relies on instability of lower-level components (e.g. in a stationary oscillating system, individual cells will switch between the "on" and "off" states during the oscillation cycle)

The arrangement of higher level structures that can "process" and "excrete" incoming fluctuations and/or disorder underlies the term "self-organising system", as the system is seen to adopt a configuration (i.e. to organise itself) so as to persist under conditions that would otherwise disintegrate it.

Within the physical world, such systems can be commonly observed. The convection cell formed by boiling water, and the tornado are two examples. A number of authors have also described human societies using the concept of self-organisation (e.g. Allen, 1992, 1994a; 1994b; Hinterberger, 1994; Park, 1995; Faber & Proops, 1994; Waldrop, 1994).

Arguably the game of life and related cellular automata are a simple class of 'complex' system. The rule-set itself is not hierarchical, and, although new 'higher level' components emerge from the low-level rules, there is no genuine 'emergence' analogous to the development of a new species. Other classes of complex system, such as genetic algorithms (Belew & Mitchell, 1995), do allow for 'evolution' of the rule set over time, but again this is simply effected on top of an invariant set of 'metarules' (i.e. the rules that govern the definition of rules). The question of whether 'true emergent behaviour' can be generated by a formal system is hotly debated within the complex systems literature at present, with no clear answer being apparent at present.

2.2 Key Properties of Systems

This section is intended to act as a simple guide to key features typical of systems and their behaviour. Certain key properties are identified and defined, to which reference will be made in later discussion.

2.2.1 Control, Dependence & Multi-factoriality

A system can be formally described as a set of components or sub-units, which interact with one another over time. The component may be a molecule, an animal, an economic sector, or whatever. The underlying formalisms are applicable to most situations.

Changes in the property of one component will generate changes in other components, creating further changes. Any single interaction between two components is causal and directional, with changes in the controlling component affecting the dependent component. However, this distinction is local only to the given interaction. Even in a relatively simple system, many variables will act as both controller and dependent.

The controller/dependent distinction may be blurred further by the existence of feedback loops. These occur where a series of interactions exist such that each actor's behaviour (within the "loop") indirectly influences itself. Where components A, B, C & D constitute a feedback loop, any changes occurring in A will eventually create further changes in A, and similarly with components B, C & D. A is both controller and dependent, and so is every other entity in the feedback loop. This often gives rise to "non-linear" behaviour in the system, which can be of a counter-intuitive nature.

Further, a given component may be engaged in more than one feedback loop. Where multiple feedbacks interact with one another, the net, observable behaviour of any one system component is the result of multiple competing factors. Counter-intuitive behaviour arises most readily where the net balance is small compared to the gross values of competing factors, and so relatively small changes in a contributing factor may generate large changes in observable quantities. International finance is an example of such a system. In the UK in 1991, an invisibles balance of payments of $4 billion included a credit of $78billion and debit of $77billion in trading of external assets and liabilities (CSO 1992b, Tables 1.1 & 5.1).

2.2.2 Smoothness and Stability

Systems theory has shown that stability of a configuration does not necessarily relate to smoothness of function (as in the instability of components within a dynamically stable structure, observed for the Game of Life). Holling's (1994) ecological function model emphasises the role of "creative destruction" in maintaining the vigour of the ecosystem, as does the work of Nowak et al. (Nowak & May, 1992; Nowak et al., 1994a; 1994b; May & Nowak, 1994) on spatial distribution of species, and Mollison et al. (1994) on measles epidemics. In the human sciences, Palmer et al. (1994) and Sanglier et al. (1994) have demonstrated the volatile behaviour that results in financial markets as a result of consistent learning behaviour on the part of the individual agents.

2.2.3 Equilibrium & History

Path-dependence or non-ergodicity, is the property whereby a system's current state can only be described by reference to it's previous states (Arthur, 1989). In other words, the history of the system is important, and historical events have a lasting impact upon future trajectories. In contrast, in an ergodic system, "noise" from "random" historical events will be smoothed away over time, and imposition of different random patterns on the system inputs will yield identical results in the long term.

Associated with non-ergodicity is the concept of specificity; the current state and structure of a non-ergodic system are a unique outcome of that system's specific history.

Empirical "rules" governing system behaviour derived from observation are specific, then, to that configuration of the system, and will not necessarily hold true under all conditions.

Much of the innovative nature of the complex systems approach comes from re-considering the influence of history, or incremental development upon a system. Partly due to computational expediency, much of the early operations research focussed on equilibrium states of systems, and, while the founders of the equilibrium approach may have understood the problems associated with such a timeless perspective, the concept of equilibrium became a cornerstone of much system theory, rather than a convenient approximation.

Theories of urban geography offer a good example of this process. Early developments in the bid-rent theory (see Chapter 6) of concentric zone patterns of cities were made in the awareness that the picture generated was an idealisation; that in reality, a number of 'complexities' such as landscape features, institutions, etc. 'distorted' the concentric patterns into the irregular forms of real cities (e.g. Alonso 1964). Later authors invest a greater prescriptive content to the equilibrium model; Fujita & Kashiwadani (1989), for example, attempts to measure the 'efficiency' of real urban spaces by their conformity to the bid-rent model patterns.

It is interesting to note that differences in the formal representation of the system do not necessary create differences in behaviour. The models of technological penetration of Arthur (1989) and Marchetti (1983) discussed later in this chapter are extremely path-dependent and equilibrium-based respectively, and yet both reach similar outcomes.

In Chapter 3, these issues are discussed further in relation to the representation of time in economics. The particular case of urban morphology is discussed in part 2.

2.2.4 Counter-intuitive Behaviour

Non-linear systems behaviour is often labelled as "counter-intuitive". That is, it does not behave in the way that we expect it to. This statement reflects human perception as much as it does systems behaviour. O'Connor et al. (1993) have demonstrated the inability of humans to anticipate the behaviour of discontinuous events. The tension between the discontinuous behaviour of the world and our continuous informal models is often considerable. Space precludes a more detailed consideration of this point within this thesis.

2.3 Representing Complex Systems

Even at its most rudimentary, the concept of 'system' is a model. Certainly, well-articulated mathematical system dynamics models are models, but informal conceptions of phenomena as components and interactions are models too. A degree of preparation (in Cartwright's sense of assembling a set of conceptual tools) is required to see the phenomenon in this way. One must decide the level of hierarchical detail to be represented, the number and nature of components and interactions to be considered and the nature of *their* representation (i.e. numeraire, or, more generally, aspects to be considered).

The discussions in Chapter 1 on the nature of modelling, on alternating between representations are salient here, then. One can argue against the 'mechanical' representation of reality as a general system, or, at least, against treating such a representation as though it were the truth. An analogue to the alternating approach (and to McCloskey's (1994) 'toggling') can be seen in the Total Systems Intervention (TSI) methodology of Flood & Jackson and their colleagues (Flood, 1995a; 1995b; Midgely, 1995;). TSI argues for recognition of the subjectivity of models, and the temporary adoption of one or more (typically informal) representations of a situation in order to derive a richer insight into the 'real' situation.

Complex systems theory has also arisen partly as a critique of the mechanical representation of systems. The Brussels school, notably Prigogine (Prigogine & Stengers, 1980) and Allen (1992, 1994a, 1994b) have been particularly clear on this point. Allen emphasises the importance of microscopic diversity, both in the timing of events and the characteristics of the individuals in a population, in generating 'organic' behaviour that deviates significantly from the average trajectories that a macro-scale general systems model would predict (Allen 1994a: 586-7).

As Allen and his colleagues note, the impact of these ideas on the use of the simulation models is significant, requiring the user to shift from a deterministic 'forecasting' approach to a probabilistic 'monitoring' approach (Perez-Trejo et al., 1993). The essential features of a teleological concept of time (see Chapter 3) are made explicit. The role of the modeller becomes less that of an external manager, more that of participant.

As numerical models requiring a degree of formal rigour, the simulation tools of complex systems still depend upon a mechanistic conception of reality. What has been achieved is to push the explicit mechanisms to a hierarchical level lower than that of interest to the model user, so that the phenomena of importance are developed in a pseudo-organic or pseudo-evolutionary fashion. Unlike Conway's Game of Life, *real* observed phenomena (equivalent to the puffa-trains and gliders) are not *really* generated by underlying mechanistic rules, but by processes that can either be (poorly) represented as mechanisms or analytically decomposed by reference to a further lower set of mechanisms.

In general, then, simulations of complex systems are useful as approximations to real events. By representing processes in greater detail, more realistic behaviour can be captured, side-stepping the mechanistic pitfall *at the level of interest of the particular model.* In absolute formal terms, of course, there is always another level of hierarchical representation waiting to be uncovered; the fact that this is not done rests on limitations of computational capacity and data collection and management. The models operate satisfactorily within the intellectual values of the engineer, if not of the mathematician.

The above considerations do raise a more crucial problem for complex systems models, however. At the level of mechanistic representation, simplifying assumptions need to be made. The modeller must assess whether the assumptions chosen in his/her design of model replicate realistic behaviour at the higher 'organic' level by skill or good fortune. S/he is faced with McCloskey's (1994) 'Metatheorem on hyperspaces of assumptions':

> *"For each and every set of assumptions A implying a conclusion C and for each alternative conclusion C' arbitrarily far from C (for example, disjoint with C), there exists an alternative set of assumptions A' arbitrarily close to the original assumptions A, such that A' implies C' " McCloskey p.138*

That is, the pathways involved in the emergence of the pseudo-organic behaviour from the mechanistic rules are too complicated to allow an intuitive assessment of whether the underlying causes are 'correct' or 'realistic'. Unrealistic or incomplete representations at the mechanistic level may generate plausible higher-level behaviour, but, being founded on incorrect premises, the insights derived may be drawn into question.

In a narrow sense, one may counter this by conducting a sensitivity analysis on a number of contending mechanistic micro-structures. This only offers a limited solution; there will always be one extra feedback process or component that one might have considered, but did not.

As with simpler mechanistic models, then, complex system models retain their subjectivity, albeit for slightly different reasons. The ambiguity of their link to reality compounds the narrower limits of stochastic modelling in forcing one to adopt a new approach to the interpretation of simulation results.

2.3.1 A Case Study: Three Models of Technological Change

Perhaps the best way of elaborating the above argument is by example. In the following section, three models dealing with the issue of technological change are presented below, and their approaches to the issue compared.

Allen (1994b) describes a model of an 'industrial ecology', in which a number of agents (firms) are involved in the production of goods. Goods are characterised by position in a hypothetical 'landscape'. Closely similar products are mostly in competition with one another, but, beyond a certain point, products become sufficiently dissimilar to avoid competition. Initially, divergence from a well-established product will fall within a 'competitive shadow' but may eventually move away from the 'parent' type, ultimately resulting in a rich mixture of interdependent processes. Importantly, market niches are created by the existing pattern of production, rather than innovation spreading outward to reach pre-existing niches.

Arthur's (1989) model focuses on the competition between two rival products, based on their relative market shares. The market consists of a population of customers with stochastic behaviour, who are presented with a series of choices between the products. At each point, customer behaviour is influenced by the history of previous choices regarding the products, which are subject to 'increasing returns' (greater market penetration promotes new customers to favour a product over its rival). What is initially a randomly-fluctuating pattern eventually reaches a point of no return at which one technology dominates the other following a positive feedback process (in Arthur's terminology, the market 'locks in' on the dominant product). Importantly, there is no way of predicting which product will dominate, only that one or the other eventually will.

Marchetti & colleagues (Marchetti et al., 1977; Grubler et al., 1993; Grubler, 1995) have applied 'logistic substitution equations' to a wide range of competitive situations, such as world energy supplies (Marchetti, 1983), Transport Systems (Marchetti, 1994; Grubler et al., 1993), and the spread of monasteries throughout Europe (Grubler 1995). These models are purely descriptive, and in some cases the authors invoke dynamic equilibrium style arguments speculatively when discussing their results (e.g. Grubler & Nowotny, 1990), and in others refer to path-dependent properties such as 'emergence' (e.g. Grubler et al., 1993). In all cases, the full pattern of penetration by a new technology or practice is entirely predictable given the first 5% or so of the data, if the logistic equation is applied. This assertion seems at odds with the path-dependent principles of complex systems, although the outcome can be interpreted as quite similar to Arthur's increasing returns model.

Some salient features of the three models are summarised in table 2.1 below.

	Allen	Arthur	Marchetti et al.
2.3.1.1 Aspects Considered			
Origin of Innovation	yes	no	no
Consumer Decisions	yes	yes	no
No. of Competitors	many	2	2
Properties of Product	yes (abstract)	no	no
2.3.1.1.2 Epistemology			
Causal Explanation	yes	yes	no
Determinism	no	no	yes
(Mostly) Predictable*	no	yes	yes
2.3.1.1.3 Behaviour			
'Lock-in'	no	yes	yes

beyond the first 5% or so of market penetration, the outcome is predictable

Table 2.1: Comparison of three models of technological change

2.3.2 Aspects Considered

Some of the difference between the models can be explained by a difference in the aspects covered. Arthur's model, for example, is the only one to explicitly model the activities of the end-users, albeit in a highly stylised form (preferences are not explained, but randomly determined). Allen's model is the only one to attempt to characterise the products themselves, although again this is handled in a very abstract way via the phase space representation. Hence Allen's model can say something about the origins of innovation, whereas Arthur & Marchetti's models take the presence of a dominant and challenging technology as a given.

From this viewpoint, different systems models can be seen as complementary; each has something to say about the situation, but none can cover the full range available to the entire set.

2.3.3 Epistemology

Below this there are epistemological differences informing the models. Allen & Arthur's models differ from Marchetti's in that the former attempt to offer a causal explanation of events. There is a difference in purpose, then - although Arthur and Marchetti provide similar generic results, Arthur is more concerned with why events occur the way they do hence the abstract nature of his formal work. In the discursive sections of his work, he discusses video recorder formats, typewriter key layouts and chalet architecture, but there is no attempt to formally link these to the models (i.e. to take the case studies beyond the anecdotal stage). Marchetti et al., on the other hand, concentrate heavily on the application of real test cases (claiming over three hundred successful applications), and display a robust scepticism regarding the influence of the underlying causes on the whole. At the root of these differences lies a difference in intellectual values, between Marchetti the physicist and Arthur the mathematician. These differences inform the design of the models at the 'aspects considered' level, introducing a degree of incompatibility at the formal level.

2.3.4 Behaviour

The third area in which difference can be examined is in the behaviour of the models. It has already been noted that, although Arthur and Marchetti come at the issue from quite different positions, the behaviour of their models shows some similar features. This echoes McCloskey's Metatheorem (see above) to some extent: not only can similar assumptions generate different behaviour, but radically different assumptions can lead to similar results. (As a second example of this, the difference in outcome between Arthur & Allen's models may be noted: Allen's multi-competitor model never settles down to a regular pattern. The stock market models of Palmer et al. (1994) produce a similar dynamic regime to Allen's model, and these are basically a direct expansion of Arthur's increasing-return agents.)

The representation of a situation as a systems model is necessarily incomplete: by comparison with other models or reference to experience it is easy to identify elements that have been omitted or glossed over. Although these omissions can be seen as failures of the model to represent the truth, this viewpoint ca be criticised on two points:

- it assumes an underlying objective truth towards which representation is aimed
- it assumes that the model is intended as a passive reflection of this truth, rather than as an active communication

These points have both been considered in Chapter 1, and alternatives based on the rhetorical model proposed. The following section discusses the implications of moving beyond a truth-based metric of fitness in simulation modelling, and discusses one methodology that may provide an indication of a way forward.

2.3.5 Representation and the Communication of Truths

Most descriptions of scientific methodology are based on a process of choice between alternative theories using some criteria of how close each idea comes to representing the truth. The simplest such approach is that of verification, as proposed by Carnap (Schilpp, 1967). Popper's falsifiability (1989) is a more subtle approach, recognising the practical impossibility of discovering the ultimate truth, but it maintains 'closeness to the truth' as its ideal. Other more relativist approaches (e.g. Kuhn, 1970; Feyerabend, 1975; Cartwright, 1983) still focus on the truth content of a theory as a guide to acceptability.

The predominance of truth-based criteria in methodological discussions stems from the focus of most philosophy of science upon the natural sciences, and physics in particular. Physics, by the nature of its subject matter, has been unusually (although not completely) successful in establishing a universal set of conventions and theoretical constructs through which inscrutable reality can be examined. The establishment of such a consensus is a necessity for developing a truth-based measure of the worth of a theory.

Cartwright (1983) describes the process of theory development or 'theory entry' as beginning with a 'preparation' of reality into conceptual entities about which communication can occur. It is argued here that the subsequent development of a theory rests to a great extent upon the degree to which a common 'preparation' can be established and agreed upon. This will necessarily depend upon the subject of study; in large part, the 'success' of physics is a result of the simplicity of defining its subject matter, rather than physics being 'more developed' as a science.

In the domain of the social sciences, one of the main theoretical entities that must be 'prepared' or characterised is the human being, and an objective characterisation of human motivation is impossible. In other words, any social science must be inherently subjective, at least as far as representing human behaviour is concerned.

Within (and not exclusively within) the social sciences, then, more than one truth exists regarding any situation. At the extreme, there is a separate truth for each participator or stakeholder, although in many cases these will cluster into a few distinct viewpoints. The choice between competing theories about such a situation can no longer be made by appeal to truth alone, because there is no one truth (not even a single provisional truth). Issues of fairness of representation must also be considered, and the process of choosing begins to develop rhetorical, as well as scientific properties.

The implications of a theory are important: especially, but not exclusively, in complex human policy issues, where there are vested interest groups involved. Umberto Eco's novel "The Name of the Rose" (Eco, 1984), for example, describes the political and social implications attached to a seemingly obscure and learned debate.

It has previously been argued that different modelling representations of an issue will focus upon particular aspects of that issue at the expense of others (see Chapter 1). A given aspect is, then, either present or absent within a given representation. This idea can be usefully extended by noting that those aspects that are present may be so either implicitly or explicitly.

It is not sufficient to include all participants within a model, as there are different ways of representing the range of options open to a human actor. For one thing, the full range of actions open to the individual is probably too broad to model comprehensively. A model representation necessarily has a constrained behavioural range; the choice of what to include and exclude is essentially subjective. Participators in a situation are therefore characterised in particular roles by a model of the situation; as active or passive, reactionary or adaptive, even as heroes or villains.

This characterisation is unavoidable (i.e. fairness, or impartiality are not completely achievable goals). It is therefore important that the characterisation be open to inspection, so that it may be challenged or discussed (c.f. the 'broad interdisciplinarity of Chapter 1). An explicit model of a range of behaviour represents each option as a discreet, visible entity. An implicit representation may 'conceal' the behavioural aspect under a utility function, feedback loop or other aggregated representation.

This is not to suggest that all models of individuals are explicit, and all aggregated models implicit. The *homo economicus* of classical economic theory conceals many behaviour patterns beneath its rational self-optimisation. Conversely, an aggregated function representing the response of a population to some event may be considered explicit, if it is clear about the reasoning behind the aggregation, and its own shortcomings.

Other properties of a situation may also be represented explicitly or implicitly, and the choice between the two may be seen as important. Further, the representation of the situation as a whole may be such that choices regarding implicit/explicit representation for particular aspects are not independent of one another. Saraph (1995) has developed these points to some extent in presenting his 'SysLogic' methodology as an alternative to conventional System Dynamics.

An example serves to illustrate. Consider a water supply system, composed of a reservoir tapping the local hydrogeological cycle, an outlet to an urban region, and local water storage tanks located within each residential block. One might model this using system dynamics, developing linkages between the demands for water locally, the levels of water in local tanks, and the level of water in the reservoir, i.e. as a stocks and flow model of the water, with rates of flow being driven by auxiliary variables representing demand. Such a representation would allow the dynamic regimes of the system to be characterised, and the feedback control structures identified.

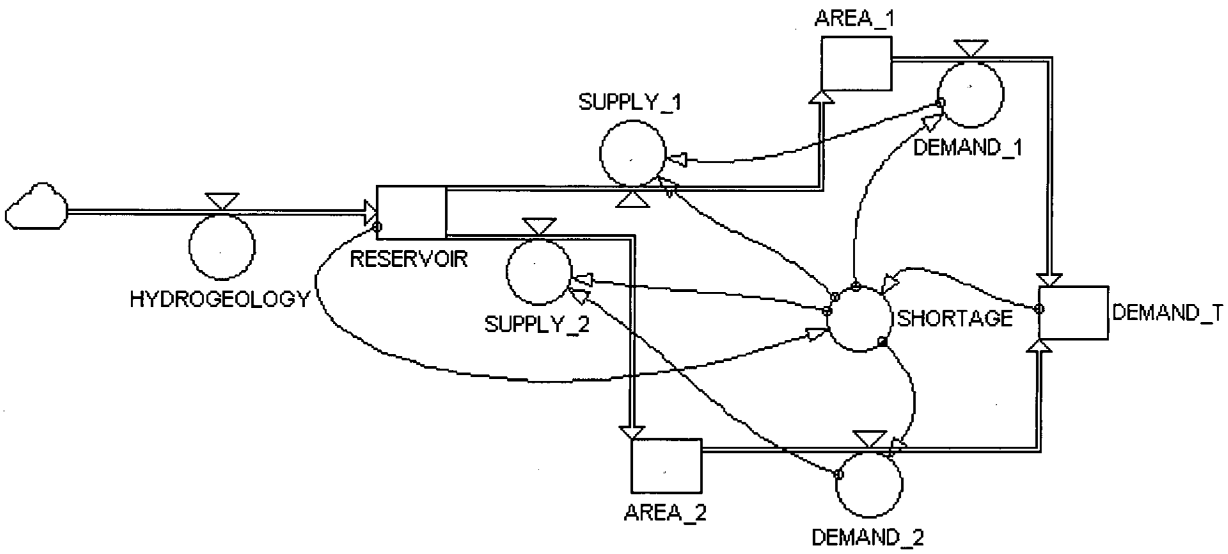


Figure 2.1: Sketch of a System Dynamics model of a water supply system. A central reservoir feeds water to two local areas. Feedbacks between supply and demand for water are sketched in, allowing for the possibility that residents would conserve water during scarce times. (We may assume that the hydrogeology rate, which feeds the entire system, is exogenous, and variable.)

Figure 2.1 offers a sketch of such a model. The system it describes is a mixture of physical laws and behavioural options. Most of the stock-and-flow system describes physical stocks of water, but the links between shortage and demand, for example, are attempts to represent people's responses to events. Many more linkages could be introduced in a more realistic model - distribution of water use between functions (household, industrial, irrigation, etc.), trade-offs between current and future water usage, etc. Although a System Dynamics representation could encode a wide range of decisions, they would not be directly visible. Upon 'opening up' the model (e.g. examining the source code, or asking the modeller about the technical details of what they have done), the reader would be presented with a nest of feedback structures from which the policy-relevant information would be difficult to disentangle.

A SysLogic encoding of the situation operates in reverse: the apparent coding of the model (that which is apparent upon reading the source code) expresses relationships in terms of actors and their responses to pre-defined events (what Saraph calls 'inscripts'). The feedbacks driving model dynamics are still present, but are implicit within the description of actors and their inscripts. Anyone wishing to question the representation of a policy option encoded into the model is given a readable account of the encoding, and alternative events or responses can easily be added to the system.

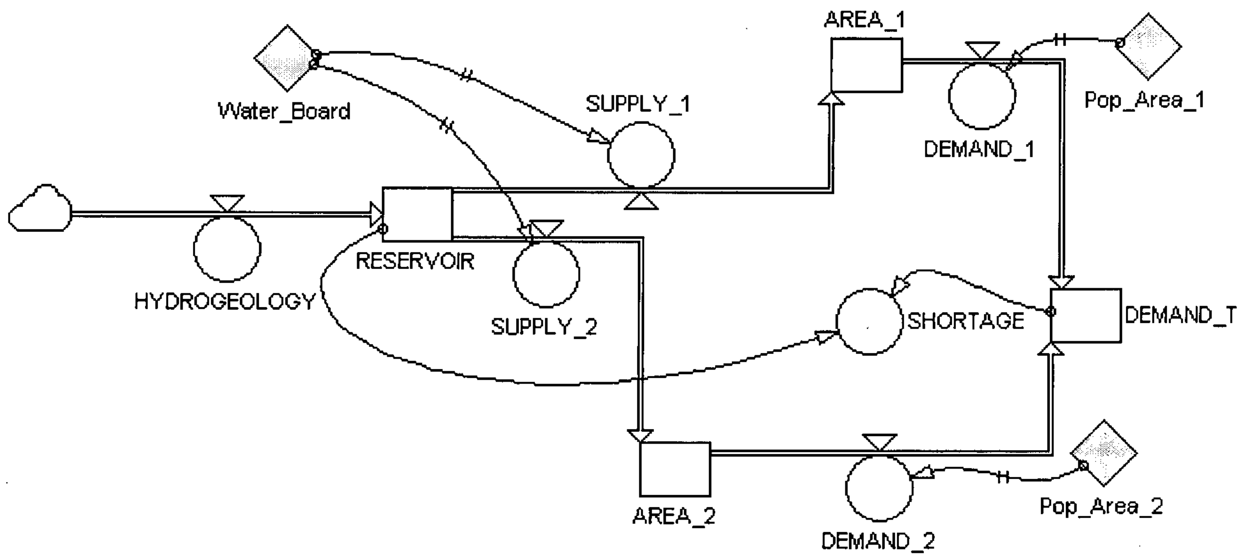


Figure 2.2: Sketch of a SysLogic model of a Water Supply System. Actors are represented as shaded diamonds, and their influence on rate variables as notched arrows.

Figure 2.2 offers a sketch of a SysLogic interpretation of the System Dynamics model given in Figure 2.1. SysLogic is still basically System Dynamics, and the physical module is unaltered - water flows through the reservoir and local storage systems. All other influences have been removed however, and replaced with 'actors', model entities representing decision-makers. Three actors are identified. The water-board is responsible for releasing water from the reservoir to the local areas, and the population of each area is responsible for releasing water from the local storage systems.

Each actor is supplied with a set of 'inscripts', determining

- what information they have access to
- how they respond to that information

The water-board, for example, might make its decisions based on the level of the reservoir, the level of the local storages, predicted hydrogeology patterns, demand, etc.

The difference in encoding is not designed to produce a different set of results, or to give access to a new dynamic regime (which would usually be the aim of converting a System

Dynamics model into a Complex Adaptive System, say). Indeed, the formal behaviour of the two models may well be identical. The purpose of opting for a SysLogic encoding is to make communication of the model more transparent, to phrase it in a way that better represents the situation as seen from a human perspective. Questions like 'who are the key players? How do they decide what to do?' are easier to grasp than 'what are the principle feedback loops?'.

In many situations, the choice of language of expression would not be a major issue, as the ideas to be expressed are subject to established conventions. In the case of complex human policy issues, however, many of the ideas involved in the model are necessarily contentious (e.g. the weightings used to ration out water in the examples above), and a readable account of them is important.

A conventional System Dynamics model can, of course, offer a readable account by supplying additional written documentation, but in order to provide an account that can be queried and altered, additional 'policy switch' variables and feedbacks will be necessary, and require reprogramming of the system. (This presents two problems: at a technical level, reprogramming opens up the possibility of introducing error; at a policy level, requests for changes require the presence of an expert reprogrammer, and probably a time delay while the model is tinkered with.) A SysLogic model is more likely to be able to offer a representation of policy that can be immediately altered without introducing error, although the presence of an expert cannot be ruled out altogether.

It can be argued that there are two quite independent factors regarding the representation of an aspect in a model. First, there is the issue of whether it is represented in the formal structure (i.e. whether some variables are designed to reflect properties relating to that aspect). Secondly, there is the issue of whether it is explicitly considered in the model, or whether it is 'accessible' to the model user. As the two are independent, there are four ways of representing something in a model:

- the entity is represented explicitly by the formal structure. There are model variables designed to reflect properties of the entity, and this design is apparent to the model user. This allows the model user to form an opinion of how the entity is represented and, ideally, modify the representation.

- the entity is represented implicitly by the formal structure. Although variables in the formal structure reflect properties of this entity, this is not obvious to the model user. Any assumptions regarding the design of the representation are hidden in the model's internal workings, and the model user can either accept them or is unaware that the entity has been 'stylised' within the formal model at all
- the entity is not represented within the formal structure of the model, but accompanying literature (either printed or online e.g. help system, a results viewing package) discusses the importance of the omission in interpreting the model results
- the entity is ignored by the model: it is not represented within the formal structure, and is not discussed in the accompanying literature

What SysLogic does, then, is provide a structure that is more likely to result in explicit modelling of human behaviour, and implicit representation of causal chains and feedbacks, whereas system dynamics operates the other way around. The issue of whether an aspect is included or excluded from the formal structure altogether remains, of course, an issue for the modeller to deal with.

A final advantage to SysLogic can be identified if the limits of the modeller's intellect are also recognised. So far the discussion has assumed that the model designer understands their model fully; in practice, this is rarely the case. Further, understanding how the model structure works, and recognising how it refers to reality, are two different things. As has already been noted, what starts out as a simplifying convention may end up as a normative prescription of how reality ought to behave, if successive generations of modellers and theorists lose sight of the subject of discussion because of emphasis on formal techniques. Further, as model design inevitably involves a filtering or abstraction of reality, and a discarding of 'non-essential' aspects, a formal representation closer to an everyday understanding of a situation is less likely to narrow its focus over time than one in which real mental effort must be made to see reality beyond the formal techniques.

A representation of a contentious situation in terms which translate easily into the entities of everyday experience is valuable to the modelling community as a whole.

SysLogic is presented here as an example of a method attempting to do this, not as a logical conclusion to the desiderata outlined above. Some Complex Adaptive Systems follow a similar route to SysLogic, in terms of providing a more human-centric representation. In breaking down aggregated parameters into populations of agents, questions of motivation are moved to the level of the individual, where they rightly belong. However, Complex Adaptive Systems modelling goes further than SysLogic in also developing new types of dynamic regime, emergent behaviour, greater adaptability, etc. SysLogic, which remains firmly within the System Dynamics school, serves as a better example here because it does not offer any technical or computational advantages, but is focussed solely on the communication issue.

Chapter 3 Conceptual Transfer in Economics: Towards a Thick Reading

This chapter discusses the development of economics as a complex human policy discipline. Initially, the discussion is about the intellectual content of the theories, which *is* central to understanding the process of development. The final section expands upon the study of intellectual content, placing the ideas of economics within their broader context so that a more satisfactory understanding of the discipline as a whole can be achieved.

The histories presented here are not intended to be comprehensive, and are inevitably slanted towards the points to be brought out in the subsequent discussion.

3.1 History of 'Conventional' Economics

The acknowledged founder of economics as a discipline is Adam Smith, whose "Wealth of Nations" (Smith, 1760) introduced the notion of the 'invisible hand of the market'. Although economic thought *per se* did not originate with Smith, he is generally credited with drawing it out as a separate discipline, whereas previous economic discussions took place within a context of other concerns such as philosophy and religion (Staley, 1991 p.3). Smith was, in fact, established as a moral philosopher prior to the Wealth of Nations' publication, and was a strong advocate of the duties of citizens and governments to intervene in the interests of justice. His ideas have since been adopted as strong arguments against government intervention.

3.1.1 The Marginal Utilitarians

The subject subsequently underwent critical changes in the 19th Century, following the rejection of the labour theory of value (that is, the value of a commodity is determined by the labour required to produce it) that had, until then, characterised the discipline as a whole. David Ricardo, initially a follower of the labour theory of value, instigated the shift towards a utilitarian theory of economics, in which value was seen to be linked more to the preference of the user than the efforts of the producer. In a predominantly Marxist analysis, Henry (1990) notes the social expediency of this shift, as the capitalist class moved from 'cottage industrialist' in the 18th century to the dominant class in the 19th.

The marginal utilitarian theory was brought to fruition by:

- William Stanley Jevons (1871) who introduced many of the concepts of marginalism regarding utility and value
- Leon Walras (1954 [1874]) who developed the mathematics of the general equilibrium
- Carl Menger (1950 [1871]) who discussed the structure of wants in relation to people's *evaluation* of goods, not market values

These authors brought two new elements into economic theory around the 1870's; the concept of utility as an explanatory term, and the idea of marginal returns and productivity, sometimes embodied by the tools of differential calculus (although Menger, and the Austrian school that developed from his work, eschewed mathematics altogether).

The introduction of utility reflected a change in emphasis from political economy to economic science, as Marshall was later to phrase it (Staley, 1989 p.134). Where the classical theory was concerned with the wealth of the state as a whole, and the distribution of this wealth between aggregate social classes, the utilitarians were concerned with the behaviour of the individual in maximising their *utility* in the case of consumers and profits in the case of producers, for given combinations of preferences and resources. This entailed a shift towards a more descriptive position compared with the policy-driven (hence 'political') work of the classical school.

The concept of marginalism was not new in itself; the agricultural economist von Thunen (1783-1858)'s location theory developed concepts of marginalism in relationship to transport costs of agricultural goods around an *isoleerte staat* (literally 'isolated state'; a remote city involved in exchange of industrial and agricultural goods with its hinterland), and also in his concept of a natural wage (Staley, 1989; 134-6). The novelty of Jevons, Walras, Menger and Pareto was in applying marginalism to utility.

Jevons, Walras and Menger developed their theories mainly independently from one another. Certainly, it would be misleading to treat them as a unified school, or to ignore the considerable differences in their work (e.g. the extent to which mathematics was considered important). A full discussion of the finer points of the marginalist revolution is outside the scope of this thesis, however, and it is necessary here to deal only with an amalgam of their work. The basic principles of the early utilitarian model are laid out below (based mainly on Staley's (1991) description of Jevons' and Walras' models).

The concept of utility originates with Bentham's felicific calculus of pleasure and pain (Bentham, 1789). Utility is an aggregate concept intended to measure the sum of pleasure experienced and pain avoided by consuming a commodity. Marginal utilitarianism distinguishes between the total utility obtained from consuming a good and the increment of utility obtained from consuming an additional amount. A decrease in marginal returns is assumed for all goods, i.e. each subsequent unit consumed produces a lesser increment of additional utility than the last (in other words, appetites become sated). Young (1928) and, much later, Arthur (1989) were to question this assumption, and demonstrate the marked differences that increasing returns would make in some markets.

Where multiple goods are considered, the utility gained from each is taken to be independent from that obtained via other goods. (This latter point is, presumably, a simplifying assumption made for tractability's sake.) From this description, trade, for example, could be understood by suggesting that both parties benefit more from the utility of goods received than by the utility foregone in goods sold.

The economy as a whole is viewed as a series of interconnected markets, with events in each one influencing those in all others. The price of a product depends upon the price of it's substitutes, as well as on the income and preferences of purchasers. Purchaser's income depends upon the revenue they obtain from the products made with the goods that they own. In short, everything depends upon everything else, resulting in what might be termed (in a language that did not exist in the 1870's) a holistic system driven by feedback loops. Walras and later Pareto (1984 [1906]) and Edgeworth (1925) developed these ideas into a tractable mathematical set of differential equations.

During this time, economics was heavily influenced by the development of the physical sciences, notably energetics and the emergence of thermodynamics. The early marginalists adopted the formal models of the pre-entropy thermodynamicists with little or no alteration. Mirowski (1989) argues that the close identity between formal models arose from a failure of the economists to understand the physical theories, although other authors (e.g. Menard, 1988) have stressed the necessity of distortion in maintaining the vitality of a concept when transferred from one discipline to another.

At the same time, interest in applied political economy continued. The quite separate 'statistical' school of Whewell, Jones a.o. (Henderson, 1995), proposed a more empirical, descriptive (although definitely numerate) approach. The statisticians operated from within the British Association for the Advancement of Science, as section 'F', and were constrained by the internal politics of that body to the role of passive observer, the identification of causal connections being too politically contentious for the organisation as a whole.

3.1.2 The Post-war Neo-Classical School

The history of economics in the twentieth century has followed from the lead of the utilitarians, although a number of rival approaches have emerged and established themselves with varying degrees of success. Within the mainstream, the trend has been towards increasing mathematical sophistication, with Samuelson (1947) setting the tone for the post-war years, and the works of Fisher, Debreu, Arrow and others. This increase in formal closure of the models has tended to result in a narrowing of scope.

The main advances have been mathematical in nature, building upon the outline of interconnected markets developed by Walras and Pareto. This does not necessarily imply stagnation in the discipline, or a complete retreat into formal method, although both criticisms have been levelled at the neo-classical school (e.g. Eichner, 1983; Ormerod, 1994). The mainstream school has fostered some debate of an applied nature, and new ideas have been introduced (e.g. Arrow's (1968) examination of imperfect knowledge), but many of the advances have narrowed rather than broadened the scope of the models (strictly, the Arrow-Debreu model (1954) applies only to an infinitely large economy).

The most contentious feature of the school is, perhaps, it's claim to be 'value-free' i.e. politically neutral; a description of what is rather than a prescription for a better society. The desirability of this claim lies in its analogy to the methodology of physical science, and the seeking of 'scientific' status by the economics profession. A number of critics have pointed out the implausibility of a value-free theory of society; as Mair and Miller (1991; p.13) note, the criterion of Pareto optimality places primacy on the efficiency (c.f.

equitability, for example) of the allocation of resources, and this in itself is a value judgement.

3.1.3 The Austrian School

Perhaps the most notable alternatives to have emerged were those of the Austrian school (Kirzner, 1982; Menger, 1950 [1871]; Schumpeter, 1950 a.o.) and the Keynesians (see below). The Austrian school has its roots in the works of Jevons' & Walras' contemporary Carl Menger. Like Menger, it is fundamentally opposed to many aspects of the developing neoclassical theory, arguing strongly against aggregation and mathematical representation of most types in favour of a descriptive rational discourse.

In the early Austrian Subjectivist school of Menger, von Mises, Bohm-Bawerk a.o., the concept of capital accumulation as a process occurring in real time played a minor role in characterising the discipline, but began to play a greater role in successive generations of Austrian economists. In particular, the "neo-Austrian" school developed by Hicks (1973), while emphasising the passage of time in building up the means of production, followed a formal, highly mathematical approach quite different in character from the subjectivists. Following Hicks a.o. 'neo-Austrian capital theory', this school was partly reabsorbed by the highly mathematised mainstream, and later adherents, such as Friedrich Hayek, attained considerable standing within the mainstream canon.

The Austrian school as a whole is perhaps better identified by a methodological position than by any single model. If follows a process of *subjective deductivism*, whereby a set of starting assumptions have a very rigorous and systematic logic applied to them in order to derive a continuous chain of causation. The assumptions adopted tend to follow the tenets of a *methodological individualist* approach, in which individuals operate in a rational, self-interested manner, which may include an existential form of altruism, but tends to develop libertarian ideas. The emphasis on causation and teleology (the study of purpose) also marks the Austrian school with an unusually strong interest in dynamic processes, for a discipline that is largely concerned with complex static analysis.

3.1.4 The Keynesians

A similar fate befell the 'Keynesian revolution'. Although he is perhaps better known as a proponent of state intervention and demand-driven economics, Keynes' most fundamental intention was to incorporate the effects of time into the mainstream theory more effectively (Chase, 1983 a.o.), following his own experience of the macro-economic boom-bust cycle in the 1930's. The emphasis in previous theory had been on the identification of equilibrium states, under which oscillations of the type Keynes observed were not theoretically possible. Keynes' project was not finished within his lifetime, and 'post-Keynesian' theory assimilated a diluted version of his ideas within the equilibrium - based mainstream, losing much of his pioneering work on uncertainty and limited knowledge in the process.

Keynes' own work is liberal, and mainly macro-economic in nature. That is, it supports the notion of an active government interfering in the operation of a market in order to assist in market clearing where the economy is complex and interdependent. Specifically, Keynes focussed on the market for Labour, and policies to avoid involuntary unemployment.

3.1.5 Input-Output Analysis

Wassily Leontief's Input-Output methodology (Leontief, 1941; 1966) represented a considerable change in economic methodology, in some ways harking right back to the Physiocrats of the 18th century, from whom he derived the inspiration for the input-output tables (Staley, 1991; p.31).

Leontief's conception of the economy as a number of interdependent producers and consumers was compatible with the multiple-commodity equilibrium model of the neo-classicists, and his manipulations of the matrices developed from his painstaking empirical research made assumptions about re-establishment of equilibrium in the face of perturbations. These features, and the high degree of mathematical formality, allowed the model to find a sometimes tenuous place within the mainstream, in spite of the strong empirical content of the work. Later developments of the methodology have been sporadic, and, while a number of national statistical offices have published input-output tables, they have tended to be utilised merely as addenda to the national accounts. (The CSO in the UK, for example, uses input-output tables principally in balancing it's estimates of GDP and it's sub-components.)

Again, let it be noted that the above history is brief and incomplete. In particular, the characterisation of a 'neoclassical mainstream' glosses over a number of internal schisms, such as those between the Chicago school and the Yale/Harvard approach to the subject.

3.2 History of 'Ecological' Economics

In discussing 'ecological economics', it is intended to define the area as broadly as possible. The definition that shall be adopted covers all economic theory drawing significant inspiration or concepts from the life sciences. Hence the energetist schools of thought described by Martinez-Alier (1987) shall be included, as will the numerous attempts to draw upon population ecology and evolutionary theory throughout the last century or so. As Martinez-Alier points out, even within the energetist sub-category, no coherent 'school' emerged. The history of the broader 'ecological' discipline as defined above is similarly fragmented.

3.2.1 The Energetists and 'Social Entropy'

The term "energetism", coined by Georgescu-Roegens (1971) and taken up by Martinez-Alier (1987) refers to an essentially reductionist school of thought which seeks to reduce an understanding of social systems to an analogue with the physical science of energetics. Both authors use the term in a pejorative sense; Georgescu-Roegens describes the school as a "dogma". Martinez-Alier's account is more historical and neutral, but is mainly concerned with showing the failure of the school to develop as a coherent whole. Grouping these authors together as a "school of thought" is, then, a post hoc classification. Many developed their ideas independently and were (or are) unaware of one another's work.

The early energetist thinkers saw the analogy between energy and society in a very straightforward, realist fashion. Ostwald for example, promoted the development of an international lingua franca in the belief that energy was being wasted in performing translations (Martinez-Alier, 1987: Ch 12). By 'energy', he meant the energy discussed by his peers in the physical sciences, that is, he was concerned with the dissipation of excess energy as heat in the brains of translators. Such an outlook seems excessively reductionist to the modern reader, but is perhaps understandable in the context of the tremendous success of the physical sciences in Europe at the end of the 19th Century, in both a scientific and political sense. Similar certainty can be seen, for example, in Quesnay's wholehearted adoption of the 'body politic' metaphor (Christensen, 1995), outlining the functions of circulation and nutrition in the economic body in considerable detail.

Contemporaries of Ostwald were concerned with applying the same reductionist thinking (with a little more success) to the understanding of agriculture as a physico-chemical process subject to mass conservation laws. Podolinsky introduced concepts of entropy and 'net energy production' into agricultural analysis in the 1880's, although he acknowledged that social hierarchies were necessary to explain the distribution of production, and that thermodynamics could not explain these hierarchies. Sacher's analysis of around the same time was similar in scope, although somewhat more reductionist in intent. (see Martinez-Alier 1987: Ch 2-4 for a detailed discussion).

The biologist and urban planner Patrick Geddes was in correspondence with Leon Walras regarding the development of the latter's general equilibrium theory. Geddes criticised Walras' treatment of utility as a scientific fact (rather than a mathematical abstraction), likening it to the concept of 'vitality', which had hindered the development of biology, in Geddes' opinion (Martinez-Alier, 1987: pp.89-91). Geddes also advocated the need to distinguish between the mathematical theory of exchange and studies of material resources and actual living conditions, pre-dating some modern criticisms of theoretical economics by almost a century.

In his "Cartesian Economics" lectures of 1921, Frederick Soddy (Nobel laureate in Chemistry in 1921) argued against the abstraction of the economic model. (Martinez-Alier, 1987: Chapter 9). He argued for a dynamic understanding of wealth, as a transient flow that could not be captured or accumulated. Real wealth came only from the flow of energy from the sun, according to Soddy. Although his critique of compound interest was valid, his focus on solar energy alone arguably betrayed a reductionist approach to the problems of economics, and a failure to appreciate the complexity of the intervening processes. As with Geddes, Soddy's criticisms had little impact on the development of economic theory, and failed to give rise to a cohesive alternative school of thought.

In 1925, Alfred J. Lotka published his major work "Elements of Physical Biology", which described a systematic attempt to understand biological and human processes in terms of the maximisation of available energy flows (although Herbert Spencer had qualitatively described much the same concepts earlier; Spencer, 1971). In many ways, Lotka's work prefigured that of Howard Odum's Systems Ecology (Odum, 1971; 1982) and James Miller's Living Systems Theory (Miller, 1975), both of which stress the role of organisms as optimising processors of material and energy.

Both Odum and Miller's approaches are too detailed and involved to describe in detail here. Odum attempts a system for mapping the physical metabolism of ecological and economic processes in a unified manner that does not require a special treatment of either. His starting point is the notion that both are driven by solar energy, ultimately, although it may be necessary to follow events backwards into geological time to recognise this (specifically, fossil fuels are 'stored solar energy'). Odum uses sophisticated techniques to map these connections, and to calculate the embodied solar energy or 'eMergy' inherent in a good, process or ecosystem. Having established a common numeraire, formal connections between ecological and economic systems can be made.

Miller's analysis begins by outlining a handful of common processes that are common to every 'living system'. As with Odum, this category is broad enough to subsume both natural and human-made systems. Miller's ideal living system contains processors of both matter and energy, encapsulated within roughly twenty sub-processes.

Both Odum and Miller are aiming at 'grand unification theories', which are general enough to encapsulate (or gloss over) the complexities and peculiarities of individual situations. Notably, both attempt to deal with both natural and human systems by uncovering an ideal underlying template common to both, rather than empirically determining the nature and type of the interconnections between the two.

Following a period of relative inactivity during the war and post-war years, elements of the debate re-surfaced in the 1960's and 70's alongside the popular ecology movement, with a number of authors expressing concern at the failure of economic analysis to account for the limits of the Earth's resources. Although often expressed somewhat differently, the key issues remained the same as those developed by Soddy, Geddes and other pioneers.

The concept of entropy was central in this new expression of the debate. Daly (1992), for example, argued for an inclusion of the second law of thermodynamics into economic thinking. Georgescu-Roegens (1971) proposed a 'fourth law of thermodynamics' which referred explicitly to economic systems, and which physical scientists did not incorporate into their canons. Odum (1971; 1982) developed his systems ecology theory and applied it's 'maximum empower principle' to human activity.

3.2.2 An Aside on Entropy

The concept of entropy has itself undergone a number of transformations, and was being further developed during the 1960's. One can trace the development of the concept through a number of stages, following Sabelli (1995):

1. Clausius definition of entropy in energetic terms, as $S = dQ/T$, where S is entropy, Q is the heat content of the system and T is absolute temperature. Here, entropy is purely an accounting entity, representing the discrepancy between the energy content and work availability of a physico-chemical system at equilibrium.
2. Boltzmann interprets Clausius' entropy in his statistical mechanics account of ideal gases as a measure of the distribution of energy states of the individual molecules. This draws upon a mathematical formulation originally developed by DeMoivre in 1756.
3. in 1964, Shannon (1964) extends DeMoivre's mathematical model to all probability distributions. He carries over some of the terms used by Boltzmann in applying this mathematical model to simple physico-chemical systems, and so he terms the measure of probability of distributions in the general case as 'entropy'. Using Shannon's formulation, it is possible to measure the 'entropy' content of a passage of text or music, for example.

During the 1960's, entropy returned into non-academic thought also, being associated with the broader (and much more suggestive) concept of order. Whether Shannon's information theory helped to re-kindle interest at this point is uncertain; the fin-de-siecle mood of the 1890's was certainly conducive to the 'vulgarisation' of the second law of thermodynamics at that time, and the general mood of revolution in the 1960's may have similarly leant itself to a renewed interest in the concept. In Moorcock's "Jerry Cornelius" novels (1965-76), for example, entropy is (poetically) associated with political instability and cultural change, and the degradation of old certainties. Activist and writer Jeremy Rifkin's (1980) "Entropy" draws similar associations in a non-fiction context. In any case, a fourth conceptualisation of entropy can be identified here, as a colloquial, metaphorical term, linked to political, cultural and metaphysical factors.

It is worth mentioning this cultural concept of entropy here because the colloquial and scientific developments of the concept were not isolated. Inasmuch as science is a creative process, a combination of popular conception and Shannon's broadening of the domain, entropy has become a very suggestive concept within the social sciences (e.g. Faber et al., 1987; Ayres, 1994; Bailey, 1995) as well as in popular culture.

Shannon's work provides the link between 'social entropy' and the second law of thermodynamics. The latter arises directly from Clausius' considerations of physico-chemical systems, suggesting that this entropy must act as an 'arrow of time'. The same is true of Boltzmann's application of the DeMoivre model, because it is applied to simple physico-chemical systems, and may therefore be supported by an energetics analysis. Shannon, however, applies DeMoivre's model to other systems for which no supplementary support exists. The reasoning that a Shannon entropy must increase over time (or, by extension, dissipate local entropy to its environment) is founded purely on an unsupported mapping of terminology from one domain to another.

For those espousing physical reductionist views (as many of the modern authors, e.g. Ayres, Miller appear to), the connection is somewhat stronger than linguistic. The analogy can be sustained if one assumes that the intervening layers of hierarchical organisation of matter from the molecular to social level impose no qualitatively new and irreducible phenomena in higher-level entities. This is a highly contestable assertion, as the discussion in Chapter 4 will show. Here, let it suffice to note the continuation of an appeal to 'hard science' by economics through wholesale borrowing of mathematical models and concepts, and the degradation of clarity occurring as the ideas change hands.

3.2.3 The Evolutionary Economists

A second group of economists who may be termed "ecological" is those who have drawn strongly upon evolutionary theory in describing change in the economic system. Again, the history of this group is somewhat disjoint, with no coherent school of thought perceivable throughout.

Evolutionary theory and economics have drawn inspiration from one another from the beginning. Charles Darwin was inspired by Thomas Malthus when formulating his concept of evolution, borrowing the idea of a struggle for existence from the earlier economic author (see Mirowski, 1995; Young, 1985 a.o.). Mirowski (1995) summarises the early interplay of ideas between the natural and social sciences thus:

> *"Take the interplay of political economy and Darwinian evolution... To put the sketch crudely, Malthus began his essay by comparing people to animals in order to fix his conception of population pressing upon resources. Darwin...read Malthus and the political economists, and this (by his own testimony) prompted him to see competition and the division of labour in animal Nature. Darwinism was quite rapidly reprojected back upon society in the form of social Darwinism. Mix two parts social Darwinism with a dash of simple Marshallian microeconomics and you arrive at E.O. Wilson's theory of sociobiology; opt instead for two parts game theory and you get the new population ecology. And since the spiral never stops, mix some elements of the new evolutionary synthesis with varying proportions of population biology and previous economics, and you might end up with either a slightly less mechanistic Marshallianism or a rejuvenated institutionalism, ..." p.15*

Again, one can perceive the influence of broader cultural and social belief systems on the development of academic thought, as industrial capitalism encroached upon traditional feudal patterns of existence. Times of great change were conducive to the articulation of a theory of change.

In many cases, only the surface appearance of the theory was seized upon. Herbert Spencer, for example, adopted Darwin's notion of selection through competition and applied it to the economic realm, while assuming that the mechanisms could lead only to greater order and progress. Hayek was to make a similar mistake in interpreting biological evolutionary theory several decades later.

The evolutionary perspective was articulated again by the middle-period Austrian school of economics (see Kirzner, 1982 for an overview), notably Joseph Schumpeter. Schumpeter is a key figure in the development of evolutionary economics, being among the first to clearly articulate the concept of "creative destruction" and of economic cycles within the mainstream. (Kondratiev had described long-wave economic cycles some twenty-five years earlier, but his ideas were only disseminated in the English-language community relatively recently; see Watt, 1992: 45-6). In addition to his major revisionist history of economics (Schumpeter, 1954), he published an account of economic theory in which an early understanding of the non-linear behaviour of 'stocks and flows' models could be discerned (Schumpeter, 1950). Schumpeter's vision, although still broadly positivist, was of an economy capable of discontinuous progress and temporary set-backs.

The evolutionary legacy of the Austrians was further developed by Friedrich Hayek (Hayek, 1949) although he made little explicit reference to evolutionary theory in his work (and where he did so, sought to play down Darwin's role in favour of his economist contemporaries). Hayek developed the ideas of a 'self-organising' economy, that is, one in which the regulation of the system as a whole is performed unconsciously by its individual members. Hayek drew from this his concept of 'the Good Society', in which spontaneous order leads to a Utopian free market state.

Clearly, Hayek failed to understand a number of properties of the non-linear evolutionary system. As Hodgson (1995) points out, spontaneous disorder is as good a description of the process as spontaneous order. As with the social appropriation of the entropy concept, the neutral concept of organisation and the colloquial, value-laden concept of order have become conflated, so that change has been misinterpreted as growth. Unlike Spencer, Hayek did not see the perfection of society as inevitable (he had lived through two world wars), but his writing retains a strong utopian streak.

More recently, interest in evolutionary economics has continued. Distinguished academic economists Richard Nelson & Sidney Winter published a comprehensive treatise on the subject in 1982, attempting to draw detailed analogies with the newly emerging and highly successful 'genetic reductionist' biology of Dawkins (1989) and Smith (1984) a.o.

Faber & Proops (1990) a.o. have continued to develop the neo-Austrian line of thought, employing modern computing resources to model the development of capital accumulating economies, albeit in a highly stylised and simple fashion.

Outside of the recognisable discipline of economics, 'Systems Theory' was being developed. One can trace the roots of the modern theory to the 'Operational Research' of the second world war, as described by Waddington (1977) a.o. Early contact between economics and systems theory was made in the 1960's by Kenneth Boulding (1970) a.o., and in the simulation models of Jay Forrester's group at MIT (Forrester, 1968, Meadows et al., 1971). Systems theory as such did not necessarily constitute an evolutionary theory, although it did help to foster the development of the complex systems theory that emerged in the 1980's (see below), through the work of Waddington (ibid.), Conway (see Gardner, 1979) and others. Complex systems theory is discussed in greater detail in Chapter 2.

In the 1980's, quantitative developments in evolutionary economics centred around two core groups. In the US, the work of the Los Alamos National Laboratory's Non-Linear Studies group and MIT led to a greater understanding of the mathematics of self-organising systems in general (Langton, 1984; 1990; Kaufmann, 1992; Wolfram, 1984a; 1984b), resulting in the formation of the Santa Fe institute, a multi-disciplinary research institute devoted to the study of the 'new science of complexity'. The institute included a sizeable economics programme, following the work of Brian Arthur (1984; 1989; 1991; Palmer et al., 1994) on increasing returns and 'lock-in' behaviour. in some ways, Arthur's work follows on from that of Kenneth Arrow's critical paper of 1968, and the work of Arthur and his collaborators has received some support from the mainstream (and from Arrow himself), with refereed publications being split between economics journals and the non-linear physics publications favoured by the broader 'complexity' research program.

In Europe, the research programme in non-equilibrium physics and chemistry led by Ilya Prigogine led to a number of interdisciplinary developments. Following early work on transportation and simulation modelling of termite nest-building (Bruinsma, 1977), the theory of self-organisation of urban centres and regional land-use was developed in detail by authors at or connected to the University of Brussels (Allen & Sanglier, 1981; Sanglier & Allen, 1989; Engelen, 1987; White & Engelen, 1993; 1994; Perez-Trejo et al., 1993; Engelen et al., 1995 a.o.). Similar techniques were applied to fisheries (Allen & McGlade, 1987), stock-markets (Sanglier et al., 1994), human speech development (Nicolis et. al, 1989) and as broad descriptions of the essential unpredictability of human activity (Allen, 1993; 1994a; 1994b). Allen, Engelen & Sanglier's papers have appeared in regional economic journals (in themselves somewhat removed from the core of the 'high neo-classical' publications base identified by Earl, 1983), but the majority of these works have appeared in interdisciplinary journals outside the mainstream.

At the same time, other authors within the mainstream continued to develop evolutionary perspectives, largely separately from the detailed quantitative & simulation approaches of the Santa Fe and Brussels schools. Kaldor (1985) outlines a broad theory of 'transformational' economics compatible with Prigogine's vision. Evolutionary theories of technological change have been developed by Kemp (1994), Hinterberger (1994), Park (1995) and elsewhere.

3.3 Summary of Historical Patterns

Overall, the development of economics as an intellectual discipline can be seen to have occurred in close step with developments in the natural sciences at around the same time, from the initial exchanges between Darwin and Malthus and the Utilitarians and energetic physicists onwards. Notable recent developments are the resurgence in interest in evolutionary economics following a strengthening of the mathematical basis of biological evolution in the late 1970's, and the leading role of non-linear physics, chemistry, ecology and immunology in developing the economic ideas of both the Santa Fe and Brussels schools.

In all these cases barring the Darwin-Malthus connection, the transfer has been primarily one of mathematical formalism rather than qualitative concepts, although Prigogine & Stengers (1984) and Allen (1993, 1994a; 1994b) have been keen to stress the qualitative understanding that arises from the adoption of their new mathematical approaches (note, for example, the emphasis on "wisdom" in the closing remarks of Allen's 1994a paper).

If any pattern is evident, it is that both 'streams' have been shaped considerably by external influences, often resulting in similar types of developments at similar times.

3.4 Mainstream and Ecological Economics as Complementary and Exclusive

The focus here is on the distinction between a 'mainstream neoclassical' and 'ecological' school of thought, and on ways of defining the demarcation. The distinction has been made already as a convenient starting point in discussing the history of economic ideas, and has been made elsewhere (e.g. Faucheux, 1993), particularly in posing the question "Can mainstream and ecological economics be reconciled?" or "Are the two schools complementary or exclusive?" This question will be adopted as a reference point for an examination of the differences in the formal structures of the theories.

As the historical study has shown, the distinction between the two schools is somewhat blurred, and by proposing and applying two potential demarcators, it will be suggested here that the demarcation is, at best, useful in some situations only.

3.4.1 Classification of Economics by Numeraire

The role of a numeraire in theory and model development has already been touched upon in Chapter 1. To recap briefly, the choice of numeraire is linked to the stage of formal theory/model preparation in which the aspects of the system at hand to be included in the formal framework are chosen.

3.4.2 Numeraire as Analogy

Following Hesse (1966), any model can be considered as containing three types of analogy (positive, negative and neutral). A numeraire will only be able to represent certain aspects of reality, and therefore will tend to incorporate all three types of analogy into a model. In the case of money, again, a money-based model cannot be used to predict the colour of future imports, as money has no colour. Colour as a property is a part of the neutral analogy, until the model is extended, say, by a table listing empirical correlations between commodity types and colour. Current-value money is subject to inflation, a property not shared by the physical commodities that it is designed to represent (inflation as a property is part of the negative analogy). Introduction of constant-value money is used to generate a new numeraire which does not contain that particular negative analogy.

This last example is instructive, in that it points to two different types of numeraire, both of which may be labelled as "money". Both have a valid place in the theory, as each can represent something that the other cannot; current money value represents the *actual* price one might expect to pay for a particular commodity at a particular place and time, whereas constant-value money allows *commensurate* comparison over periods of time.

Here, the use of two types of numeraires in economic theory will be considered; the energy numeraires of the energetist/ecological economists and the money numeraire used as a surrogate for utility in most economic models.

3.4.3 Energy Numeraires in Economics

Most uses of energy numeraires in economics (e.g. energy analysis (IFIAS, 1974; Odum's school (Odum, 1971; 1984) employ some concept of process analysis. To simplify somewhat, process analysis is a systematic accounting methodology for assigning some portion of an activity 'downstream' in a chain of processes to the subsequent users. As a simple example, an activity that uses electricity may have assigned to it some of the energy use to produce the electricity, as 'indirect consumption of energy' or 'embodied energy'.

Energy-based process analyses have been developed to a considerable extent, particularly following the OPEC price hikes of the 1970's. In addition to straightforward process analyses, techniques such as Input-Output Energy Analysis (Wright, 1973; Ballard & Herndon, 1974; Pete, 1976; 1991; Wilting, 1996) have been developed.

Depending upon context, some measure of energy flow may be seen as a desirable numeraire for several reasons, e.g.:

1. It is a measure of the effort involved in changing matter from one form to another. Energy throughput is therefore seen as a useful measure of the physical effort of maintaining and expanding social infrastructure.
2. Fossil fuels are seen as a depleting stock placing limits upon future development. Every unit of fossil fuel used is seen as advancing us one step closer to this limit. This is the prime reason for the IFIAS convention's (IFIAS, 1975) adoption of a fossil-based measure of primary energy, in which renewable energy resources are assigned zero cost (i.e. are "free").
3. Fossil fuels are seen as an environmental menace in terms of atmospheric pollution (e.g. global warming). Every unit of fossil fuel used is seen as advancing us further into environmental trouble. This is similar in scope to (2) in that it focuses on a means of accounting for contributions to perceived problems.
4. In an appeal to "energetic dogma" (Georgescu-Roegens, 1982) or an "energy theory of value", optimisation of energy balance may be seen as the fundamental driving force behind all life, human and otherwise. This is seen, for example, in Odum's statement of a "maximum empower principle" (Odum, 1972). This can be

seen to be related to (1), but expressed more strongly and allowing less space for complementary alternative measures.

Note that these definitions are not necessarily mutually exclusive. In the ECCO model, for example (see Chapters 4 & 5), the energy numeraire is adopted primarily for reason (1) above. However, once adopted, it also gives access to resource depletion and pollution issues, both of which have been discussed using ECCO models (e.g. Slesser and King, 1994; Crane, 1996 respectively).

Having mentioned the ECCO model, it is useful at this point to distinguish between representations of energy flows and energy accumulations. In general, an accumulation arises from a flow, and so the nature of the flow (as defined above, i.e. the reasons for selecting those characteristics of the flow as relevant) defines the nature of the accumulation. This definition is incomplete, however.

Where the embodied energy content of an artefact is defined simply as the cumulative sum of all expenditures of energy seen to be necessary in the creation of that artefact, then any of the four measures listed above could be used. ECCO uses reason (1). Odum's eMergy uses definition (4), sometimes accumulating flows over geological time spans. The choice of definition to be adopted should be guided by the purpose of the model or application. The distinction between conventional energy analysis and eMergy analysis is discussed further in Brown & Herndon (1996), in which a largely unsuccessful attempt to reconcile the two disciplines is made.

In choosing a definition of an *embodied* energy numeraire, one must specify the rules by which the accumulation is calculated. Two options are immediately apparent:

1. An accurate historical record of the accumulation of energy flows through a system.
2. A measure of the energy that would be required to replace or replicate the structure by the system in its current state.

Note here that the difference between these options is only recognised in the case of systems undergoing changes in quality of the flow over time. The term 'quality' indicates here that some other property of the flow is changing at a rate different from the rate of change of energy content. In the case of measuring fixed capital stocks by their embodied energy content, a change in quality could arise through changes in the technology of energy extraction, or of capital production (see Chapter 4 for a detailed application of this issue to a functional model).

Again, the choice of numeraire will depend upon the purpose to which it will be put. If the aim is primarily a historical account, then option (1) seems preferable. On the other hand, if the key priority is an identification of possible threats to the infrastructure (e.g. modelling a civilisation based on an actively volcanic island) then option (2) has more to offer. Similarly, where the accumulation is required in order to calculate maintenance or depreciation requirements, option (2) is the more useful.

3.4.4 Money Numeraires in Economics

Most economic theory uses money as a surrogate for value, in empirical cases at least. It is worth noting here that much of the 'high neoclassical' theory that is often used to characterise mainstream economics (especially by its opponents) is very non-empirical, and that much of the mathematical treatment occurs at a far more generalised and abstract level than requires the manipulation of actual numbers (see Bausor, 1994, for a discussion on these "qualitative dynamics"). Nonetheless, the mathematics requires the concept of a scalar numeraire, and this numeraire follows the tradition of money/utility.

Neoclassical theory (and, indeed, all theories of value) is founded upon the concept of exchange between conscious actors. A number of actors (whether people, companies, nations or whatever) are involved in the exchange of a range of commodities (goods, services, ideas, etc.). The nature of the exchanges is determined by a number of factors, such as:

- **the process** by which the seller acquired the commodity
- **the use** that the buyer intends for the commodity
- **the use** that other potential buyers intend for the commodity
- **the existence** of other potential sellers or buyers
- **the ability** of the buyer to create the commodity for itself
- **other factors** governing the relationship between buyer(s) and seller(s)

These factors can be compacted into a concept of value/utility, which represents the overall desirability of the commodity to the seller and buyer, taking any number of factors into account. Most commonly in practice, the money value arrived at by the market for a commodity is taken as a reflection of the real value of that commodity. That is, the market is assumed to provide a mechanism whereby all salient factors are expressed.

The neoclassical theory has been extended to cover various faults implicit in that assumption, such as the inability of future generations to express their preferences, and the concept of "shadow prices" in which factors omitted from the market price are restored. Nonetheless, these extensions do not alter the basic foundations of the theory.

This theoretical framework can be seen to have considerable explanatory power in certain subsets of the socio-economic system. These subsets occur within the human subsystems. Market economies are concerned to a great extent with trading in commodities, and a wide range of factors, some physical, some socio-political, do influence the development of these trading patterns.

The neo-classical theory, then, is designed to explain the behaviour that arises when people interact with other people. Non-human system actors have no direct access to the value system underlying the market mechanism, and so a direct interpretation of the interactions between people and other 'system components' lie outside of the domain of this theory.

3.4.5 Comparison of Energy and Money based Economics

Human society is hard to characterise, even were all specialist disciplines capable of freely communicating with one another. In attempting to manage it, then (and this is the practical purpose of most economics), pluralism in economic theory is in some ways a very necessary thing. As this complexity necessitates a sharper understanding of the relevance of each sub-discipline, argument about which theory provides the "correct" economic representation is seen to be of secondary importance to establishing the legitimate domain of each theory (as discussed in Chapter 1).

To borrow the terminology of system theory, the socio-economic system (in the absence of reference to lower hierarchical levels), can be seen to contain a wide range of component types. As a broad simplifying measure, these components can be classified into two types:

1. human components, which have access to higher levels such as the aesthetic, juridical, ethical and credal (after Dooyeweerd's (1975) classification). These may

be individuals, companies or nations, depending upon the level of aggregation adopted.

2. non-human components, which do not in general have access to these levels in themselves. Human components may ascribe values based on these higher levels, but that is a function of the human component. Non-human components include both natural and artificial things.

Within this simple classification scheme, it can be seen that three types of interaction may occur:

1. human components may interact with one another
2. non-human components may interact with one another
3. human & non-human components may interact

From the discussion above, it is clear that the neoclassical theory and the physical theories have overlapping but largely separate domains. Neoclassical (and any value-based) theory describes the interactions between human actors, and physical theory describes the interactions between human and non-human actors.

Table 3.1 highlights the differences between these theories (using a prominent example from each class) in terms of the design decisions discussed in Chapter 1. Note that some degree of overlap is evident; both theories treat human beings as conceptual entities, and there is even some similarity in the range of attributes assigned to them. (both theoretical entities are credited with the ability to make decisions). There are, however, differences related to the purpose of the theories; the *Homo economicus ifias* of energy analysis makes decisions mainly about resource usage and extraction rates, whereas *Homo economicus neoclassicus*' decisions are primarily related to maximisation of utility as guided by it's preference attributes.

Energy Analysis (IFIAS)		Neoclassical Economics	
Boundary of Region of Interest			
Point at which fossil fuel enters human economy		Human valuation of an object i.e. point of becoming a commodity	
Components	**Attributes**	**Components**	**Attributes**
Human beings	Decision-making ability	Human beings	Decision-making ability
Human made Capital	Embodied Energy		Preferences
Depleteable Energy Reserves	(Calorific) Primary Energy Content	Commodities	Attributed value

NOTE: Both theories will in practice contain a number of different sub-disciplines, covering a range of specialised design decisions. This table is intended to be illustrative only.

Table 3.1: Design Decisions in Energy Analysis & Neoclassical Economics

Separation of the socio-economic system along the lines of these two theories would, in practice, be difficult to achieve. The overlap noted above is only one of many, and the two theories do not deal with different sectors or regions of economic activity, but with different aspects of the same interactions. Value- and physical considerations are mixed together, then, right down to the level of the individual, and any policy issue will probably require consideration of both aspects. Growth, for example, is less likely to be limited purely by physical resource constraints or human agent interactions than by a mixture of both factors.

In order to assess the importance of each theory in the policy domain, one must assess the importance of the constraints that it generates on the real world. Coming at the issue of development from a physical point of view, one can state uncategorically that any economic process is also a physical process. It can be viewed as a transformation of matter from one state to another. Even seemingly ephemeral economic activities, such as the performance of music or a banking service, have a physical resource dimension.

Such a description fails to capture the nature of a real human society in a number of ways. Firstly, there is the possibility (and high probability) of a tension between demands for the transformation capacity of the system, or rather for the manufactured commodities that it generates. In order to discuss this competition for the output of the production process, one must refer to a concept of value.

Secondly, few real economies are, or have been, closed to foreign trade altogether. Perhaps the only current example is the global economy, when viewed as a whole. Allowing for the existence of inter-society trade removes the absolute physical limit on production experienced by the closed economy. The limits replacing it are based on the competition for potential imports between a variety of trading agents. From a global perspective, the absolute physical limits still apply, but no individual economy experiences them so directly.

The (pre-theoretical) way in which the world is viewed influences the (theoretical) appreciation of it; the aspects that one will subsequently pay attention to. Classification provides a set of filters. When viewing the world as a single economic bloc, competitive behaviour might be filtered out in order to focus on system-wide constraints, and when viewing as a series of sub-regions, cooperation might be filtered out in order to appreciate complex trade dynamics. Reality, in both cases, remains a complicated mixture of competition, cooperation and ambivalence.

Returning to the main theme of value- and energy-based economics, it seems fair to suggest that a similar filtering process is occurring here. Once one adopts an energy-based approach, one will tend to filter out human-human interactions; with a value-based approach, one filters out human-nature interactions. The pre-theoretical or informal design decisions affect the course of the analysis (and of the theory) from thereon.

3.4.6 Classification of Economics by Treatment of Time

A second dichotomy in economic theory relates to concepts of time. Time is a difficult subject to grasp in many ways. As Augustine notes in his "Confessions":

> *"I know well enough what it is, provided that nobody asks me; but if I am asked what it is and try to explain it, I am baffled."*

Samuelson (1947) distinguishes between three basic treatments of time in economics; statics, comparative statics and dynamics. In statics, the description relates only to a single point in time. A comparative static analysis contrasts two points in time. Dynamics deal with series of moments, and Samuelson divides this third class into causal and historical. A historical dynamic analysis may simply record data over a series of instants without involving the essence of time as a one-way process. In contrast, causal dynamic analyses do just this, employing "theoretical and not historical" sequences of events (Schumpeter, 1954: p. 965).

Faber & Proops (1990: pp.61-) note six approaches to time in economics, using the concept of reversible or irreversible time as a second separatrice. They note the importance of treating time's special properties, rather than a simple space-like conception of it, noting the two 'Arrows of Time' of classical thermodynamic entropy and self-organising processes (Prigogine & Stengers, 1980). A concept of time is denoted as reversible if it takes explicit account of these directional properties.

Three types of reversible time analysis are identified, following Samuelson's categories of static, comparative static and reversible dynamic. In the latter case, time is treated as a fourth spatial dimension, "a purely logical calculus that does not involve time in any essential way" (Leijonhufvud, 1984: p.27).

Within the highly abstract models that increasingly characterised the neoclassical school, e.g. Arrow & Debreu (1954), the same commodity at different points in time is treated as identical to two different commodities at the same time. It is tempting to characterise all neoclassical economics as denying the nature of time, although a number of methods have been developed to correct for certain features, notably the uncertainty of knowledge regarding the future (Arrow, 1968; Boland, 1978; Arrow & Fisher, 1974; Arthur, 1989; a.o.). These efforts can be seen as attempts to introduce concepts of irreversible time into the neo-classical model. As Pindyck (1988) notes, the issue of irreversibility raised by Arrow in 1968 have since been largely neglected. No clear school of 'irreversible' economics has arisen from these ideas. Possible reasons for this will be discussed later.

Faber & Proops also recognise three treatments of irreversible time. Firstly, the concept of risk recognises an asymmetry in time arising from the "asymmetry of information structures" to which (subjective or objective) probabilities can be applied. Recognition of risk does not prevent an economic agent from globally optimising behaviour, with the caveat that the calculus may rest on subjective probability weightings.

Uncertainty implies a more fundamental asymmetry than risk. Some processes are inherently unpredictable, drawing upon the theory of evolution and non-linear/chaotic dynamics. In an uncertain world, an agent has no way of assigning reliable probabilities to the full range of outcomes.

Finally, they define the "teleological sequence", a "social kind of irreversibility" in which the nature of the (ultimate) goal is affected by the process of getting there. ('Teleological' implies a 'telos', an ultimate goal not achievable by direct or immediate action.) This concept draws heavily on the Austrian school's focus on the time-irreversibility of investment processes, but is applicable to the wider economic framework.

The traditional focus in economics on reversible or static time underlies the main critique offered by the System Dynamics school, as epitomised by the work of Forrester (1968), Meadows et al. (1971) a.o. System Dynamics is concerned explicitly with the order in which events happen, and the causal repercussions of events as time passes. In particular, consideration of reversible time raises the challenge to the notion of equilibrium; dynamic equilibria may establish themselves in causal dynamic models, but, as the approach towards equilibrium happens at a finite rate, subsequent events may prevent the end state from being reached. The consequences of these ideas are significant, and will be taken up again in the following chapter.

Note that the treatment of time is tied in with the treatment of rationality. As Simon (1967) points out, only within a well-defined environment can an economic actor act with "substantive rationality", that is, with a complete knowledge of the operating conditions allowing calculation of a global optimum. The weaker "procedural rationality" available to actors in poorly characterised environments seems inevitable once one introduces an explicitly dynamic element, especially where the 'computational capacity' (i.e. decision-making ability/rate) is limited.

Much of the appeal of substantive rationality has been it's usefulness in developing mathematically elegant theories. Indeed, at times it has been a prerequisite for tractability. Recent advances in simulation modelling related to the complex systems literature (notably Palmer et. al, 1994; Sanglier et. al, 1994; both models of stock-market behaviour) have allowed modelling of the more realistic procedural rationality, although these are mathematics of a different nature, applied rather than pure (see McCloskey, 1994: Ch. 10-14 on the "values of the math department"). At the same time, the broader rationality debate in economics is active (e.g. Faucheux & Froger, 1996). While the full range of this debate lies outside the scope of this thesis, suffice it here to note the connection with the issue of time.

The introduction of reversible or static time is obviously unrealistic, if one measures it against one's own everyday experience. The reasons for adopting these ideas, then, are not realist reasons. Rather, they are mathematically pragmatic: only by making assumptions that imply a reversible time can the theoretical system achieve a greater degree of closure. The issue, then, is one of intellectual values, of realism versus formalism. The traditions of the 'mainstream' and 'opposition' are consistent with the representations of time that they offer. Mainstream theories favour formalism and closure, and are therefore liable to opt for a reversible time. Opposing views frequently stress the unrealism of such assumptions, and put forward irreversible models of time in either less formal fashion (e.g. the Austrians) or using applied mathematics (here Arrow, 1968 could be viewed as an 'opponent'). Attempts to address the irreversibility of time without sacrificing the formality/closure of the model have been able to deal only with those aspects of irreversible time that have the least consequences on the broader framework (in Faber & Proop's terminology, risk and sometimes uncertainty, but not teleology).

3.4.7 Comparison and Discussion

The mainstream and opposing theories of economics can be partly characterised by two separatrices, then; physical versus value numeraires, and reversible versus irreversible models of time. The two are theoretically related, of course, in that irreversible time as a concept is most completely defined by reference to thermodynamics, and entropy in particular. The link is not a necessary one, though; the work of the Brussels school, for example, has developed from an understanding of non-equilibrium thermodynamics without their models incorporating explicitly physical numeraires. At the other side, input-output energy analysis is *methodologically* a static procedure applying physical numeraires, although it's *purpose* may rest on an appreciation of the irreversibility of energy use. (Note that the distinction between reversible and irreversible time here is between the way time is incorporated into a worldview, not the way it is modelled in a formal sense.)

In short, then, neither numeraire nor time-model serves to completely identify a coherent mainstream or opposing tradition. Both offer some degree of characterisation, and the links can be seen to other, deeper issues such as the intellectual values held by the practitioners (and from there into institutional, behavioural and other considerations; see the previous chapter).

To return now to the question with which this discussion opened: "are mainstream and opposing theories of economics exclusive or complementary?" the separatrices identified here can be of some use.

Following the division of reality into human and non-human components, it can be argued that physical and value numeraires operate on overlapping but different domains. Further, these domains are, in realistic situations, tightly intertwined. From this the two approaches may be treated as complimentary in a narrow theoretical sense. By 'narrow' it is meant that the theories may be usefully joined into a larger consistent theory that embraces both domains (see 'narrow interdisciplinarity' in Chapter 1).

Time-models do not offer this narrow complementarity. The equilibria upon which reversible-time models depend are challenged by irreversible-time models, which illustrate quite different types of behaviour from their reversible-time counterparts. For example, the Arrow-Debreu model (Arrow & Debreu, 1954) demonstrates the existence of stable equilibria in continuous markets. In contrast, Palmer et. al (1994) and Sanglier et al. (1994) present markets with no endpoint or stability, subject to speculation bubbles and crashes. Both refer to the same real-world phenomena. The difference in behaviour lies with the difference in perception of the phenomena, right down to the level of informal preparation. In other words, the metaphysics of the models are different.

In the narrow sense, then, there is a dilemma. Mainstream and opposing theories seem complementary in some ways (on grounds of numeraire) but fundamentally exclusive in others (through metaphysical differences). The only recourse, then, is to broaden our notion of complementarity to include the 'broad interdisciplinarity' outlined in Chapter 1. Given that one has two models of a phenomenon, which differ in behaviour and are not formally reconcilable, one is not bound to choose one and reject the other. Reality is more 'real' than either (or, indeed, any) model, and, as models of complex human policy issues, we are not bound to make our choices solely in terms of closeness of fit to some objective reality. The 'true' nature of time is perhaps a subject worthy of study by cosmologists: the purpose of economic models is to present ideas and viewpoints, and to persuade others of the validity of these ideas *for the situations and issues to which they are to be applied.*

3.5 Towards a Thick Reading of Economics

3.5.1 Summary of Histories

In Chapter 3, the history of the economics discipline as a whole was reviewed. At the same time, developments outside academia have influenced the pattern of interest in economics. Notably, much of the resurgence in ecological economics in the 1960's was brought about by shifts in popular attitude. Energy analysis as a modern discipline gained considerable impetus following the OPEC cartel price-hike of 1974.

Following the development of new ideas in economics, the new theory has followed one of two broad patterns, either generating a brief revolt before being reabsorbed into the mainstream, or developing as a separate discipline with little communication to the mainstream.

In the case of reabsorption, notably for the neo-Austrian and Keynesian schools, it seems fair to characterise the process as a neutralisation of the new theory rather than a reorganisation of the neoclassical model. In the transition from Austrian to neo-Austrian theory, few of the characteristics of the Austrian school were retained. Mathematical aggregate modelling was re-introduced (following the conventions of the neoclassical model in many ways), including the concept of a scalar measure of utility. The only real feature retained in the neo-Austrian model was the view of capital accumulation occurring in real time. Similarly with Keynes' theories, revised approaches moved back towards the equilibrium model while retaining some features of the original.

This is not to say, of course, that the neoclassical model remained unchanged throughout the course of these 'revolutions'. Rather, the changes made were introduced from within, rather than by cross-fertilisation with the radical alternatives. In Kuhn's terminology, the existing theory of Walras, Pareto and Jevons has simply been *articulated* by subsequent authors, from within the dominant tradition (and, at the same time, narrowed considerably in scope).

Those alternatives that generated alternative approaches have also often been short-lived. As Martinez-Alier demonstrates, many ideas in energeticist economics were reinvented several times, with no effective communication between contemporary practitioners nor passing of ideas through time occurring. In the evolutionary economics 'school', a similar lack of cohesion can be seen. According to Kaldor (1985: 63-4), Allyn Young outlined the theory of increasing returns (leading to non-equilibrium markets) in 1928, in the Economics Journal. Following Young's death shortly thereafter, the ideas were not revived significantly until Brian Arthur 'rediscovered' the concept in the early 1980's (Arthur, 1984), and framed it in a highly mathematical language to which the economic culture of the day would be sympathetic.

The characterisation of economic theories as either 'mainstream' or 'ecological' can be reconsidered here. The definition of 'ecological' that has been given is a very broad one, covering transferred ideas from both physical and natural sciences (and from attempts to unify the two). At the same time, however, the mainstream theory has received much of it's theoretical grounding from the physical sciences at least. Leon Walras and Vilfredo Pareto, the key developers of the mathematical Utilitarian theory, were both trained as engineers before embarking upon their economic careers, and later practitioners (e.g. Koopmans: see Faber & Proops, 1990: p.65) have also been successfully integrated following careers in the physical sciences. To suggest that the neoclassical school has maintained itself by ignoring 'physical fact', is, then, somewhat simplistic.

Nonetheless, the criticisms raised by many dissenting voices have been similar in nature, with both energetic and evolutionary schools focussing upon aspects of the concept of reversible time employed by the neoclassical model. A century of protest has done little to remove this feature from the 'mainstream' theory, a fact that seems quite incomprehensible from the point of view of a history of ideas. Here, some partial explanations of the persistence of an (ill-defined) 'mainstream' are offered by looking into the context surrounding the intellectual activity (what McCloskey (1994: Ch. 8) calls a 'thick' reading of economics).

3.5.2 Socio-cultural Explanations

The neoclassical school of economics gained dominance of the field rapidly following its inception. The broad theory has remained unchanged throughout the twentieth century, in that much of the articulation has involved the addition of further axioms rather than overthrow of existing ones (Kaldor, 1985: 13). Throughout its history, the theory have been challenged, and the axioms upon which it has been supported have been refuted many times. Nonetheless, the theory has either absorbed or excluded alternatives based upon these criticisms, and no competing cohesive school of thought has emerged.

The academic case against the neoclassical theory is well established. Agents do not have access to all pricing information, nor perfect foresight. Even if they did, they lack the 'computational capacity' to behave rationally (i.e. life is too complicated). Empirical evidence supporting many aspects of the model are weak, indeed, certain aspects such as the measurement of utility are essentially unverifiable by empirical means.

To assume that any theory will stand or fall on the merits of its content alone is naive. As with economic agents, academic practitioners lack the computational capacity to fully explore the ramifications of a set of axioms, and, as shown in Chapter 1, any set of axioms chosen must be done so on a subjective basis. No 'fact' can be extracted from reality without some prior 'preparation' (in Cartwright's sense).

Taking the persistence of the neoclassical school as a socio-cultural event, one can advance a number of arguments offering some degree of explanation. The early transfer of metaphors between Darwinism, economics and energetic physics occurred during a period of great expansion in Britain and Western Europe, in which the practical success of the physical sciences in transforming the lives of most people was manifest. It is therefore unsurprising that the early utilitarians' preparation of the economy as an optimising, progressing, rational system found favour.

The history of the early twentieth century was somewhat more turbulent, leading, as McCloskey (1994: p. xii) notes, the Modernist movement split between the rational, "amateur positivist" ideals of architecture, economics and planning, and the subjectivist primitivism and romanticism embraced by literature and the arts. Importantly (to our analysis), having been conceived in a time of great optimism, the positivist mood was successfully carried through times less conducive to its development or survival.

It is worth noting that within the field of economics, the Modernist era produced mainly revolution, with both Keynesian and middle-period Austrian schools developing between the wars (and the former in part due to Keynes' own experiences of the Great Depression of the 1930's). Only with an upsurge in economic conditions and a renewed optimism in the 1950's did positivist economics really reassert itself and develop in a strong way once more, notably in the US.

It seems unlikely that this broad sketch of cultural 'mood swings' can explain the development of economic theory in full, but it is worth noting the importance of cultural norms especially in establishing the informal preparation of theories. Thus the development of theories as a whole is influenced, particularly in their infancy when the informal preparation is more explicit and therefore open to debate.

3.5.3 Scientific Cultures as an explanation

One can also discern distinct 'cultural' attitudes within science. Hesse (1963) characterises scientific mind-sets as "Campbellian" & "Duhemist", after the British NR Campbell and French Pierre Duhem respectively. Campbell's outlook was distinctly empirical, whereas Duhem's tended more towards precision and unity of formalisation. The distinction here is not one between qualitative and quantitative ideas - most mature theories contain an element of both - but one of the relative importance granted to formalisation and description. In many ways, the distinction is similar to that between quantification and mathematisation, as discussed in Chapter 1. This distinction may be useful in determining why certain new ideas became incorporated/neutralised within the neoclassical framework and others were excluded.

In Hesse's terms, the neoclassical model is distinctly Duhemian (possibly more so than Duhem's own work). That is, it is developed favouring mathematical clarity and completeness over empirical validity. The early struggle between the Utilitarians and Section 'F' statisticians can be seen as splitting along Duhemian-Campbellian lines.

Of the 'reabsorbed' schools, Keynesian economics is similarly Duhemian; Keynes was a gifted mathematician and logician, and, although he was concerned with opposing some of the axioms of the neoclassical model, he attempted to restructure his theories along similarly formalised lines. The early Austrian school, in contrast, was decidedly Campbellian, but later developments leading to Hick's 'neo-Austrian Capital Theory' effectively re-couched the new ideas in a formalised fashion (or, rather, the new ideas amenable to mathematisation; the critique against aggregation was dropped altogether). Leontief's input-output tables, although qualitatively offering some challenge to the neoclassical interpretation, was in itself an exemplary mathematical achievement of great elegance, and one compatible with the central concept of equilibrium.

A number of competitor theories may have failed to gain access to the neoclassicists' attention because they appealed to a physical interpretation of the ideas. Geddes' critique of Walras amounts to a critique of mathematisation of economics. Soddy was concerned with the physical phenomena of solar flux as the starting point of his objections, possibly recalling the failed warnings of scarcity made by Malthus. Later energetists such as Ayres and Odum may themselves have been prone to mathematisation, but they did so from the starting point of physical science rather than the accepted neo-classical framework, hence generating a disciplinary barrier to understanding.

In the case of the recent evolutionary economists, the failure of Nelson & Winter to generate interest within the mainstream is interesting, given that both authors were established and highly regarded mainstream economists. It may have been the case that their approach was too empirical, focussing as it did on case studies and a 'business management' approach rather than an overarching description of principles. The differences between the Santa Fe and Brussels programmes may be more instructive from the Campbell-Duhem viewpoint. Notably, Arthur's research has met with greater interest from the mainstream (although it took five years for Arthur (1989) to be accepted by the Economics Journal, according to Waldrop, 1994). Much of his work has been expressed in highly mathematical terms.

This contrasts with the discursive and diagrammatic approach taken by many of the Brussels school's publications, in which a greater emphasis is placed on the insights offered by the (often extremely sophisticated) mathematical treatments. While it may be simplistic to characterise the Santa Fe programme as 'Duhemian' and the Brussels programme as 'Campbellian' (the difference between European and American cultures may also go some way to explain the difference in styles, for example), the differences in the rhetoric employed may account in part for the degree of incorporation into the mainstream.

3.5.4 Class-based/Marxist explanation

Other explanations can also offer some insight. As already noted, Henry (1990) provides a "whiggish" (i.e. rationally reconstructed) history of the development of neo-classical economics in terms of the manipulation of content (or rather of conclusions) by class interests. Although Henry's ideas are persuasive, they underplay the subjective nature of the process of drawing conclusions from a theory. Certainly, a theory based on utility rather than labour value is more conducive to generating conclusions in the interests of a capitalist class, but the same ideas may be interpreted in a number of ways. Hayek's 'Good Society' serves to illustrate this point; using evolutionary arguments, he arrived at extremely libertarian conclusions quite different to those of other evolutionary economists. Similarly, Hahn illustrated the role of interpretation by turning the neoclassical model around so that, rather than arguing from the axioms to show the optimality of a free market as a proven fact, he took the profusion of axioms to illustrate the narrow range of conditions under which a free market *could be* considered optimal (Kaldor, 1985: 14).

3.5.5 Behavioural & Psychological Explanations

Earl (1983) offers a behavioural description of the motivations of economists as individuals. While compatible with the 'cultural' explanation offered above, Earl assumes the existence of a closed institution as a starting point, and so makes little headway in explaining the development of the school. At best, his analysis offers some insight into the persistence of the school once it did become established, although these arguments are equally applicable to any established body of knowledge. There is little remarkable in Earl's explanation: tenured economists will practice theories that win the support of colleagues, are conducive to them retaining their tenure, and do not entail too many challenging new ideas.

One can look for psychological explanation pertinent to the formation of the neo-classical school in Ephraim Fischbein's (1987) study of intuition and overconfidence. Fischbein argues that overconfidence is a necessary survival feature. Given limited computational capacity and an extremely complicated environment, one is forced to rely on heuristics that have not been rigorously tested, in order to act at all. Although Fischbein concentrates on the teaching of elementary mathematics, his ideas are applicable to research-level learning, with the caveat that no 'corrective' presence such as a teacher with the correct set of answers can be assumed. Given the positivistic environment in which the Utilitarian theory developed, there was great incentive to develop a 'scientific' economics comparable to physics. The role of overconfidence would allow the empirical merit of this theory to take a secondary role.

3.5.6 Institutional Explanations

One may view the neo-classical school as an 'institution', in which the individuals engaged in the research are chosen by their predecessors for their ability to maintain the status quo (one of the motivating factors described by Earl, above). Canterbery & Burkhardt (1983) show the hegemony exercised over the discipline by seven US economics faculties, by analysing the source of doctorates by contributors to key economics journals, and of members of staff of the economics departments of the major universities. It is unlikely that this practice is peculiar to economics, but nonetheless, it may provide some understanding as to why certain theories have been accepted or rejected. Certainly, it is compatible with a number of the other explanations offered regarding scientific cultures and individual behaviour.

A second institutional viewpoint can also be adopted. Institutions as discussed above are essentially power structures. They are, in reality, also language communities, and the 'institute' of economics (both the neoclassical and as a whole) has developed a language of it's own. McCloskey (1994) discusses the role of specialised language as a "blub-blub effect" and "Latinate blather" intended to "terrify the onlooker" (p.118-20). In addition to such (arguably) intentional erection of language barriers, McCloskey does acknowledge the inherent difficulties of communication:

> *"In most communication, the message is not a preformed slug, a mere telephone number...Commonly the message is changed by the demands of the communication - which is to say, the presence and character of the audience, the attitudes of audience and speaker to each other, the language spoken in common, the style of the customary medium, the history of earlier and similar talk, the practical purpose to be achieved from the communication. They do not always 'distort' it (the metaphor of distortion assumes again the preformed slug sits there ready to be found)." p.35*

The conventions surrounding communication within a specialised language community are connected to the informal theory preparation process described by Cartwright (1983) as discussed in Chapter 1. Both relate to the underlying assumptions of a school of thought. The users of both are generally unaware that they are using them, outside of moments of reflection separate from their day to day work, at least.

Most importantly, these types of barrier will make it difficult for practitioners from other disciplines to 'break into' economics. Some people have done so, Keynes the mathematician being a notable example, but this is not to say that the barrier does not exist.

It is worth noting, of course, that alternative schools of thought have, in themselves, developed similar institutional structures, although these are generally not so well-developed. Over the last ten years or so, a number of journals devoted to ecological economics have appeared, and other sub- or inter-disciplinary journals (e.g. in the field of regional economics and economic geography) are also in existence.

3.6 Conclusions

A number of ideas can be advanced then, that offer insights into the progress of the economics discipline from the development of the Utilitarian theory onwards. The failure of alternative approaches to successfully challenge the defects of the theory cannot be explained from a purely academic viewpoint, given the obvious falsity of many of the models axioms. It can, however, be partly understood as a combination of socio-cultural, behavioural, institutional and political factors. This broader perspective is necessary to understand economics, in light of its status as a complex human policy discipline rather than a positivist science.

Chapter 4 Natural Capital Accounting & Endogenous Growth Models

The following two chapters comprise an extended case study of policy-relevant simulation modelling using the ECCO model (Slesser, 1992). The ECCO model and the insights gained from it here will subsequently be re-used in the IPSO model in Chapter 8, following the broad interdisciplinary approach to modelling described in Chapter 1.

The results developed by the model case studies in these two chapters are also pertinent to the polarised economic growth debate described in the introduction to the thesis, and in Chapter 3. The ECCO model is seen to be capable of representing both resource limitation and technological innovation to some extent, although it is limited in the latter capacity. These limitations are partly addressed by the IPSO model.

ECCO is a System Dynamics modelling technique for looking at national and large-scale regional economies. It places a strong emphasis on the physical processes underlying economic growth. It also emphasises the interrelationships between activities, and the dynamics that arise from these interactions. On both counts, it is strongly aligned with the values of the ecological economics movement.

Because of the combination of integrated dynamics and resource constraints, it sometimes produces results that are not in keeping with many ecological economics ideas. For this reason, it is an interesting starting point for developing insights into the growth debate via simulation modelling.

The ECCO model also serves as one source of ideas for the IPSO model developed in Chapter 8.

This chapter introduces the ideas of Natural Capital Accounting and relates them to human-capital schools of endogenous growth theory within the economic mainstream. The following chapter applies this discussion to an ECCO simulation model of the Australian economy, and specifically water resource policy, in order to highlight a specific example of the unexpected behaviour noted above.

4.1 Principles of Natural Capital Accounting

Natural Capital Accounting is a procedure developed to compute the effects of the natural resource base upon the growth of industrial economies. NCA applies primarily to the energy resource base, both primary resources such as fossil fuels and renewables, and secondary resources such as refined fuels and electricity. NCA has developed from the discipline of energy analysis, which attempted to understand the use of energy in industrialised economies.

Natural Capital Accounting can also be said to be 'holistic' in that it stresses the interdependence of components within the economic system, and the dependence of the economy upon its physical context.

The tenets of Natural Capital Accounting can be summarised as follows:

- (Available) energy is required for any physical transformation
- Any economic activity entails physical transformation
- Non-natural physical transformations require the mediation of physical structures (physical capital) in order to occur
- The production of physical capital is a non-natural physical transformation, subject to the above restriction
- Physical capital will decay over time, and cease to function
- In addition to energy and capital inputs, most economic processes will require other physical inputs, most of which are products of economic activity.
- All activities within an economy are connected by this mutual use of one another's products
- The growth of an economy is limited by its ability to provide the energy, capital and other necessary inputs for its physical production processes
- Human labour provides an insignificant energy input into the economy - its purpose is to *manage* physical transformations, to make decisions

The first five tenets are derived more or less directly from thermodynamics and energy analysis, and can be considered to be essentially correct. Debate about the importance of energy analysis depends, of course, not upon whether statements such as these are correct, but whether they are relevant. A worker in the 'knowledge industry' may still require some physical inputs (paper, pens, a computer, etc.), but these may or may not be seen to be a significant factor in understanding the economics of what they do. The additional statement that, as a physical entity, an economic process cannot travel faster than the speed of light, for example, is right (or, at least, in agreement with modern physics). It would have little relevance in a discussion of the real limits on real economies, though, and so it isn't included in the above list. The first five statements in the above list are included in the belief that they are relevant, not as an appeal to the primacy of physics as a science.

The remaining statements develop a stylised picture of an economy as a series of interdependent processes. These borrow from a number of economic disciplines, such as input-output analysis, and from the process-flow techniques of chemical engineering. The final statement is developed by reasoning involving both the thermodynamic and economic concepts. As this final statement is the most policy-relevant, it can be seen that Natural Capital Accounting relies upon both physical science and a process-based system of economic concepts.

Each of the tenets will be expanded upon briefly below, in order to develop the Natural Capital Accounting argument.

Available Energy is the Driving Force behind any Physical Transformation

In physical science, energy is measured in two ways; by it's heat content and it's ability to do work (in the sense of exerting a force e.g. accelerating a mass through space). Heat content simply sums the energy content ascribed to individual molecules within the system. The availability, quality or work content of the system also accounts for the degree of order, or negentropy, in the arrangement of the molecules. Low negentropy energy cannot be directed to a specific purpose in the way that high negentropy energy can, and so two systems with equivalent energy content will not necessarily share similar properties.

In the economic context, the distinction of availability is important because energy is put to a number of uses. Some, such as space heating, do not require high negentropy energy, whereas others, such as moving motors, do. Availability analysis (e.g. Paterson, 1993) extends energy analysis by looking at ways of matching the availability of an energy carrier to the availability requirements of the end use.

A physical transformation can be characterised as a transition between an initial state and an end-state. The transformation is a process of rearrangement of molecules in order to reach the end-state. Both the initial and end-state can be characterised as having a certain energy content. Usually, these will differ, and the transformation will entail either a net release of energy (exothermic e.g. fossil fuel combustion) or a net usage (endothermic e.g. smelting an ore). Exothermic (i.e. energy releasing) processes do not happen spontaneously because an intermediate state in the rearrangement has an energy content that is higher than the initial state (if this were not the case, the initial state would not be found in nature, as the transformation would have already occurred!).

Both types of transformation process result in a decrease in the availability of the system as a whole, following the second Law of Thermodynamics.

Any Economic Activity Entails a Physical Transformation

All economic activities occur in physical space and time, and are therefore subject to the discussion of the previous point. This point is obviously more relevant to some economic processes than others. Mining, farming and construction are obviously physical transformations; pay-rolling, designing and composing music are less obviously so.

As noted already, the key issue here is whether the physical aspect of a process is important enough to be considered within an economic theory.

Non-natural Physical Transformations require the mediation of Physical Structures (Physical Capital) in order to occur

All economic processes can be described as non-natural, as they are using states found in nature as feedstocks (either directly or after earlier processing stages). Whether endothermic or exothermic, the transformation from the natural state is not a spontaneous one, or the natural state would not occur.

In addition to requiring energy, these processes require physical structures to contain, channel and direct the energy inputs, plus any energy released by the transformation. Physical structures are also required to arrange the material feedstocks; to bring them together, separate them, mix them or whatever.

The Production of Physical Capital is a Non-natural Physical Transformation, subject to the above restriction

It is unlikely that the physical structures required for a specific non-natural physical transformation would occur in nature. Economic activity is therefore necessary to produce the structure.

Physical Capital will Decay over Time, and cease to function

This follows from the second law of thermodynamics, which states that the tendency of any closed system is to decrease in negentropy over time. This tendency can be turned about by opening the system to external negentropy input (by 'sucking' negentropy from the environment or context of the system).

Thus physical capital will decay if untended. It can be maintained by a continual process of repair and replacement. This process is, like all economic activity, physical in nature, and so has ramifications for the energy and capital use of the economy as a whole.

This concept is not peculiar to thermodynamic interpretations of the economy, and is very similar to the conventional economic concept of fixed capital depreciation.

In addition to Energy and Capital Inputs, most Economic Processes will require other Physical Inputs, most of which are products of economic activity.

The remaining tenets are not grounded directly in thermodynamics or energy analyses, but draw in additional economic concepts in order to make the thermodynamic ideas relevant to policy.

This introduces the idea of economic processes, as stylised 'recipes' by which a number of inputs are brought to a stock of fixed capital in order to transform the inputs into outputs. The characteristics of individual process types are derived from classification of real processes (agriculture, for example, might be summarised as feeds, fertiliser and tractor fuel transforming into food. In this particular example, one would need to bear in mind the livestock, as well as the stock of fixed capital).

The differentiation between primary and secondary resources is also introduced here. A primary resource is a resource abstracted directly from nature, whereas a secondary resource is the output of another economic process. Relatively few economic processes use primary resources. Although all processes use energy, they will generally receive this energy as a refined fuel rather than a primary material (e.g. gasoline rather than crude oil). Similarly, most consumer purchases of food are refined products (even staples such as flour, pasteurised milk, cuts of meat) rather than raw agricultural produce.

All activities within an Economy are connected by this mutual use of one another's Products

From discussion of the previous point, it can be seen that the pattern of interdependence in a large economy is liable to be complicated. As a first insight into this, it can simply be stated that all parts of the economy are interdependent.

For a fuller analysis, one can draw upon a number of applied mathematical techniques. The ECCO model, for example, follows the tradition of the Input-Output table (Leontief, 1941), in dividing the economy into 'sectors', defined in terms of their main product. These stylised sectors, in a fully developed table, will have only one output each, and receive as input every type of product circulating in the economy. The restriction to a single output allows for a manipulable matrix representation of the economy.

Another possibility is to follow the tradition of process chain analysis (e.g. Ayres, 1994; Simon, 1993; Schmidt-Bleek, 1994), restricting all processes to a small number of inputs and outputs, and analysing the resulting network for 'process chains' and 'loops', upon which energy (e.g. Nieuwlaar, 1988) and material (e.g. Schmidt-Bleek, 1994; Ayres, 1994) analyses can be conducted. This latter approach has been adopted as a starting point for the IPSO model discussed in Chapter 8.

The full range of options and their individual merits cannot be explored fully here. Suffice it to say that Natural Capital Accounting does not restrict itself to any one way of stylising the fact of intersectoral dependence, as most of the stylisation is done in order to provide a tractable mathematical model rather than to provide a closer fit to reality.

The Growth of an Economy is limited by its ability to provide the Energy, Capital and other necessary Inputs for its Physical Production Processes

An economy that cannot 'feed' its processes with energy and other inputs, nor repair and maintain their required capital structures, shall necessarily suffer a reduction in volume of output. As outputs of most processes act as inputs to others, reduced activity in one part of the economy will generally have consequences throughout the system. To this extent, then, the above statement is essentially correct. Again, the key is relevance.

Other economic theories describe the principle limits to growth as being based on the co-ordination of individuals activities, and the effective transfer of information rather than materials. The relevance of this statement, then, can be brought into question by other schools of thought (and, in so doing, much of the relevance of Natural Capital Accounting as a whole).

If energy constraints only limit system growth to 300% p.a., then other constraints restricting to much lower growth rates will kick in first, and the energy-based constraints will never be realised. Experience with ECCO models suggests, though, that growth rates calculated on the basis of physical constraints often are very realistic.

There is certainly overlap between the information and material aspects of an economy. For instance, natural capital accounting describes only the limits on the ability to produce the fixed physical capital required to maintain and expand an economy. It says nothing about the allocation between sectors, which is primarily an information issue. Similarly, technological change is an information-driven process to some extent, and yet it has important consequences for physical production.

Human labour provides an insignificant energy input into the economy - its purpose is to *manage* physical transformations, to make decisions

Human labour, often referred to colloquially as 'work', provides very little work in the strict thermodynamic sense of rates of transfer of energy over time. Human labour is undeniably important to an economy. In natural capital accounting terms, labour's importance lies with its ability to organise and manage physical processes, even in the case of 'manual labour', which usually involves skilful use of tools to manipulate materials.

Natural Capital Accounting theory is not, then, an all-encompassing theory of economics able to stand on its own. It is not designed to be so. Rather, it acts as a means of reintroducing some important aspects of the real world into economics. An application of Natural Capital Accounting must account for both physical and behavioural aspects, and so address issues considered to be within the domain of the mainstream economics traditions.

4.2 ECCO Models

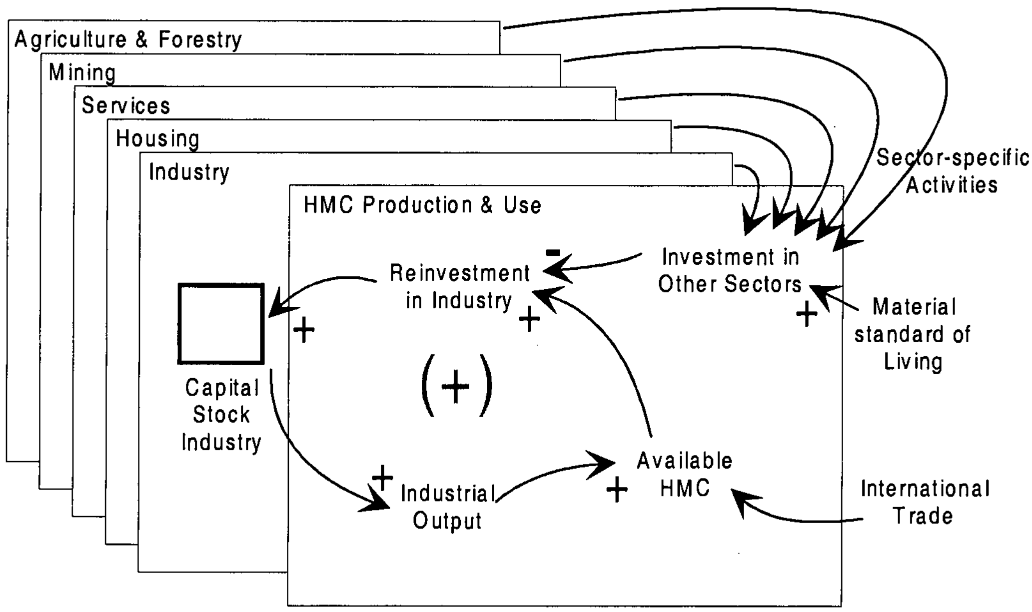
The ECCO model is the main implementation of Natural Capital Accounting theory, having been developed over the last twenty years by Malcolm Slesser & colleagues (Slesser, 1979; 1992; Slesser & King, 1988; Slesser, King, Revie & Crane, 1994; Slesser, King & Crane, 1997). Early ECCO models of developing countries such as Kenya and

Mauritius represented relatively aggregated economic sectors. Larger subsequent studies, such as those of the UK, EC Europe and Australia, have mainly extended the methodology by representing economic sectors in greater detail, and by incorporating mechanisms for dealing with delinking between embodied energy and services provided (see Section 4.2.2).

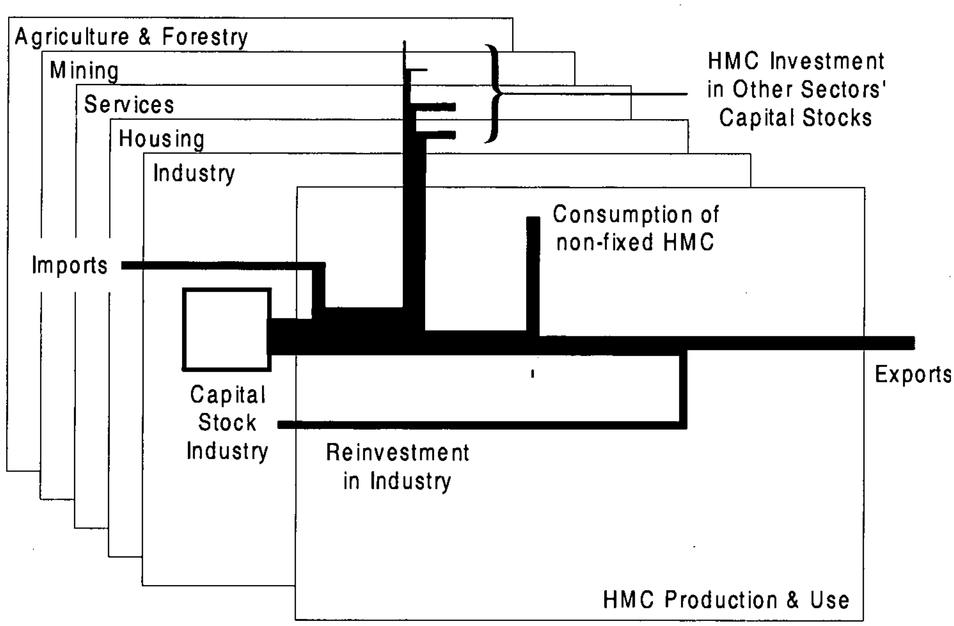
ECCO uses system dynamics to track resource use through an economy composed of a handful of sectors (in larger models, typically ten sectors splitting into as many as thirty or forty subsectors - see Chapter 5 for an example). The industrial sector produces a single product termed Human-Made Capital (HMC) corresponding to the fixed physical capital in the preceding discussion of Natural Capital Accounting. In addition to reinvestment in fixed capital stocks within the economy being modelled, the following 'sinks' for HMC exist:

- the consumption of non-durable HMC by private individuals, covering everything from biro pens to fish fingers. The relationship between consumption and reinvestment in industry is usually determined empirically.
- Some ECCO models (Slesser, King, Revie & Crane, 1994) introduced non-durable HMC consumption within other sectors as a series of non-fixed HMC terms (notably covering agrochemicals).
- the net export of HMC required to balance trade in other commodities, including fuels, services, agricultural produce, etc. and external debts. Some trade terms are determined using simple supply-demand equations. Others are left as exogenous terms for users to enter their own scenario forecasts.

Typically, ECCO employs a 'rest' or 'residual' theory of investment, drawing a distinction between industry and other activities, as the immediate demand for HMC cannot be calculated. The HMC requirements of other sectors are calculated according to their size and activity, and the residual between this and available HMC is allocated to industry. The growth rate of the system is therefore determined semi-internally, and will respond automatically to any policy with a physical dimension that is introduced into the model. This 'endogenous growth' feature implements the final statement given above regarding Natural Capital Accounting. The growth-determining feedback loops present in a simple operational model, and the HMC allocation pattern resulting from these are shown in figure 4.1 below.



Primary Influences on human-made capital creation and use



Primary flows of human-made capital

Figure 4.1. A diagram of the central growth-determining loop in the ECCO model, with the aggregated industrial sector depicted here as the core resource on which growth depends. The processes of fixed- or human made capital (HMC) are depicted as (a) an influence diagram, illustrating the main causative features

represented in the model (b) a flow diagram illustrating the sources and sinks of HMC. (Black lines indicate HMC flows into, out of and through the economy, with flow rate being represented by line thickness. The total HMC available is the sum of imports and native production. This is a 'snapshot' representation, and the ordering of flows from left to right here does not imply any temporal ordering of events).

4.2.1 ECCO and Energy Numeraires

In Chapter 3, the difference between energy- and money-based economic theories was discussed in a general way. The choice of numeraire was seen to relate to the aspect of the system to be emphasised.

ECCO uses an energy content numeraire for representing stocks and flows of HMC, through which overall system growth is determined. The model is not strictly energetist, and does not try to record all quantities solely in energy terms. Agricultural produce (grown for food) is typically measured in tonnes protein, for example, although this is not a hard rule that every ECCO model must follow. There is generally a preference for physical units, but pragmatism is the key concern.

Within the core embodied energy numeraire, the issue of thermodynamic availability is circumvented by the adoption of a reference availability corresponding to that for fossil fuels; oil, gas and coal are all within 5% of each other - see IFIAS (1975). Energy carriers with different availabilities, notably electricity, are treated as separate commodities. Electricity is never measured in GJ, but in kWh, and the demands for thermal and electrical energy are not directly summed. The term 'FEREL' is used to represent the thermal energy 'embodied' in the electricity.

As noted already, a comprehensive implementation of Natural Capital Accounting must draw upon both physical and economic concepts. While the energy numeraire serves the purpose of representing physical flows very well, it does not work well as an economic numeraire. The embodied energy associated with a stock of HMC says nothing about the functions that it can perform, or why it is desirable to maintain. Further, there are a number of situations under which the service provided by a good and its embodied energy content will diverge or 'delink'.

This possibility has serious consequences for ECCO models, because the growth-loop algorithms at their simplest use the embodied energy content of HMC as a way of estimating the service that the HMC provides. If service provided and embodied energy content delink, that estimate becomes inaccurate, and that inaccuracy is passed on to the growth loop. As most policy-related uses of ECCO are based on comparing changes in growth rate (or variables strongly influenced by the growth rate), that inaccuracy matters. It is important for ECCO models to be able to represent situations in which delinking might occur with a good degree of accuracy.

This problem was first described and corrected for by Ryan (Ryan, 1995; Ryan & Peet, 1995), and corrective mechanisms have also been proposed and implemented by Noorman (1995). The problem is discussed in greater detail below.

4.2.2 Introduction to Problem & Definitions

4.2.2.1 Delinking of Growth and Output

The concept of 'delinking' refers in general to any two measures of an activity that we would ordinarily expect to increase or decrease in proportion to one another. The measures 'delink' when some change in quality of the activity means that they no longer do so.

Delinking of the 'good' and 'bad' aspects of growth (very simply, welfare and pollution, respectively) is an important issue in ecological economics. In biophysical representations of economic systems, the delinking can be split into two separate issues:

1. delinking between physical measures of output (volume, mass, embodied energy) and the usefulness of that output (service provided, in the sense of a definable service such as kWh electricity generated, protein produced, passenger-km transport, etc.)
2. delinking between the definable service provided and the demand for that service (i.e. it's utility).

As a brief example, consider transport. Changes in engine technology, technology of fuel production, availability of physical resources associated with the production of cars, roads or fuel, or a modal shift (e.g. from cars to trains) may 'delink' the embodied energy of transport activities from the passenger-km or tonne-km service provided (type 1). This has nothing to say about the purposes or ends to which transport is put.

As a different issue, changes in family structures, lifestyles, population distribution patterns, working practices, or a society's attitude to the satisfaction of needs may 'delink' the passenger-km or tonne-km of services from the demand for or desirability of transport. This has nothing to say about the means by which transport is provided.

At a broader scale, the issues aren't always separate. For example, the demand for transport may increase because local supplies of minerals are exhausted, and minerals are now being shipped in from a distant mine. The issue of 'ends' isn't divorced from the issue of 'means' altogether, but they do provide a useful distinction here when examining the finer details of implementation in a formal model.

Because ECCO deals mainly with the technical details of the physical aspects of production, and with behaviour/demand in a simple and/or exogenous way, there is a need for solutions to 'means'-based delinking only, as the model doesn't attempt any automated calculation of the welfare or utility ultimately associated with output.

The key technical issue that must be dealt with is the use of embodied energy numeraire to represent fixed capital stocks. There are a number of examples of events that might change the embodied energy content of a capital stock from an accounting perspective without altering the actual activity of that stock at all. (e.g. fossil fuels become less accessible, the process by which the capital is manufactured becomes more energy efficient, etc.) The next sections describe this problem (and proposes solutions) in detail.

4.2.2.2 Representing Fixed Capital Stocks

In reality, a stock of fixed capital will be heterogeneous in nature. Significantly, it will be of varying age, and therefore operate a variety of technologies. As technology improves (by whatever criterion), the capital base is said to "deepen" as opposed to (or in addition to) expanding in volume. That is, the value of the capital increases through an increase in quality rather than quantity.

Assumption of an average intensive characteristic for the entire stock is therefore fraught with danger, as the relative sizes and characteristics of various homogeneous sub-stocks will vary dynamically. A full analysis of capital deepening process will therefore require:

1. detailed knowledge of the range of characteristics encountered within the stock
2. cohort structure, with sub-stock classification based on these characteristics (either directly or through strongly correlated characteristics, such as age).

Clearly, the increase in model complexity and, more significantly, data requirements, is considerable. For that reason, cohort structuring has not been adopted as a standard feature. (The IPSO Model presented in Chapter 8 operates on a similar level of detail to a cohort model. The limitations imposed by such large data requirements are discussed further there.)

A practical measure of embodied energy content must start at a given point in time, and usually at one in which some energy has already flowed through the system, and therefore become embodied in a stock.

In choosing a definition of an embodied energy numeraire, one must specify the rules by which the accumulation is calculated. Two options are immediately apparent:

1. At each timestep, calculate the incremental increase in embodied energy by adding the current rate of increase. Measured this way, the stock will correctly reflect the embodied energy passed through the system over time.
2. Keep an incremental record of the stock in another numeraire (say, money). At each timestep, estimate the stock's embodied energy content by converting this other value using a coefficient (say, embodied energy per unit money). Measured this way, the stock will reflect the physical effort required *by the system in its current state* to replace the entire stock.

Note here that the difference between these options is only noticeable in the case of systems undergoing changes in technology over time (see table 4.1 and attendant discussion later).

Again, the choice of numeraire will depend upon the purpose to which the model will be put. If the aim is primarily an account of resource throughput, then option [1] seems preferable. On the other hand, if the key priority is an identification of maintenance requirements or other actions to be undertaken in the present then option [2] has more to offer.

Note that the definition of embodied energy also requires a definition of the system boundaries to be used in process analysis chains. That is, there is a need to specify how far back to track instances of energy use in the creation of an artefact. In general, there is little debate over this point (in theory at least), with the IFIAS conventions (IFIAS, 1975) setting out clear definitions of fuels and primary energies.

4.2.2.3 Embodied Energy & Service provided by Capital

The choice of embodied energy as a numeraire in ECCO is made, then, on the grounds that it reflects the physical transformations involved in building and expanding the infrastructure. In order to implement the growth loop, the allocation of HMC between sectors must also be considered, bringing up issues of demand.

Traditionally, demand for HMC has also been represented in embodied energy terms, on the assumption that the embodied energy content of fixed capital is closely correlated to the "usefulness" of the capital, to the service that it provides or the activity that it performs. As embodied energy content is primarily a measure of effort expended, there is no clear theoretical reason for making this link. Two pieces of equipment offering identical functionality will not necessarily have required the same effort to be created, if one is "better designed" than the other. Rather, the argument rests upon expectation of a correlation between energy input and functionality *for a given technology* because both are correlated directly to the size of the capital stock, *in those cases where no known factor is operating that will cause a delinking between the two terms*. It is important for ECCO to be able to relax this assumption where necessary, and proved to be a limitation on early ECCO models.

Even when using a relatively simple model of capital production, one can postulate a number of instances in which a decoupling *might* occur. In ECCO, an aggregate capital-production process is assumed, drawing in a range of inputs. These inputs can be classified at a broad level as capital, energy, and other inputs (e.g. "raw" materials, transport, agriculture, services) which indirectly consume capital and energy themselves (i.e. they are generated and brought "to the factory gate" by other capital- and energy-consuming processes). Note that energy inputs are directly dissipated in the production process, whereas capital inputs are not. The contribution of capital stock to the production process is generally represented as a rate by attributing a fixed lifetime to the capital, from which an imputed depreciation rate can be calculated. Thus the total energy embodied in a flow of manufactured capital can be approximated as:

$$E_{emb,out} = SUM(E_{in}) + SUM(RDC_{\$,in} \times EI_{HMC}) \qquad .....(4.1)$$

where

E_{in} = inputs of fuel to manufacturing or pre-manufacturing process

$RDC_{\$,in}$ = capital depreciation (money value) inputs to manufacturing or pre-manufacturing process

EI_{HMC} = average energy intensity of human made capital

Note that the coefficient EI_{HMC} may not give the same relative weighting as would a money analysis of production costs, or as an analysis conducted in some measure linked to the functionality of the capital produced.

Factor	**Energy:Size affected**	**Service:Size affected**
1. microscopic diversity in the energy supply system		
e.g. large-scale substitution of supply technology towards one with a radically higher or lower GER *	yes	no
2. microscopic diversity in the supply system of other factor inputs to industry (HMC-making sector)		
e.g. electricity, raw materials, services: in general, these inputs will be made commensurate with direct energy inputs by some form of energy/process analysis	Yes	no
3. increased input use efficiency in industrial sector **		
the GER of inputs remains the same, but the volume of inputs required per unit output changes, e.g. energy-efficient technologies	yes	no
4. increased capital use efficiency in industrial sector **		
i.e. changes in the potential output rate per unit of capital stock	yes	yes

*** GER is gross energy requirement of a process, usually expressed as primary energy per unit finished product from that process, in this case GJ/GJ fuel delivered. GER incorporates all direct and indirect energy inputs, including the fixed capital depreciation for all capital in the process, back to a clearly-defined system boundary (see Crane & Slesser, 1995: Chapter 4 for a discussion of primary energies and fuels).**
**** These cases are cited only for the industrial sector here. Similar changes may occur in other secondary production sectors, and these *may* decouple embodied energy from functionality, but these are simply special cases of factor types 1 (for energy supply sector) or 2 (for other input supply sectors) above.**

Table 4.1: Examples of factors liable to cause a decoupling of embodied energy and functionality of a fixed capital stock

Some examples of factors liable to decouple embodied energy and functionality measures of capital output are tabulated in table 4.1 above, with a note as to what kind of delinking might occur. Within the 'means-based' category, two types of delinking can be identified; that of the embodied energy:capital size ratio, and of the service provided:capital size ratio, where capital size is visualised as a physically-conserved term such as mass or spatial volume, for example.

Only in case 4 does the service:size ratio alter, and therefore in all other cases we can expect that size will serve as an adequate substitute for functionality. Note that our aim here is not to cease relying on a *ceteris paribus* type of argument, but simply to correct for specific factors in those cases where it is known not to hold.

4.2.3 Analysis of Solutions for simple ECCO Model

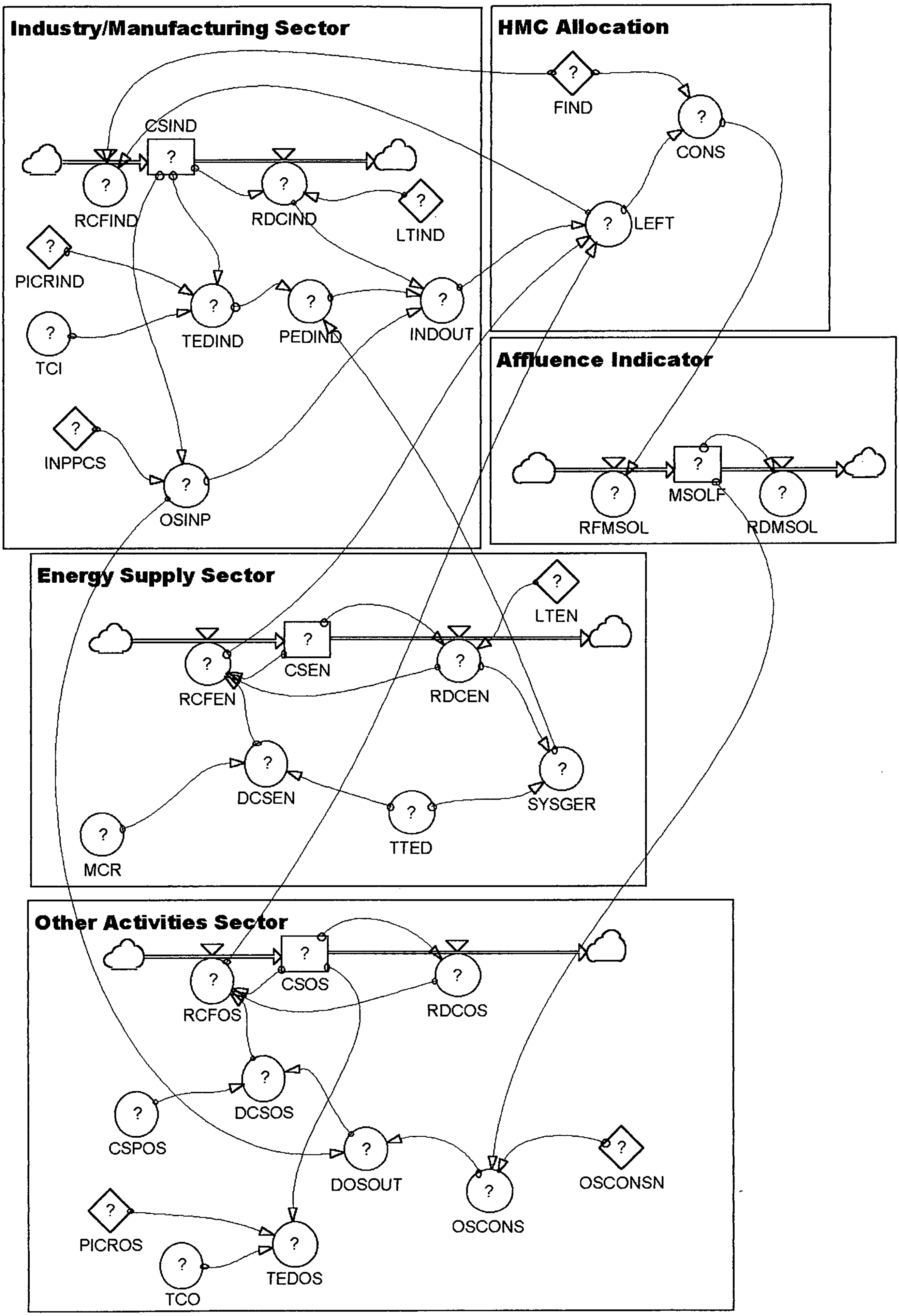
In this section, a simple demonstration ECCO model will be used to examine two possible implementations that address the capital deepening issue. The solutions are assessed on the strength of the results generated by simulating a number of changes for key parameters when each is applied to the model.

4.2.3.1 Demonstration Model Structure

The demonstration model used in this section has been simplified as far as possible in the interests of clarity. There are four sectors to the model:

1. Industry, including a central growth loop structure
2. Energy Extraction, represented by a Capital Stock term
3. "Other" sector, represented by a capital stock term. This sector serves both industry and individuals.
4. Consumption and material affluence. Consumption rate is calculated in the usual fashion, and the affluence index determined by both consumption of goods and depreciation of "other" sector capital (a constant population base is assumed here, to simplify the dynamics). The affluence index is used to drive the demand for "other" sector services.

The model is initialised using fictitious data, designed to generate a realistic moderate growth rate for the system over a forty year period. A schematic of the model structure is given in figure 4.2.



Industry/Manufacturing Sector
CSIND
RCFIND
RDCIND
LTIND
PICRIND
TEDIND
PEDIND
INDOUT
TCI
INPPCS
OSINP
HMC Allocation
FIND
CONS
LEFT
Affluence Indicator
RFMSOL
MSOLF
RDMSOL
Energy Supply Sector
LTEN
CSEN
RCFEN
RDCEN
DCSEN
SYSGER
TTED
MCR
Other Activities Sector
CSOS
RCFOS
RDCOS
DCSOS
CSPOS
DOSOUT
OSCONS
OSCONSN
PICROS
TEDOS
TCO

Figure 4.2 (previous page): Schematic of the demonstration ECCO model. The variables involved in the central growth loop are shaded.

In order to function effectively, the model must be robust to all the four conditions described in Table 4.1. These conditions are simulated by the following parameters (which are exogenous in this simple model, but in a larger model such as the one presented in Chapter 5, will be partly dynamic).

change in GER of energy supply system

A table function MCRT determines the marginal capital requirement of the energy extraction sector, relative to the initial value.

change in GER of factor-of-production supplier to industry

Table functions TCOT & CSPOST determine the fuel energy input and capital requirements per unit output respectively for the "other" sector, both relative to initial conditions.

change in input use ratio by industry

Table functions TCIT & FOSTIN determine the fuel energy input and "other" sector input requirements respectively for the industrial sector, relative to initial conditions.

change in capital use ratio by industry

Table function CAPINT determines the capital stock required per unit output by industry. Note that, because of the assumption that capital productivity is limited only by the supply side, altering this term will not reduce the capital input to industry, but boost output (i.e. the same stock of industrial capital exists, but is now creating output more efficiently).

4.2.3.2 Solution 1

The 'Solution 1' version of the corrected model records all capital stocks using the embodied energy numeraire as the primary measure, correcting as it goes along. A second record of industrial output, called INDOUTB, is kept, in which all inputs are corrected to a constant volume, by replacing current technological coefficients with those existing at the start of the simulation run. A general correction coefficient measuring the reduction in industrial energy intensity, REDEII is calculated as the ratio of embodied energy to corrected output measures.

The primary effects of the four types of change are dealt with as follows:

Factor [1] requires no direct correction factor. TEDIND feeds into INDOUT primarily as a direct fuel use, not an embodied one. As changes in the MCR of the fuel only affect the embodied energy content, no direct correction is needed. However, as PEDIND rather than TEDIND feeds directly into INDOUT, the INDOUTB equation is modified by replacing the current system GER with that at the start of the simulation. A similar manipulation of the OSOUT term is also undertaken.

Factor [2] is dealt with by setting an OSINPB term into the INDOUTB equation. OSIPB is identical to OSINP, but is corrected overall by a factor that accounts for structural changes in the OSOUT expression, via an OSOUTB term (similar to INDOUTB).

Factor [3] is dealt with by correcting PEDINDB by the TCI factor, and OSINPB by the INPPCSF term. That is, any changes due to variation in these terms are effectively undone, so that PEDINDB and OSINPB are calculated as though the initial input requirements still held.

Factor [4] is dealt with by setting up a CSIND1 term, which represents the current CSIND value as though no changes in capital use ratio had occurred. The PEDIND & OSINP equations are corrected at source for this factor. It is assumed here that primary energy and other inputs to industry are actually coupled to the rate of output rather than the size of the capital stock. In the absence of factor [4] type changes, capital stock serves as an adequate substitute, though. So, as capital productivity increases, output increases, and so the resource throughput per unit capital stock will increase.

Under solution 1, capital stocks are still primarily measured in embodied energy terms. As the factors described above will decouple embodied energy from capital functionality, one may expect that the stocks of capital will be of heterogeneous functionality. A direct correction of this would probably require a cohort structure of some sort. Where, as here, several parameters may lead to decoupling at differing rates, a large number of narrow age ranges would be required. That is, the cohort model required would be extremely complicated, and has therefore not been developed, as solution 2 offers a simpler remedy.

Lack of a cohort structure in the solution 1 model raises problems in the case of those terms driven by capital stock variables (here, these are TEDIND and OSINP driven by

CSIND[8] and TEDOS driven by CSOS). As the capital stocks are being measured in (historically correct) embodied energy rather than functionality terms, some correction ought to be implemented, as the demands are theoretically driven by functionality. One possibility is to correct the driver terms (i.e. the capital stocks) by the generalised REDEII term in these equations, but this may over-correct, as it would re-scale the capital stock as though it were a replacement rather than historical embodied energy measure. As no clear solution is available in this case, two versions of solution 1 are offered here. In the original solution 1, no corrections for these terms are made. In version 1a, the REDEII term is used to (over)correct them.

The full professional dynamo program listing for the demonstration model incorporating solution 1 is listed in Appendix 1. A schematic of the revised industry and HMC allocation sectors, in which the major changes are implemented, is given in figure 4.3.

[8] More correctly, CSIND1 drives these terms. This corrects only for changes in the CAPINT term, though, and not for general secondary effects.

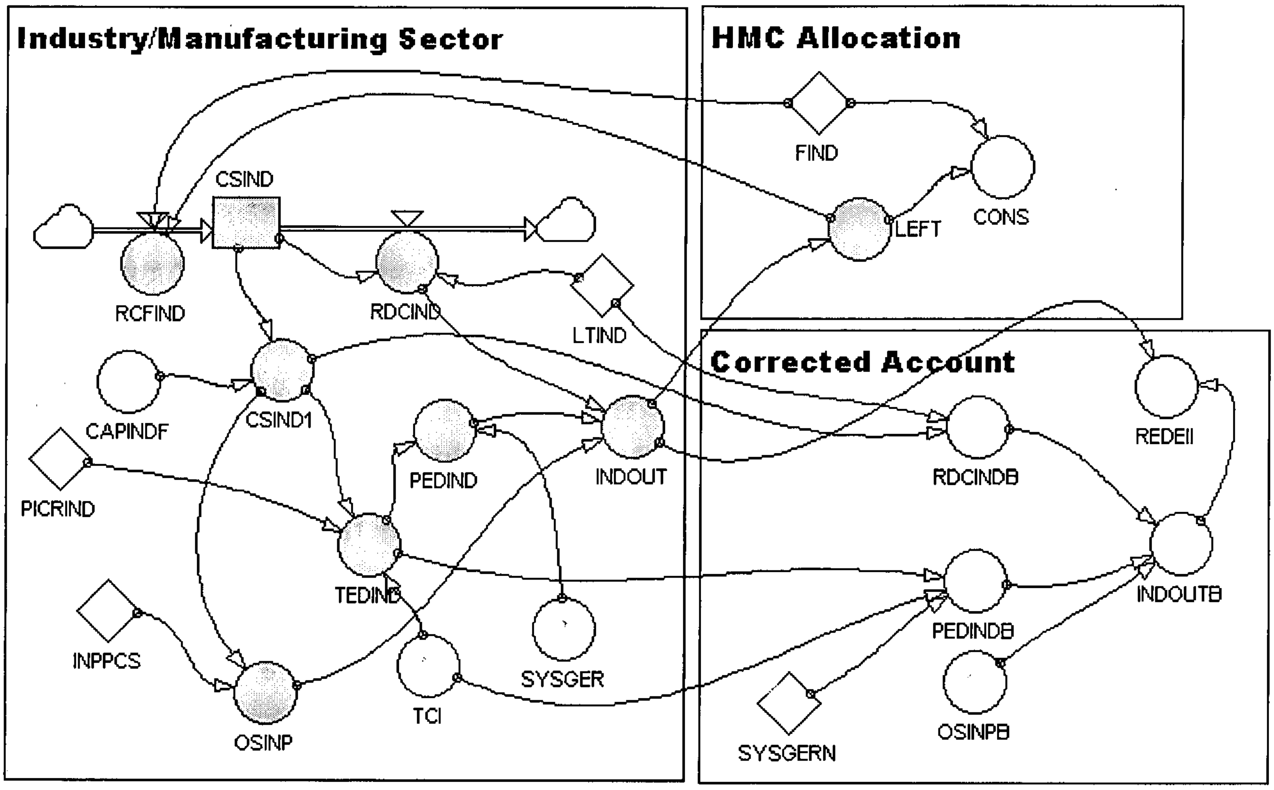


Figure 4.3 Revised schematic for demonstration ECCO model with solution 1 implemented. A corrected account for INDOUT is included, but the growth loop is still driven by the uncorrected INDOUT term, with the corrected account only serving as a set of indicators.

4.2.3.3 Solution 2

The 'Solution 2' version of the model tries to run all capital stocks using a constant embodied energy numeraire as the primary measure. This numeraire has no direct physical meaning, but serves as an adequate substitute for the service provided, in that all factors described in this report that may create an embodied energy:functionality decoupling have been corrected for.

Solution 2 is similar to solution 1 in terms of the approaches taken to correcting factors [1] to [4], as described in the previous section. Additional modifications have been made to allow the model to run using the constant embodied energy numeraire, as follows:

The general term REDEII has been applied to all rates of capital investment outside the industrial sector, hence expressing them in constant functionality terms. There is therefore no need to adopt a cohort model, nor to correct for capital stock-driven quantities such as TEDIND, OSINP and TEDOS. Where secondary accounts in real embodied energy are required, they can be derived by use of the REDEII term also, as replacement values rather than historically correct accumulations. Where the latter were desired, a secondary level variable could be set up, although there seems little use for such a measure in most ECCO model applications.

In the standard model, the consumption and reinvestment in industry terms, CONS and RCFIND are calculated from the central growth loop term "LEFT" (the HMC left over after other sectors have reinvested). Here, the term LEFTB is used, a corrected, constant-numeraire term. Hence the capital stock of industry is also measured in constant terms.

Further, because CONS is measured in constant terms, the affluence indicator is also a service-corrected measure. This is highly appropriate, and, given the important of MSOLF as a driver in more sophisticated ECCO models, highly relevant.

Solution 2 differs from solution 1, then, in that it converts the entire model, most notably the central growth loop, into the constant numeraire. In doing this, it offers a more robust assessment of the changes in growth rate that the system is likely to experience as a result of technological changes, while screening out erroneous changes in growth using the solution 1 techniques. The differences in performance of the two solutions can be seen in the sample results that follow.

The full professional dynamo program listing for the demonstration model incorporating solution 2 is listed in Appendix 1, and a schematic representation of main changes is given in figure 4.4.

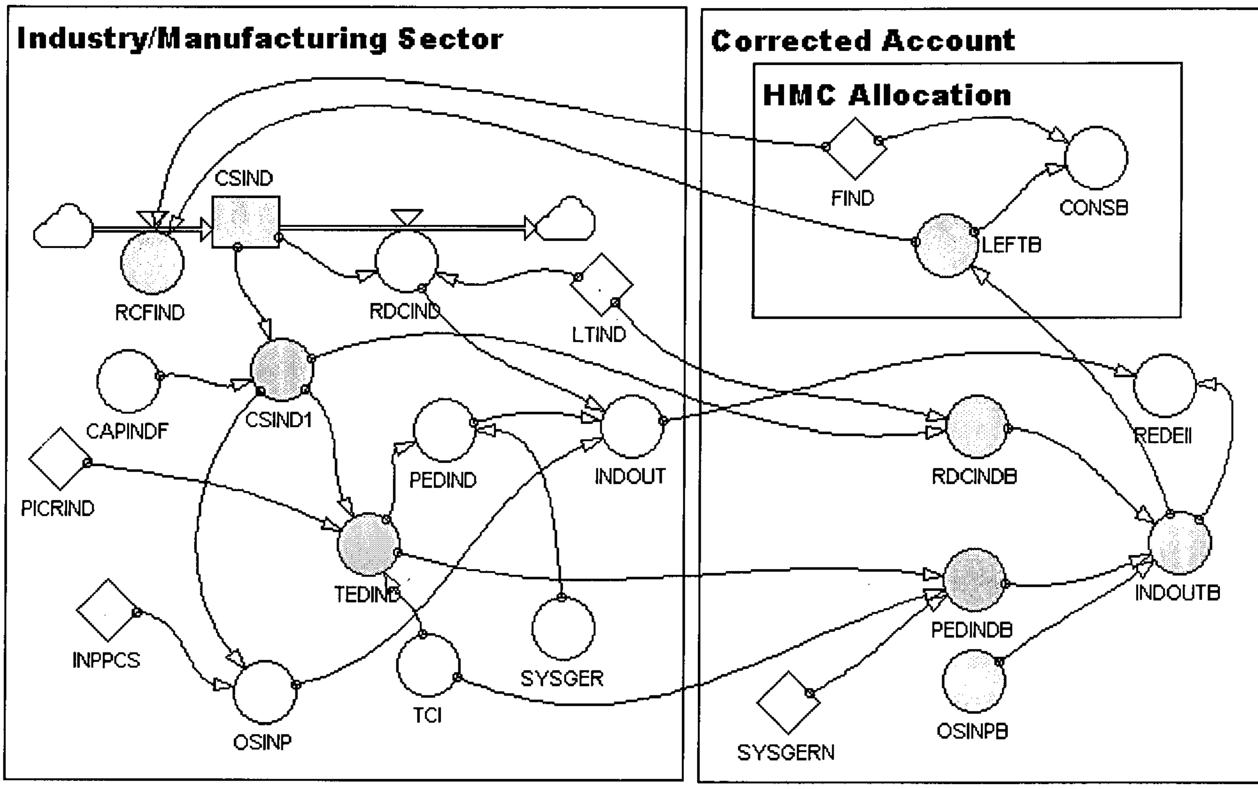


Figure 4.4 Revised schematic for demonstration ECCO model with solution 2 implemented. The corrected account for INDOUT is now used to drive the growth loop. As the equation for OSINPB is quite complex, it has been omitted from this diagram, although the OSINPB variable itself is still present. See the code in Appendix 1 for the full equations.

4.2.3.4 Sample Results from Solutions 1 & 2

For the purposes of testing the solutions described above, the demonstration model was run through a series of six scenarios, in which each of the six table functions MCRT, TCOT, CSPOST, TCIT, FOSTIN and CAPINT was reduced over a forty year period to half its initial value, while the other five functions were held constant.

MCRT represents the marginal capital requirement for extracting thermal energy resources, that is, the capital required per unit of energy extracted from the ground. A reduction is this parameter is equivalent to the introduction of a new lightweight energy resource extraction technology.

TCOT is the thermal energy demand coefficient for the 'other activities' sector. Reducing it is equivalent to introducing a large energy efficiency drive in non-manufacturing sectors of the economy.

CSPOST is the capital required per unit of output by the 'other activities' sector. Reducing it is equivalent to introducing lightweight technologies into those sectors.

TCIT is the thermal energy demand coefficient for the industry/manufacturing sector. Reducing it is equivalent to introducing a large energy efficiency drive in manufacturing sectors of the economy.

FOSTIN is the 'other inputs' required per unit of output by the manufacturing sector. Reducing it is equivalent to reducing material inputs such as paper, wood, agricultural products, ores, etc. to manufacturing processes.

CAPINT is the capital required per unit of output by the manufacturing sector. Reducing it is equivalent to introducing lightweight technologies into that sector.

The aim here was to give a robust testing rather than realistic changes. Solutions 1, 1a & 2 were run for each scenario. The results of each parameter change are shown in figures 4.2 to 4.7 respectively. The results of the simulations are discussed below.

4.2.3.5 Lightweight Energy Resource Extraction Technologies

Expected Effects: In the initial year, the energy sector consumes less than 2% of industrial output. Even a large change in the GER of fuel supply will therefore be unlikely to affect system growth to a great extent. Similarly, because direct fuel inputs to industry are counted in direct rather than embodied energy terms, the decrease in actual embodied energy output terms will be small. One would therefore expect little change in either case.

Actual Effects: The actual effects of this change, as shown in figure 4.5, confirm expectations. The changes using either solution are too small to count as significant. Because there is no delinking taking place, this simulation cannot be used to assess the merits of the three solutions for correcting for delinking behaviour.

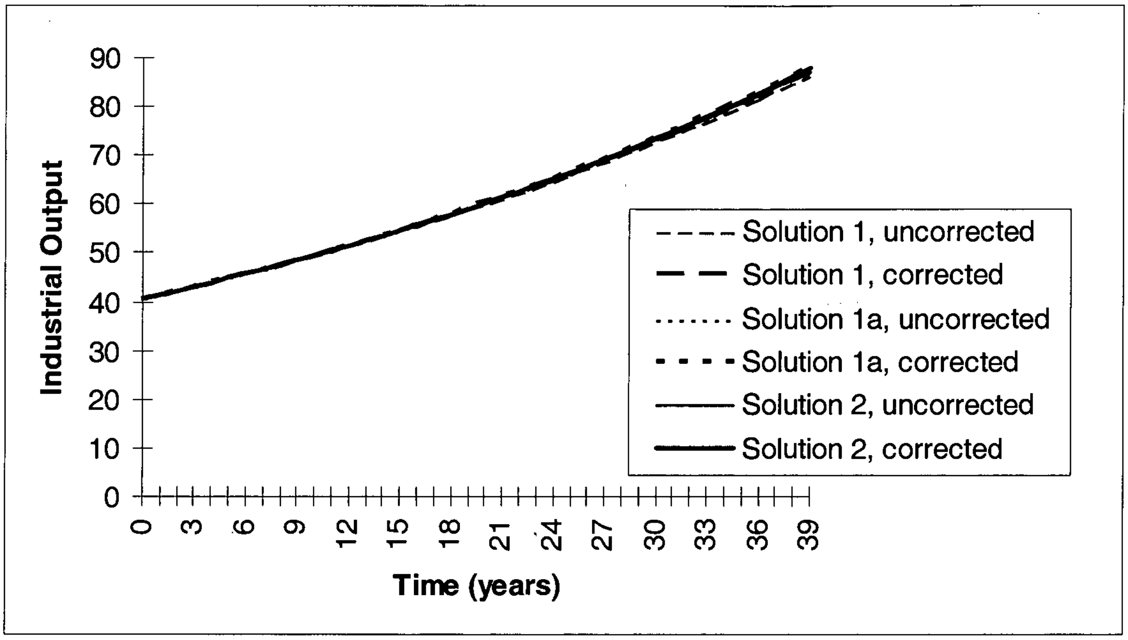


Figure 4.5: Effects of halving the GER of the Energy Supply System over forty-year period in each of the three corrected demonstration models. Each model produces two measures of INDOUT, labelled in the legend as 'corrected' and 'uncorrected'. The uncorrected measure accurately tracks changes in embodied energy throughput, whereas the corrected measure tracks changes in the service provided by the output. Very little delinking occurs as a result of this change.

4.2.3.6 Energy Efficiency & Lightweight Technologies in Non-Manufacturing Sectors

Expected Effects: Inputs from the other sector account for 25% of INDOUT in the initial year, with an embodied energy content approximately 82% direct fuel and 18% capital depreciation. Hence change in thermal fuel consumption will have a big impact on the embodied energy output of the other sector. In service-corrected terms, one would expect that a reduction in this term would reduce demand on the energy supply sector, freeing up HMC for use by other sectors. Changes in capital input will be expected to show less increase in growth.

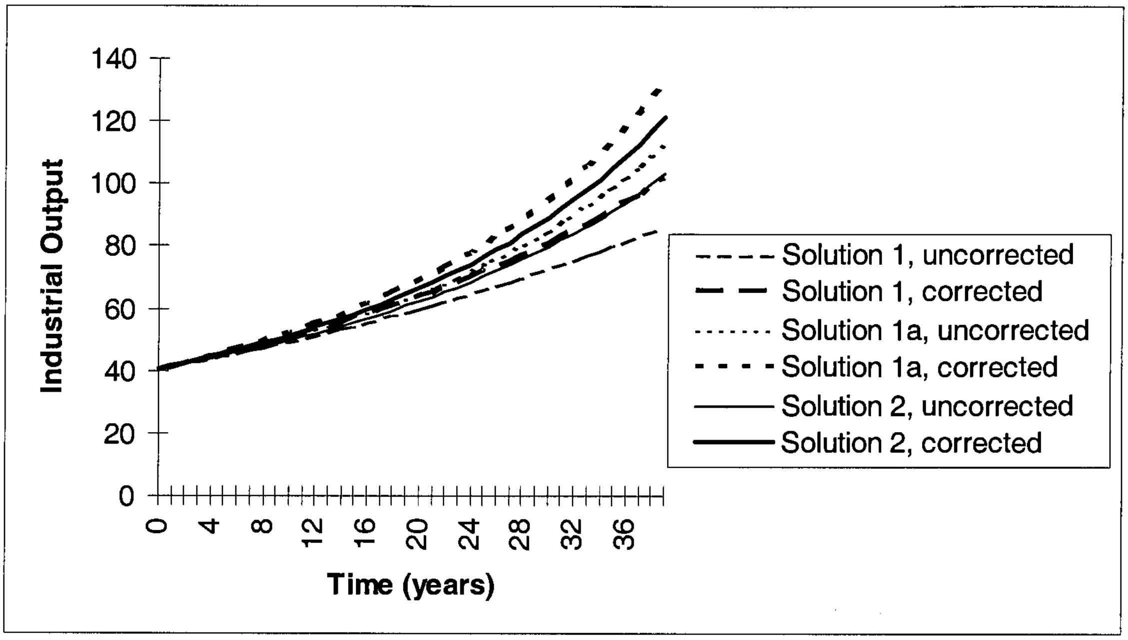


Figure 4.6: Effects of halving thermal energy input per unit 'other sector' output over forty-year period in each of the three corrected demonstration models. Each model produces two measures of INDOUT, labelled in the legend as 'corrected' and 'uncorrected'. The uncorrected measure accurately tracks changes in embodied energy throughput, whereas the corrected measure tracks changes in the service provided by the output. As the simulations here represent reductions in resource throughput without a drop in service, corrected terms are larger in each case.

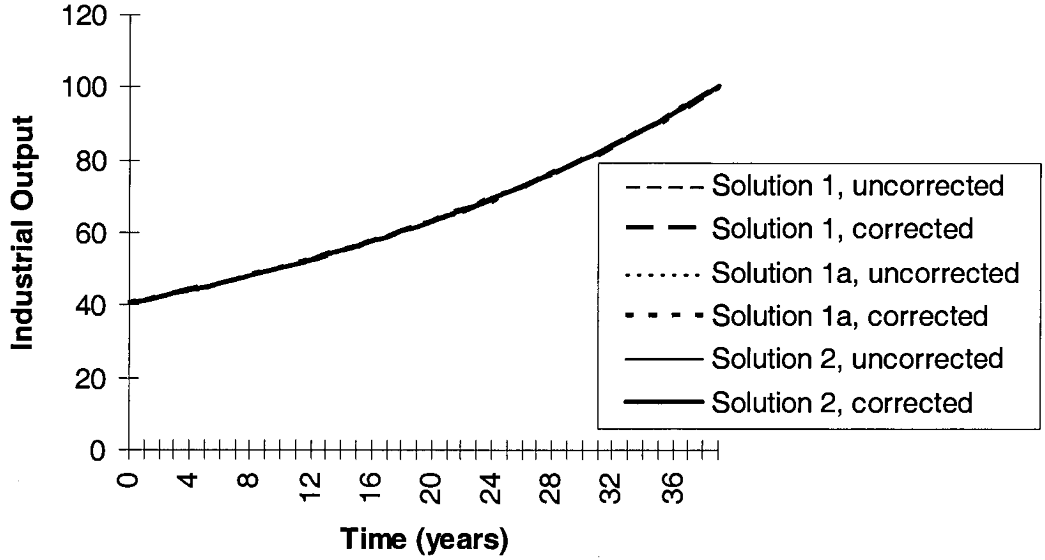


Figure 4.7: Effects of halving fixed capital requirements per unit of 'other sector' output over forty-year period in each of the three demonstration models. Labelling is as per figure 4.7. Very little delinking occurs as a result of this change.

Actual Effects: For changes in thermal fuel use (figure 4.6), all three solutions do show an increase in growth of (service-corrected) output, with the relative order 1a > 2 > 1. In solutions 1a and 2, the increased growth more than offsets the direct reduction in energy intensity of the other sector, so that embodied energy of output also rises on the reference case (for which functionality and embodied energy do not link). In the case of reducing capital requirements of the other sector (figure 4.7), a small increase is seen for all solutions, with all experiencing the same increase in output. No delinking between service-corrected and actual embodied energy is observed, though (i.e. REDEII=1.00 throughout the simulation).

4.2.3.7 Efficiency of use of Energy and Other Inputs by Manufacturing Sector

Expected Effects: In the initial year, industrial output is composed approximately 64% direct thermal inputs and 25% other sector's inputs. Both of these factors contribute significantly to INDOUT, and one would therefore expect a strong delinking of INDOUT and INDOUTB, with the former decreasing as a direct result of the changes. INDOUTB might be expected to increase due to the "rebound" effects of growth (see Chapter 5), i.e. reduced inputs by other sectors leads to reduced investment in those sectors, and therefore more HMC available for industrial reinvestment.

Actual Effects: Reduction of both inputs does create the expected delinking (figures 4.8 & 4.9). In solutions 1a and 2, increased growth does result from these changes, although this is minimal for solution 2.

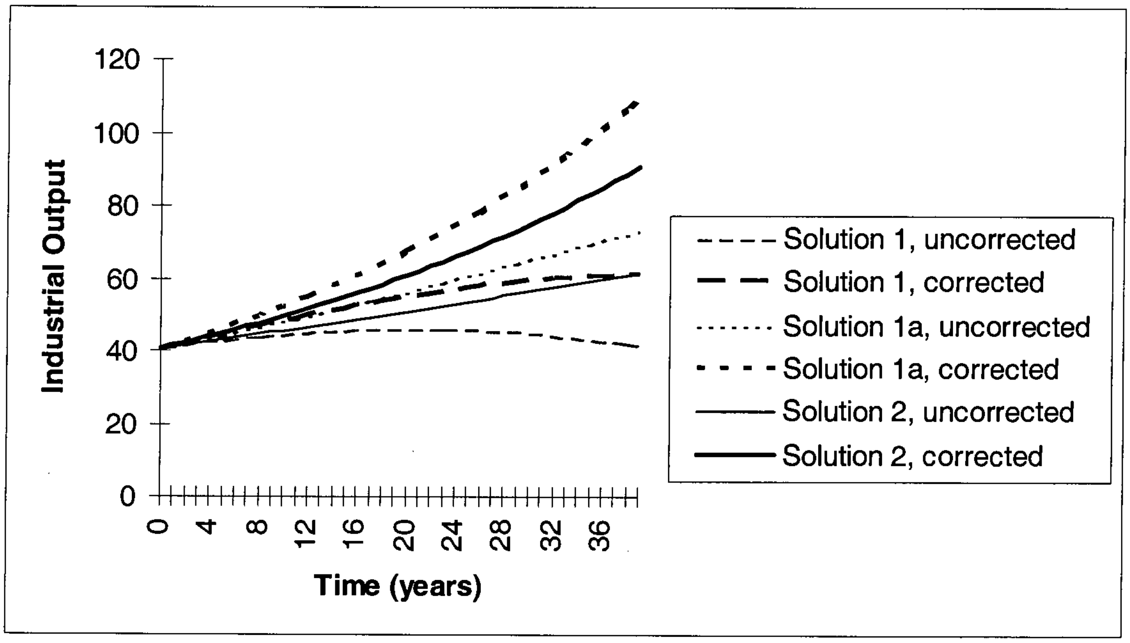


Figure 4.8: Effects of halving the thermal energy input to industry coefficient over forty-year period in each of the three corrected demonstration models. Each model produces two measures of INDOUT, labelled in the legend as 'corrected' and 'uncorrected'. The uncorrected measure accurately tracks changes in embodied energy throughput, whereas the corrected measure tracks changes in the service provided by the output. As the simulations here represent reductions in resource throughput without a drop in service, corrected terms are larger in each case.

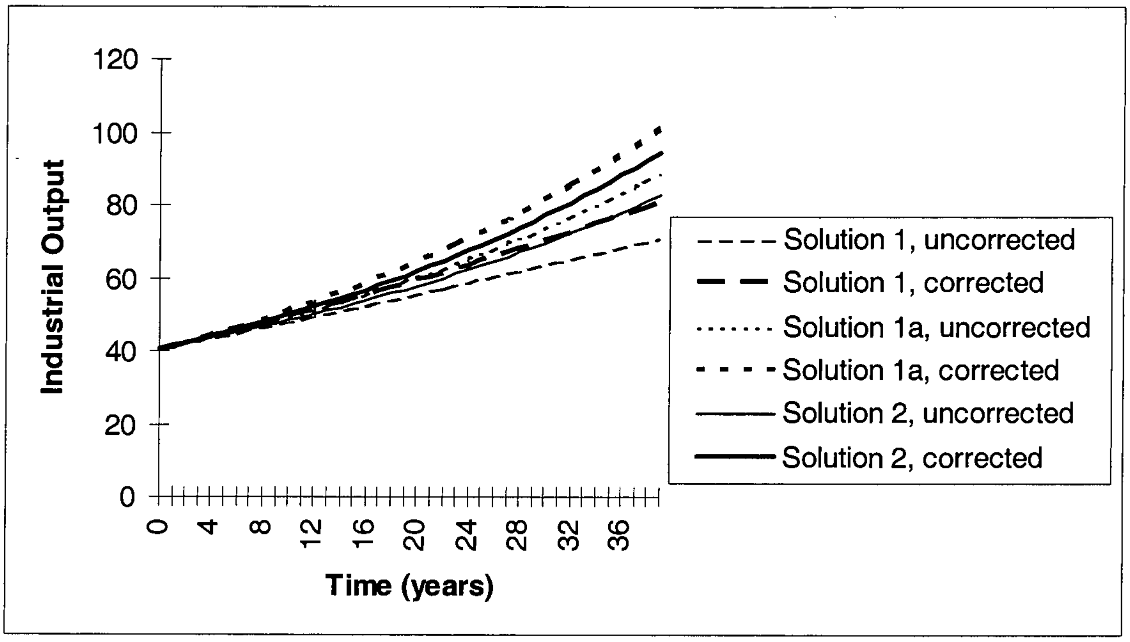


Figure 4.9: Effects of halving input requirements by 'other sectors' to the manufacturing process over forty-year period in each of the three demonstration models. Labelling is as per figure 4.9. Again, delinking is significant, with the service-corrected measure exceeding the uncorrected one.

4.2.3.8 Lightweight Technologies in Manufacturing Sector

Expected Effects: In the initial year, only 12.5% of industrial sector inputs derive from capital depreciation. However, doubling the productivity of this factor should have a large effect on growth, which is restricted primarily by the availability of capital stock.

Actual Effects: This change does indeed have a huge effect on the growth trajectory of the model (figure 4.10), with the final output values ending up roughly four times as large as in the reference run. Some minor delinking does occur between INDOUT and INDOUTB, although the increase in growth far outweighs direct reductions in embodied energy. The order observed for increased growth rate is 1a > 2 > 1, again.

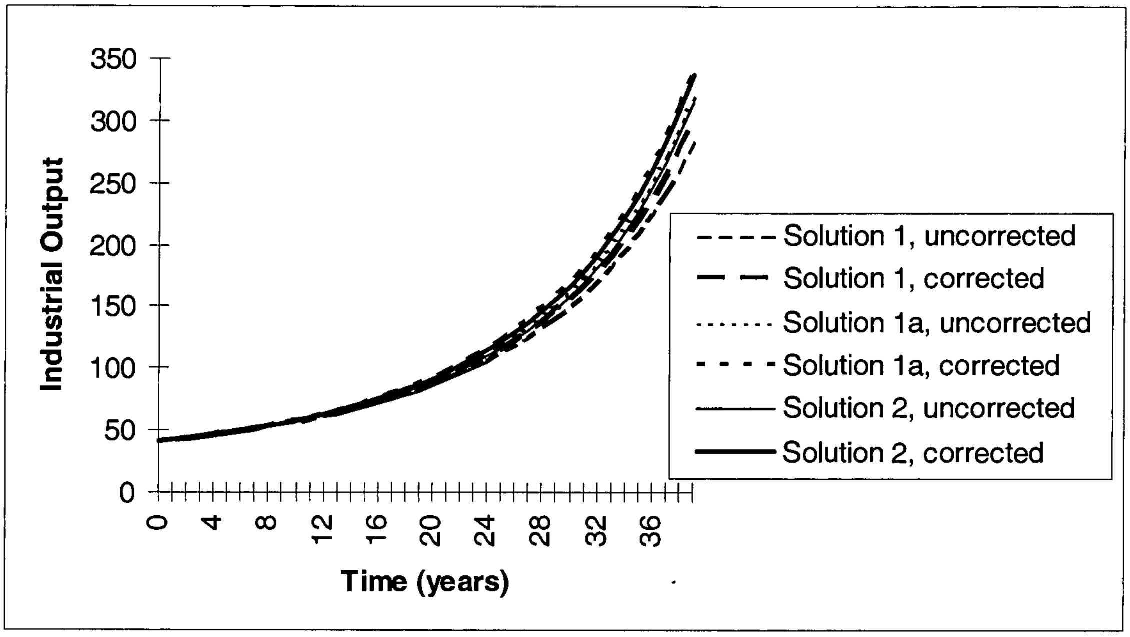


Figure 4.10: Effects of halving fixed capital stock requirement by industry per unit output over forty-year period in each of the three corrected demonstration models. Each model produces two measures of INDOUT, labelled in the legend as 'corrected' and 'uncorrected'. The uncorrected measure accurately tracks changes in embodied energy throughput, whereas the corrected measure tracks changes in the service provided by the output. The effects on growth are significant, although relatively little delinking takes place.

4.2.3.9 Summary

In several cases, a general pattern has been observed, whereby reduction in some input terms has led to an increase in growth rate, as a result of freeing up HMC that would otherwise be engaged in producing that input. A more energy-efficient economy requires less investment in energy extraction and supply, for example, and is therefore more "streamlined", and able to grow more rapidly. In some cases, this increased growth effect has been sufficient to outweigh direct decreases in embodied energy (e.g. figure 4.10); in other cases not (e.g. figure 4.8). Effects of these types are potentially important for policy-advice, and will be returned to in Chapter 5.

As noted at the outset, ECCO models require the ability to account for delinking in order to remain useful. The introduction of a 'rebound effect' complicates matters because it suggests that the correct solution will not be one in which the introduction of a delinking technology does not influence the growth rate. Some impact on the growth rate ought to be expected, and a correctly-functioning ECCO model will reflect that.

A comparison of the three modelling solutions is relevant here. Solutions 1 and 1a both attempt to measure the primary accounts of capital stocks and flows in actual embodied energy units, performing corrections to a standardised volume-corrected account only for key outputs as a secondary set of accounts. Solution 1 provided no correction for demand-driven factors, whereas solution 1a applied the same corrective ratio as that between actual embodied energy output of industry and the volume-corrected measure of output. Given that the output terms are derived directly from stock terms, and the demand terms are straightforward rates, solution 1a was expected to produce an over-correction.

Solution 2 computes all primary growth loop terms in volume-corrected embodied energy, and derives a secondary set of accounts in actual embodied energy where needed.

In all cases, the ranking of "growth effect" under the three solutions has been 1a > 2 > 1. This supports the hypothesis that solution 1 under-corrects and solution 1a over-corrects, as a result of their inability to deal with a heterogeneous embodied energy content of capital stock. As noted earlier, this problem doesn't apply to solution 2, in which the capital stock is homogeneous in terms of the numeraire used ('service-corrected' embodied energy).

Accordingly, solution 2 is deemed to be the best option, because it does not present theoretical problems with heterogeneity of stocks, and employs a numeraire consistent with the central purpose of the model; to determine the ability of an economy to meet its goals within a constrained capital production system.

By moving away from a single numeraire, the above modifications to the ECCO model have increased its robustness to a number of situations, particularly those involving technological change. This has been accomplished without compromising the underlying ideas of Natural Capital Accounting.

In addition to laying the foundations for the case studies in Chapter 5, this modification also serves to illustrate the advantages of understanding the role of numeraire in a model as a means of selecting certain aspects of the system for study. The shift in emphasis from 'metabolic' or 'biophysical' measure of the production and accumulation process to a service-based treatment of demand for HMC is quite subtle, and, while the separation could be achieved without referring to the ideas presented in Part 1, the ideas have served as useful tools in distinguishing between the range of possible solutions and achieving a clear and comprehensive outcome.

4.3 Resource Scarcity, Human Capital, Technological Change & Endogenous Growth

The ECCO modelling approach falls within a loosely-defined group of economic models developing from the work of Jay Forrester's work (Forrester, 1968) and the Club of Rome's 'Limits to Growth' study (Meadows et al., 1971). These models have emphasised the importance of essential, finite, depleteable resources in constraining the range of options available to an economy, a stance that found favour in the early 1970's following the OPEC oil-price hikes.

These 'resource-constrained' models have been criticised on a number of fronts (McCutcheon, 1979). At the same time, other explanations for economic growth have been advanced, centring on the development of human resources or human capital (e.g. the Mankiw, Romer and Weil (MRW) extension to Solow, and the Uzawa-Lucas model of education), and the effect of technological change as a driver of growth (see Barro & Sala-i-Martin, 1992 for an overview of growth theories).

A number of attempts at modelling these issues have been made in recent years; in general, the models presented are more concerned with expressing types of relationships in abstract economies than representing specific situations. The emphasis is on showing whether single or multiple equilibria exist (e.g. Greiner & Semmler, 1996; Greiner, 1996; LadrondeGuivera et al. 1997), whether cyclical behaviour can occur (e.g. Jones & Newman, 1996; Greiner, 1996) and the existence of 'takeover' dynamics within the skill-differentiated labour market (e.g. Betts, 1994; Jovanovic & Nyarko, 1996). Having said this, some authors do attempt to calibrate their models against actual situations (e.g. King & Robson, 1993; Tzanidakis & Kirizidis, 1996).

The technological argument has been advanced with considerable optimism in recent years (e.g. Ausabel, 1996) arguing that human ingenuity can find a solution to practically any problem, in a way that a system dynamics model cannot predict. Some fuel has been given to this argument by the newer generation of complex systems models, which are able to replicate some sorts of innovative behaviour, although complex systems models have also been advanced by the 'resource constraints' side of the debate.

The argument as a whole seems to be in danger of polarising., as though growth were *either* generated by technological innovation or limited by resource scarcity. Some attempts have been made to consider both sides within a single formal structure (e.g. Meadows et al., 1991), or to incorporate elements of one side into the other (e.g. Ryan, 1996) but much of the literature is written in a dismissive style, and fails to address relevant issues such as the limits to rates of technological innovation. This viewpoint is expressed well by Jesse Ausabel in the preface to a 1996 special edition of the American Association for Advancement of Science's journal 'Daedalus' (despite the fact that very cautionary assessments of technological diffusion rates (Marchetti, 1996; Grubler, 1996) are presented in the same journal).

> *"it is well to remember that the ideas of the Club of Rome, an institute virtually ignored today, enjoyed a very considerable reputation just a few short decades ago...there seemed to be compelling reasons for exploring all such propositions [as John Stuart Mill's 'no growth society'], seeing them as something other than the fanciful inventions of a group of utopians." (p VI)*
>
> *"the liberator of our title is human culture. It's most powerful tools are science and technology. These increasingly decouple our goods and services from demands on planetary resources." (p.1)*

The ECCO model, with its emphasis on energy resources as drivers of economic growth, is formulated in resource constraint terms. However, recent developments in the methodology, particularly the identification of the 'delinking' problem (see above), have made it robust enough to be useful as a demonstration of how the various factors that shape an economic system - including resource scarcity and technology - interact. Noorman (1996) describes a 'flywheel effect' in his ECCO model of the Netherlands, and Slesser et al. (1997) identifies an 'intersectoral rebound effect' in a model of the UK, developing from the interaction of technological and behavioural effects. Both mechanisms are very similar, and offer a formal analysis of the interconnections between the starting points of the two sides of the debate. This theory will be presented briefly here, and its importance in connection with the 'service-correction' of the model numeraire discussed. The issue will then be returned to at the end of Chapter 5.

4.3.1 Rebound Effects & Energy Efficiency

4.3.1.1 Introduction

Contemporary industrialised economies have accumulated an unprecedented amount of physical structure, of an unprecedented degree of complexity. Societies are increasingly dependent upon the physical structures that they have created, both to serve perceived needs, and to maintain and service itself. As the physical human-made capital stocks accumulate, an increasing proportion of the goods and services that they provide goes to meeting the needs of the production system itself, rather than for direct consumption by a putative end-user. This point can be illustrated by resource-specific input-output methods, which show that the indirect overheads on resources such as energy (Peet, 1993; Wilting, 1996) and materials (Schutz, 1996) exceed direct use several-fold.

It is therefore perhaps too simplistic to characterise an economy as something that generates services for its human inhabitants. Given the complex interdependencies of the physical structures, much of the effort expended in maintaining and repairing the physical base of the economy is directed not towards the end-user, but simply towards the internal functions of the system itself (including the functions of structural repair).

The physical activity of the economy has its negative consequences, of course. Physical transformations require inputs from the biosphere, and the process of extracting these inputs itself creates environmental disturbances. Additionally, the biosphere serves as a sink for the waste products that these processes generate. With the growing awareness of the environmental impacts of our activities, there have been repeated suggestions that the path to a viable future lies in a de-linking of the physical impact of service provision and the volume of service provided. Some proposed solutions are primarily technical (e.g. Lovins, 1977), others focus on restructuring of activity (e.g. Daly, 1976; Ayres, 1994), and some combine elements of both (e.g. Carnoules Declaration, 1996; von Weizsacher et al., 1997).

Because of the complex interdependencies between activities, a direct reduction of the use of inputs by other activities may have unpredictable effects. Certainly, the direct demand for an input as a whole will be reduced, and a reduction in the associated environmental pressures will follow. 'Knock-on' effects will also occur; as the production rate of that input decreases, the requirement of other inputs by that process will decrease, with similar secondary and tertiary effects propagating through the economy. However, the reduction in demand for intermediate inputs will also result in a reduction in the maintenance requirements of that process's capital stock, freeing up physical investment potential for other activities. Where the economic system is constrained by the burden of maintaining its complex physical structures (and it is my contention here that most industrial economies are), then reduced use of resources or intermediate goods may lead to an increased ability to grow. With growth comes an increase in overall physical impact of the system, and so a part of the desired effects on resource use are negated. The magnitude of this negation, or 'rebound effect', will depend upon the extent to which provision of fixed capital to the resource supply burdens the economy.

4.3.1.2 ECCO Simulation Studies

This principle can be illustrated by the ECCO model in which accumulation of fixed capital stocks are directly tracked as a physical process. Using a simulation model of the UK (Crane, 1996), a number of 'efficiency drive' policies can be simulated. In order to correctly represent these situations, the potential for decoupling between embodied energy and service-corrected measure of output must be explicit; in a model running purely on actual embodied energy numeraire, a reduction in energy use would be measured as a decline in output, leading to a reduced growth rate. The model used in these examples has a full implementation of the method described in this chapter, over and above the simpler and less comprehensive mechanism found in the model described in Slesser et. al, 1994.

The physical structure of the UK economy is dominated by three broad sectors; domestic (i.e. housing), services and industry (all manufacturing and construction activities). Over 90% of the current fixed capital stock is dedicated to these sectors, and the pattern is unlikely to change under 'business-as-usual' conditions in the next few years. The 'other' category includes energy and resource supply, electricity generation and agricultural activities.

In the four simulation runs presented here, the activities of the industrial sector have been focussed upon. Industry requires a wide range of inputs, including energy, electricity, raw materials such as water, minerals, timber and petrochemicals. In addition, we treat a number of support activities as inputs; although services to industry, transport use by industry, etc. are not actually consumed in a manufacturing process, their contribution is vital to the delivering of manufactured products to the points of end-use. Four 'efficiency drive' scenarios are instigated in the model, as follows:

1. From 1996 onwards, an additional 10% of the baseline investment in industrial HMC is diverted to investment in energy efficiency measures in industrial processes. The characterisation of the relationship between investment and energy savings is based on the aggregate results of a detailed study by the TNO (Melman et al., 1990), with the assumption that the broad pattern (although not necessarily the details) of returns on investment is similar for UK and Netherlands industry.
2. From 2000 to 2010, the efficiency of use of non-energy raw materials (water, petrochemicals, mineral ores and coke) increases by a factor of 2. Due to lack of detailed data, no capital cost is associated with this increase.
3. Energy and materials scenarios (i.e. [1] and [2]) are effected simultaneously.
4. From 2000 to 2010, industry becomes more 'efficient' in its use of services by a factor of 2 (i.e. a two-fold reduction in the average service requirements per unit industrial output). This is assumed to come about by organisational changes in industry and, again, owing to lack of data, no capital cost to industry is assumed. For simplicity, no structural changes in the services sector itself are assumed.

These scenarios may be considered as somewhat unrealistic. They are not intended as detailed representations of what might happen (and certainly do not suggest how such technical change might be achieved). Rather, they are illustrative 'broad brush' approaches intended to allow an investigation of the generic mechanisms at work.

Figure 4.11 illustrates the effects of each of these policies on the thermal energy demand for the primary energy demand for the economy as a whole. In the model reference run, industry, services and domestic thermal energy consumption accounts for roughly 40% of the total primary energy demand. (Other major end-users are transport and electricity generation, and the energy supply and refining sector as a whole, which autoconsumes roughly 8% of the primary energy carriers that it processes.)

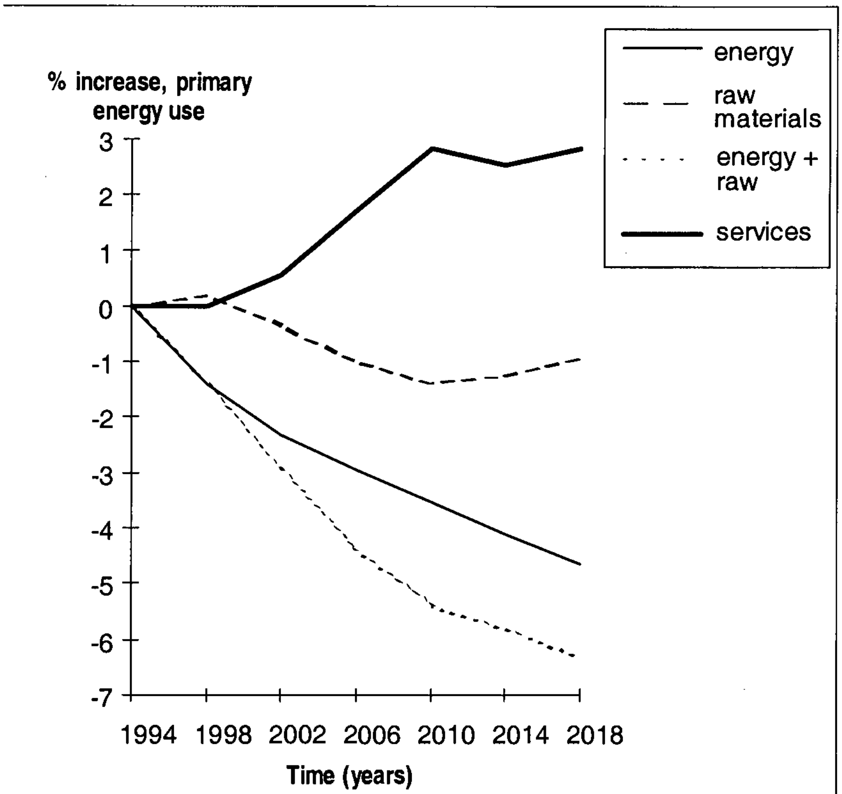


Figure 4.11 The effect on primary energy use of increased efficiency in energy, material and services use. Only the latter results in an actual increase in overall energy consumption. 'Rebound effects' for energy and materials are smaller because the provision of energy and minerals occupies only a small fraction of the UK capital stock.

The changes in thermal energy demand are shown as percentage decreases. Notably, only the scenarios involving a direct energy conservation policy generate significant savings; the materials only policy is broadly neutral. The most striking profile, though, is for the services efficiency policy, in which a net increase in energy use by all sectors is observed. This is in keeping with the assertion that the economic system's growth is constrained by the need to maintain its fixed capital structures. As the provision of services is by far the most capital-intensive activity out of those examined here, the potential for increased growth when service requirements decrease is large.

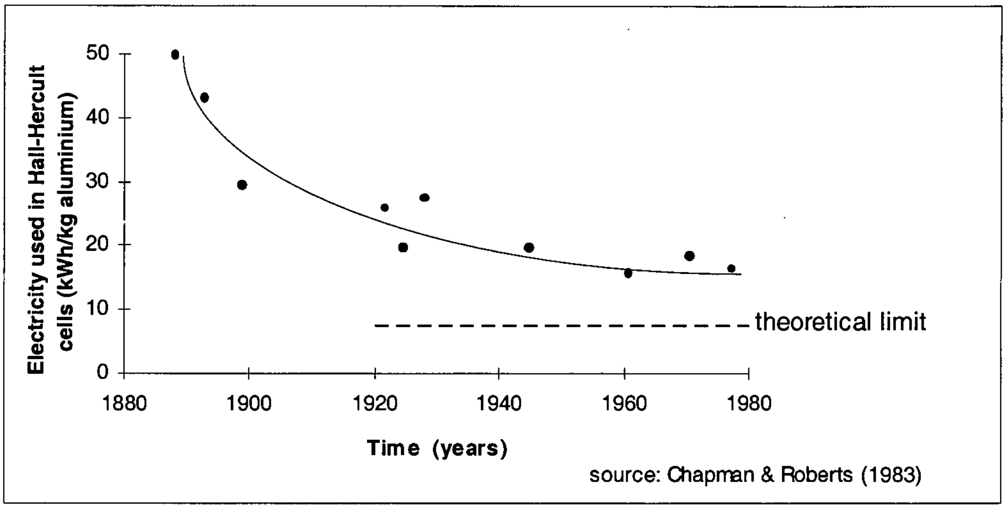
4.3.1.3 Rebound Effects: A comparison with the literature

The behaviour that has been illustrated above is similar in many ways to the 'rebound effect' proposed by a number of authors in the energy economics literature (Brookes, 1990; Greene, 1992; Grubb, 1990; Jones, 1993; Keepin & Kats, 1988; Khazzoum, 1980; 1989; Musters, 1994). Most of the work done so far in this area relates to energy efficiency of specific goods or services, such as household heating or private transport. The argument is that, as a good or service becomes less energy intensive, its price will decrease, and therefore a greater demand for it will be generated. For example, energy efficient cars will lead to greater transport use, partly cancelling the reductions in fuel use and emissions that proponents of the 'green technology' might hope for. Khazzoum (1980) points to the heart of this issue when he states that such technologies require an understanding of the feedbacks between the engineering and behavioural sectors in order to grasp their potential effects.

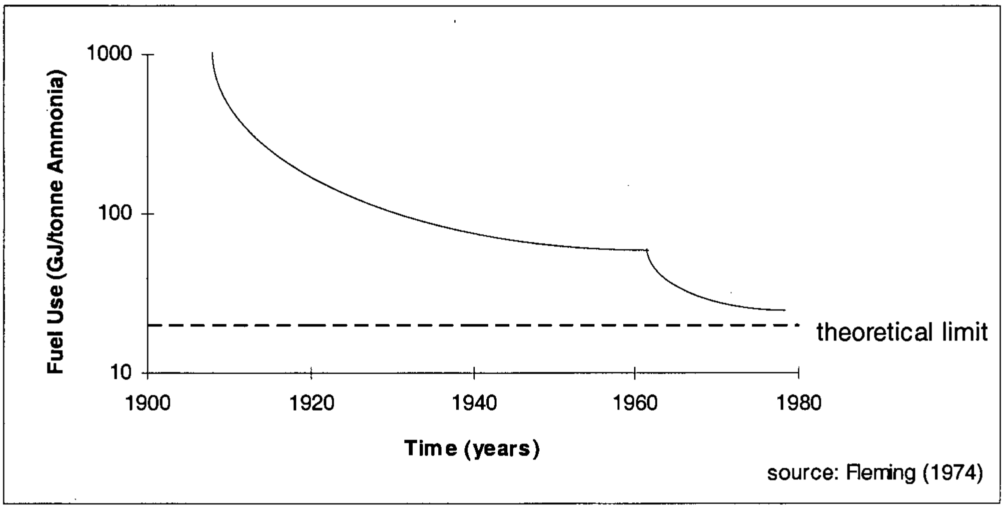
It is worth noting at this point that the 'rebound' mechanism that is proposed here is distinct from that postulated elsewhere, although the overall effect is similar. Khazzoum's explanation for the loss of expected efficiency rests on the reallocation of spending power by the individual with regard to a single commodity (e.g. transport, domestic electricity), while our description is essentially macroeconomic and cross-sectoral.

The mechanism proposed here is not completely new. Hannon (1974) identified a similar problem with energy conservation policies. Although Hannon's explanation was based on the behaviour of the individual consumer, he did recognise the role of choice; savings made regarding one product might be re-spent elsewhere. The difference in resource intensity between the available products will determine the net change in resource use. This cross-product (or, at the macroeconomic level, cross-sectoral) effect was not developed by subsequent authors.

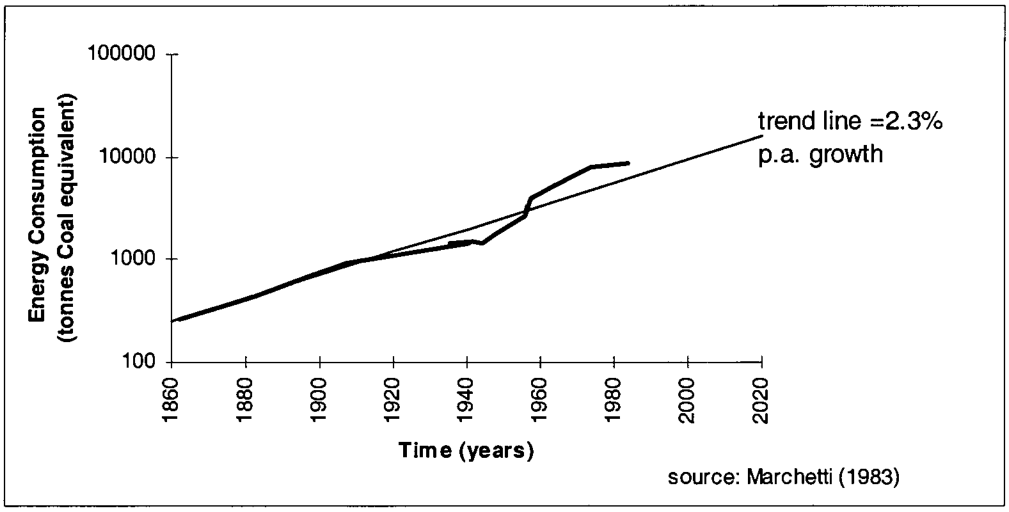
Hannon's article is interesting in another respect; by emphasising choice, he points to an alternative outcome from that given by the simulation studies above. The intersectoral rebound effect will only occur if the economy as a whole continues to grow as fast as possible under the constraint of fixed capital maintenance (and other policy-related constraints represented in the model). Technical fixes on resource pressures may be more effective when coupled with a social change away from a growth-oriented economy (or, in the short-term, by undergoing an economic recessions).


50
40
30
20
10
0
Electricity used in Hall-Hercult cells (kWh/kg aluminium)
1880
1900
1920
1940
1960
1980
Time (years)
theoretical limit
source: Chapman & Roberts (1983)

(a)


1000
100
10
Fuel Use (GJ/tonne Ammonia)
1900
1920
1940
1960
1980
Time (years)
theoretical limit
source: Fleming (1974)

(b)


100000
10000
1000
100
Energy Consumption (tonnes Coal equivalent)
1860
1880
1900
1920
1940
1960
1980
2000
2020
Time (years)
trend line =2.3% p.a. growth
source: Marchetti (1983)

(c)

Figure 4.12 (previous page): Historical long-term trends in energy efficiency and energy demand. Over the course of the century, many industrial processes of key economic importance e.g. (a) ammonia manufacture and (b) aluminium manufacture have increased in energy efficiency significantly. (c) At the same time, world energy consumption has risen considerably. Clearly, energy savings from efficiency have been more than compensated for by rapid economic growth. Was this growth in part fostered by the changes in technology?

The ECCO model used to generate the simulation results presented here has been programmed to grow as fast as possible, in the belief that that is what industrial economies are doing at present. Certainly, examining the history of resource use this century, such assertions are not contradicted. Figure 4.12a & b shows the development of energy efficiency of two key industrial processes of economic significance during this century.

Figure 4.12c shows the pattern of world energy use over the same period of time. Clearly, increased energy efficiency did not lead to a reduction in the demand for energy resources, and the intersectoral rebound effect appears to have exceeded 100% for much of the time.

There is anecdotal evidence for a similar decision when faced with such a trade-off at a smaller scale, too. Gamerman (1996) reports in the 'Baltimore Sun' newspaper on the establishment of a 'walk-in back rub' massage centre in Washington DC, in which clients are offered a no-appointments massage service in view of passers-by. A businesswoman who had skipped lunch to get a massage reported, tellingly: "I feel great. I can work longer hours in front of the computer now."

It is hard to find any counter-examples in which the choice not to grow was made. The only case that suggests an alternative is Clive Ponting's (1992) account of the encounter between the Portuguese conquistadors and native Brazilians. When the Portuguese introduced metal axes, the natives continued to fell the same number of trees as they had done previously, in only a few hours a day. The newly acquired leisure time was spent in relaxation.

4.3.1.4 The Red Queen Effect

The issue of resource efficiency is, then, far more than technical. Technical fixes may have a valid role to play in resource use policy, but they must be coupled with an understanding of our behavioural responses to technical change if they are to be effective. A real insight into the motivation in always seeking greater physical growth probably lies deep in the values of the Western industrialised mind-set, and the habit of seeking to satisfy non-material needs materially. However, one analogy to a recent development in systems ecology may provide a partial insight that is relatively accessible to structured analysis.

The so-called 'red queen effect', first described by van Valen (1972), refers to situations in which the 'strategic benefits' conferred by evolutionary change upon a species are negated by the coevolution of other species with which it interacts. For example, a prey species may develop the ability to run faster, but, as this development spreads through the prey population, faster predators will be selected for, and so the prey must continue to run at full speed in order to escape encounters. The absolute speed of the creature is irrelevant; what matters is whether it is faster or slower than it's neighbours. Under red queen dynamics, coevolution of this type may escalate without reaching an evolutionary stable-state. Like the Red Queen in Lewis Carroll's 'Alice' books, the faster one runs, the faster the ground is pulled away.

To draw in the resource use efficiency discussion, the faster prey species could be said to be facing two options: it may expend less effort in order to run as fast as it used to, or it may expend equivalent effort in order to run faster. The presence of the predator (or other interacting species) sets a lower limit to the extent to which reduced effort can be preferred over speed.

It is tempting to apply this analogy to the economic case in greater depth. The presence of competing or coevolving economic strategies may select for those that choose faster growth over lesser resource use, as Ponting's story and the subsequent development of relations between the Portuguese and native Brazilians suggests.

It is worth noting, though, that biological analogies, and evolutionary ones in particular, are prone to over-interpretation. The comparison certainly does not suggest any 'natural' justification for the choice towards growth. The economic 'selection process', after all, is not blind; it is a cultural process. Further, as Rosenberg (1994) has argued, it is not strictly Darwinian. The red queen is of interest therefore as a new way of thinking about the problem of resource use; while a detailed point by point comparison strains the analogy to breaking point, the general principles of the red queen dynamics are capable of application to non-Darwinian evolutionary systems.

4.3.1.5 Conclusions

The rebound mechanism discussed here is dependent upon the growth algorithm implemented in the ECCO model. From an economic point of view, the human-made capital allocation mechanism whereby the full residual is reinvested in industry is simplistic, in that it cannot account for situations where *demand* for industrial products becomes the limiting factor i.e. economic recessions. However, the reinvestment terms generated by the model results presented here are not excessive nor unrealistic, and are in fact very closely in line with historical data, suggesting that the residual-based approach is valid at least in this case. Comparisons with global long-term data (figure 4.9 and attendant discussion) and the 'red queen' motivation-based discussion also support the validity that, if the limits imposed by capital are not universal, they are certainly the norm for industrialised, westernised countries.

Regarding energy efficiency, it seems that the actual rebound effects are small, at least in the case of mature economies. The historical trends earlier this century suggest much higher rebound effects. The discrepancy will be noted here, and returned to in Chapter 5 after considering the case of water resources.

In conclusion, then, resource efficiency measures must be understood within the broader social context if they are to be effective. A simple technical fix mentality will make little headway in identifying genuinely sustainable options for the future. The red queen dynamics can provide one way of gaining some insight into the motivating factors that lead to intersectoral rebound effects observed in modern industrial economies, although a fuller understanding will probably require a more complex psychological and cultural interpretation of our dependence on material growth.

The next chapter presents a case study of an operational ECCO model of Australia being applied to water resource policy, in order to demonstrate the interactions between the two seemingly conflicting worldviews of the ecological pessimist and technological optimist. The issue of rebound effects are taken up again there, and the analysis presented here expanded upon.

Chapter 5 Resource-based Limitations on Economic Growth

This chapter describes the structure of a large ECCO model of the Australian economy, and gives an overview of the model's construction and validation. A case study using the model to examine Australia's water resource policies is then given, and used to develop the discussion of the inter-relationships between resource scarcity and technology in determining economic growth.

The results presented here demonstrate that the interactions between technological progress and resource scarcity, when considered as a whole rather than as two opposing arguments, are significant and complex. Few of the insights obtained here could have been understood without the aid of this or a similar model, highlighting the positive potential for simulation studies in the broader economic debate.

5.1 OzEcco: A simulation model of the Australian economy

The model is hierarchically divided into a number of sectors, as outlined in Table 5.1 below. Each sector is discussed in some detail, and the full 'Professional Dynamo' equations for the model can be found in Appendix 2.

The model has six main compartments, each of which is composed of a number of components. Compartment one describes the energy metabolism of Australia's economy at an aggregated level. Key transformations are made here to relate the energy used in the economy (in physical units Joules) with the outputs of the economy in financial terms (constant 1989/90 dollars). The coefficient "energy intensity of industry or EII" allows capital stocks in the sectors to be expressed in embodied energy terms (physical measure of constant petajoules). Various energy efficiency coefficients quantify the amount of energy dissipated to deliver one unit of fuel to the market place (Slesser, 1992). This reflects a country's energy structure e.g. in Australia nearly 30% of Australia's total primary energy use is coal converted to electricity.

The second compartment deals with natural and human resources. A simple population model describes the stocks and growth of the human population. The energy stocks, oil, gas and coal are described as the key resources which, when transformed, allow the economy to function.

The third compartment deals with the transformation of energy and materials into human made capital. This deals with highly aggregated sectors of industry, agriculture, mining, utilities, domestic housing and services. Because much of Australia's raw material are exported and consumer goods are imported there is a simple balance of payments module which keeps track of the inflows and outflows. The complexities of international markets, national debt and balance of payments are much simplified. International borrowings are simplified as embodied energy imports. They allow a greater range of sectoral activity than might be expected on the basis of domestic resources.

The fourth compartment deals with a range of consumption activities, particularly in the areas of transport and the consumption of consumer goods.

The fifth compartment reports on the amount of greenhouse gas emissions that are linked to the system wide energy usage, and contains additional sectors representing pollution abatement technologies and options.

Compartment six describes a number of system-wide indicators of sustainability, presented for reporting purposes only.

1. System Energy Transformation Coefficients					
Natural and Human Resources	2. Human Population				
	3. Resource Bases	Fossil Fuels	Oil		
			Gas		
			Coal		
		Water	Surface		
			Ground		
Human-Made Capital Accumulation	Human Made Capital Creation	4. Industrial Output			
		5. Balance of Payments	Visibles	Fuels	
				Minerals	
				Agricultural	
				Other	
			Invisibles		
			International Debt		
	HMC Consumption	6.Agriculture & Forestry	Vegetable Crops		
			Animal Husbandry	Protein Production	
				Wool Production	
			Forestry	Plantations	Eucalypts
					Coniferous
				Native Forests	
		7. Mining	Energy Resources	Oil	
				Gas	
				Coal	
			Non-Energy Resources		
		8. Industry			
		Utilities	9. Electricity	Fossil-fuelled	
				Hydro-electric	
				Bio-fuelled Electricity	
				Other renewables	
			10. Gas Distribution		
			11. Water	Agricultural Demand	
				Urban Demand	
				Water Supply	
		12. Dwellings			
		13. Services (to Industry, People, Services & Exports)			
Consumption Activities	14. Consumption of Goods				
	15. Material Affluence				
	16. Transport	Road			
		Rail			
		Water			
		Air			
17. Pollution Emission	Carbon Dioxide	Gross & Net Emissions			
		Technological Removal Options			
		Forestry Carbon Cycle			
	Sulphur Dioxide	Emissions			
18. Whole System Indicators					

5.1.1 Notes on Specific Model Components

5.1.1.1 System Energy Transformation Coefficients

The core energy transformation coefficients are set in this component via the Energy Intensity of Industry (EII), the System Wide Efficiency of Energy Delivery (SYSGER), the Fuel Energy Requirement for Electricity (FEREL). These coefficients are important for two purposes. The EII allows the transformation of stocks and flows of money contained in the National Accounts (ABS, 1995,1996) into stocks of embodied energy and flows of energy into sectors. Both SYSGER and FEREL deal with the system boundary demarcation between primary and secondary resources, and allow for translation between the two. Because OzEcco attempts an holistic analysis of Australia's energy metabolism the energy used is traced back to its origin whether it is sourced within Australia or imported. In this way the true "energy embodied in energy and materials" is accounted for .

A number of system boundaries for the energy accounting framework are shown in Fig. 5.1. The primary energy basis pulls the system boundary back to the point where the energy resource is extracted from the ground. From this boundary inwards the energy product has progressively more energy embodied within it. Oil needs fuel to pump it from the ground and transport it towards the refinery, and there is a massive infrastructure in exploration, transport, machinery and services to get it there, especially if it is imported. Once at the refinery another set of infrastructure and services is needed until finally petrol is delivered to a vehicle at the service station. The relative difficulty in extracting oil (or gas or coal) is defined by an energy requirement for energy or ERE (see figure 5.1 as auto-consumption at indigenous or foreign extraction site) and is thus factored into the embodied energy delivered in fuel at the point of final demand. Thus the coefficients EII, FEREL and SYSGER all quantify different parts of the energy extraction and usage system (Crane and Slesser, 1995).

5.1.1.2 EII

The Energy Intensity of Industry is used to convert capital stocks and flows from National Accounts data into embodied energy terms (Petajoules). The current estimated value for 1981-2 is 7.4 x 10^{-9} Petajoules/A$_{89-90}$. This figure is obtained through an iterative matching process between successive model estimates and historical gross output data taken from National Input-Output tables.

5.1.1.3 SYSGER

SYSGER is the system-wide gross energy requirement per unit of fuel delivered at final demand. The primary energy basis draws the system boundary back to the point at which the energy resource is extracted from the ground, i.e. before any of the energy content of the resource has become embodied. Rates of extraction of fossil fuel resources, expressed in primary energy terms, refer to the amount entering the extraction system.

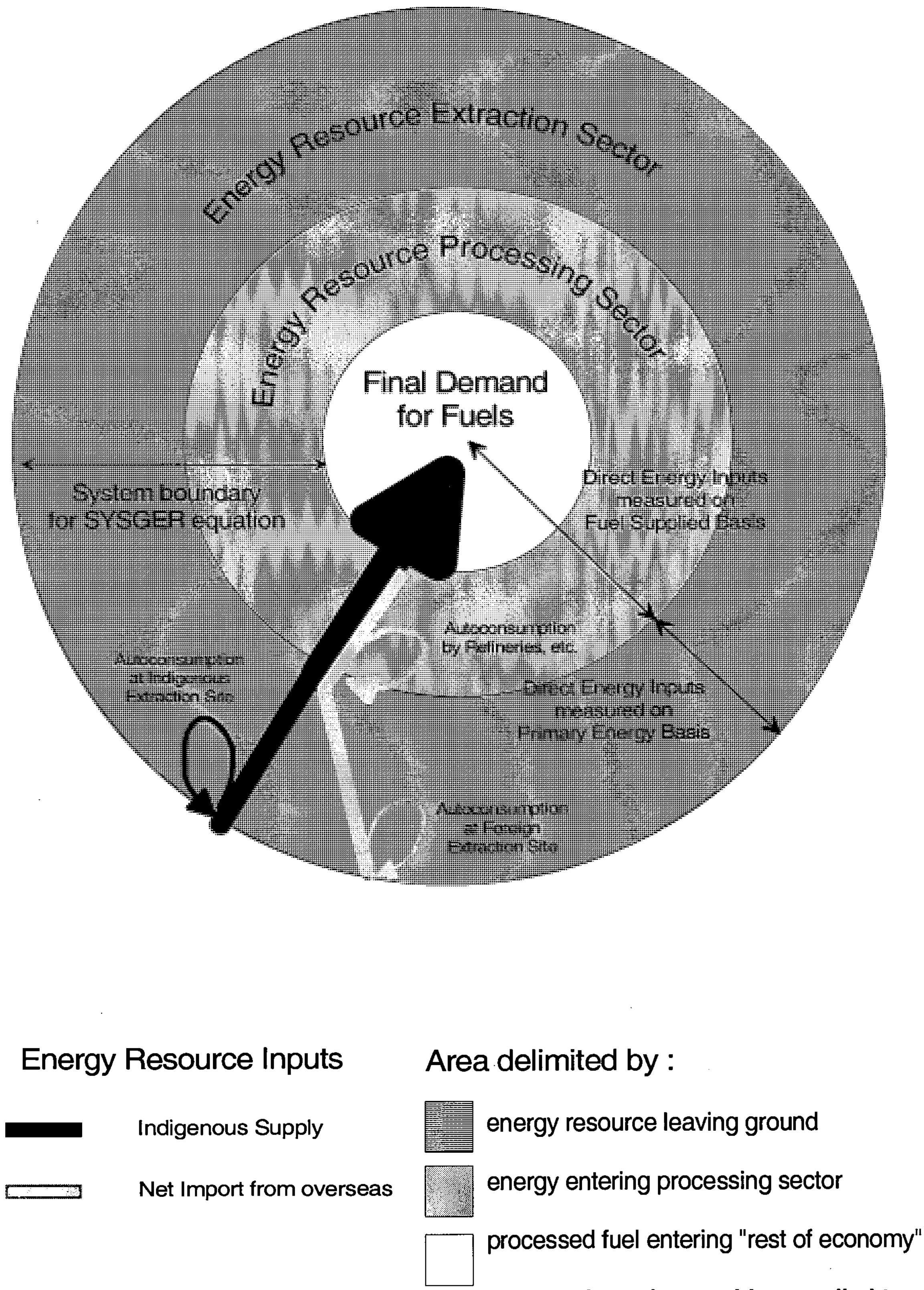


Figure 5.2 A schematic representation of the system boundary problem applied to the energy supply of a national economy

Being a system-wide average, SYSGER can be used to convert any fuel supplied basis value into a primary energy basis, without knowing the exact sources of the fuel being used. There are (at least) two conventions for defining primary energy. The IFIAS convention (1974) counts only non-renewable energy sources as primary, and assigns zero primary energy content to flux-derived sources. This distinction is useful for gaining a measure of an economy's dependence on non-renewable (and hence non-sustainable) energy sources, but, when attempting to characterise the energy use by an economy as here, can result in problems, as outlined in Section 4.2. The version of the OzEcco model described in this thesis implements a double-accounting solution based on the 'solution 2' described in Section 4.2.3.

5.1.1.4 FEREL

FEREL is the thermal fuel requirement per unit of electricity to final demand. It is used to convert electrical energy into fuel supplied terms, i.e. bringing the energy back to the outer edge of the final demand economy (the inner circle in Figure 4.). Hence, FEREL is defined as the ratio between all (fuel supplied) energy inputs into the electricity generating sector and the electricity produced by that sector consumed at final demand. The primary energy content of electricity is calculated by combining FEREL and SYSGER.

5.1.1.5 Human Population

A simple population model is included which keeps track of the population each year. For each year the population at the end of the previous year is increased by the net birth rate (the difference between births and deaths for the whole population over the calibration period) and the net immigration rate. The net birth rate over the calibration was 8.13 per 1000 population. The net immigration rate over the calibration period was 108,000 (using data from Shu & Khoo, 1992).

The main policy lever used in the population model is net immigration rate. In addition to the average rate (108,000/year) over the calibration period, a higher and lower scenario are included, giving a range from 20 to 50 million by the year 2050. A mix of both birth rates and immigration rates could be used to achieve the same end, but Australia's population growth is currently mostly through immigration.

The population sector of the pilot model is extremely simple and disaggregates neither sex nor age. This will miss several important nuances over the longer term such as the ageing of the population, but serves adequately for current purposes.

5.1.1.6 Natural Resource Bases

This section describes indigenous stocks of oil, natural gas and coal, and reserves of water. Fossil fuel resource bases are described in terms of the relationship between cumulative extraction and inaccessibility, the latter measured by the energy requirement for energy, or ERE. The ERE profile of a resource base is a stylised representation of the changes in extraction costs as the resource is depleted, where costs are expressed in terms of process energy input (direct and indirect) required to bring the resource to the surface. ERE is a function of both geology and technology; where depletion of a resource base will tend to push ERE up, changes in technology of extraction may tend to pull it down over time. Reserves and extraction rate are determined in energy units (petajoules), here referring to calorific rather than embodied energy content.

Water resources are characterised as ground- and surface water, and by grade as fresh, marginal and saline. The model characterisation follows from a state-by-state linear analysis of demand of current resource bases and linear extrapolation of demand. This is discussed in greater detail under water supply, section 5.1.1.11.

Australia has ample stocks of energy at present with up to 11 years of oil stocks, perhaps 44 years of natural gas and 245 years of coal at current rates of production (consumption plus exports), assuming no changes in technology or extension of reserves (ABS 1996b). The most recent data for stocks and their development over the calibration period, are included here together with policy levers for new stock discoveries. It is possible to set as policy the rate of discovery of new oil, gas and coal reserves.

The energy requirement for energy progressively increases as stocks run down, and transfers oil demand to Middle East oil when an ERE of 1.1 is reached i.e. indigenous oil reserves become economically uncompetitive). The ERE for all energy stocks in Australia is around 1.03 in 1995 at the start of most simulation periods, with domestic production declining post-2010.

As a whole, Australia's potential surface water supply is roughly five times that of the current demand (AWRC 1987), suggesting that there is relatively little problem with water. Many densely-populated areas already utilise over 90% of available water, and much of the spare capacity is located in areas of low population density (Heathcote & Mabbutt, 1987).

Only energy & water resources are directly accounted for in the pilot model, although a formulation similar to energy could be applied to other non-renewable resources. Three energy resources are identified: oil, coal and gas. Uranium is treated as a non-energy resource in the Australian model, as it is not used as an energy supply within the country. The characterisation of the water resources, while avoiding the pitfalls of a purely aspatial analyses, is still relatively simple. Demand for water is assumed to grow proportionally in all areas, and there are no feedbacks between water scarcity and regional growth dynamics. Further, a number of important hydrological processes are not explicitly modelled. Australia's groundwater supplies, for example, have been prone to salination through rising water tables, following the replacement of native tree species with 'European-style' crops and pastures, with must shallower root systems. (Water at the top of the landscape is not transpired away, and hence the water table downslope is raised.) Rising water tables contact salt lodes, which then enter the water table. Ideally, dynamics such as these should be incorporated into forestry policies (see section 5.1.1.6), but doing this would probably require a more detailed spatial representation of events.

5.1.1.7 Industrial Output

This section of the OzEcco model deals with industrial output in a very aggregated sense, following the conventions of the ECCO model (see previous chapter). The flow of goods (represented as embodied energy) terms from this section flows into most of the other sectors as fixed capital investment. While industry is central to growth from this perspective, it is not the only source of wealth creation in the broader sense. Industry itself requires a range of inputs in order to function; energy, electricity, transport, services, etc. With a systems viewpoint, stimulus for any sector can come from many parts of the model (or the economy) and the linkages in a systems dynamic framework allow this to occur.

Industrial sector output is calculated in embodied energy terms by summing the direct and indirect inputs to the manufacturing process. Only those contributions deemed significantly large were introduced into the INDOUT equation, for simplicity. The sectors identified (from Input-Output analysis) as making a large secondary contribution were agriculture, services and transport.

The service-corrected numeraire solution discussed in Chapter 4 has been fully implemented in the OzEcco model, and industrial output is represented as both actual embodied energy and a service-corrected value.

Intermediate goods requirement (i.e. internal cycling of goods within the industrial sector) is calculated on the basis of Input-Output studies for 1981-2 and 1992-93. It is assumed that intermediate goods re-enter the manufacturing process within one year, and so do not contribute towards the pool of human made capital available to end-use sectors.

The availability of human made capital for reinvestment in indigenous infrastructure is calculated using the residual theory described in Chapter 4 with additional accounting for international trade. Trade in goods obviously increases or decreases the pool of available human made capital Trade in "invisibles" is assumed to have a similar effect, through increasing or decreasing the capacity to buy in additional human made capital from outside. Following this assumption, a simple balance of payments sector can be drawn up. In the current model, the 'NETXPGD' term is calculated as the shortfall in all other balance of payment terms, assuming that the economy balances the books by exporting or importing additional human made capital. More sophisticated model structures can allow alternatives to this structure, for example by channelling shortfalls into a national debt (i.e. public sector borrowing c.f. the international debt sector in the current balance of payments module), whose interest repayments affect future balance of payments calculations.

5.1.1.8 Balance of Payments

The balance of payments section adjusts for outflows and inflows of (physical) wealth creation capacity due to trade. These may be met directly (i.e. trade in human-made capital itself) or indirectly (trade in services and other 'invisibles' allows the purchase of human-made capital).

In a closed economy experiencing no trade, the ability to meet demands for human-made capital would be determined solely by the domestic industrial capacity. The balance of payments summarises international trading activities that affect Australia's ability to meet this demand, and hence the potential of system to grow. It brings in those factors not directly attributable to physical processes within the country.

This section mimics the flows of goods and services into and out of Australia's national economy by using the trade flows data for the calibration period in dollar terms and representing this into flows of embodied energy. The default conversion factor is the Energy intensity of Industry (EII), but, where other data is available (e.g. for the embodied energy associated with certain visibles exports), that is used instead.

Following the Australian National Accounts conventions, the balance of payments is divided into visibles (trade in merchandise) and invisibles (trade in services plus financial flows). The current model implements the visibles flow in greater detail, reflecting the emphasis on physical processes elsewhere in the model. Trade in fuels, agricultural produce (foodstuffs and wool) and minerals are explicitly accounted for, and a 'other' category summarises other categories of merchandise not represented in detail elsewhere.

The invisibles balance is modelled largely as an exogenous phenomenon; the ECCO methodology offers little insight into the dynamics of international finance, because of its emphasis on both physical phenomena and mid- to long-range dynamics. The exogenous data is broken down into receipts, payments and flows of direct investment following National Accounts conventions, with selected items removed for more detailed modelling, specifically international debt, which influences the invisibles balance through the rate of borrowing (increasing immediate capital availability) and rates of repayment and debt interest payments (decreasing immediate capital availability). The borrowing rate can be determined by the model user, as can the rate of repayment and the debt interest rate, allowing for an exploration of the impact of debt on the system. Under default conditions (no repayments; 6% interest rates), increasing borrowing will result in a short-term increase in growth (as the borrowing allows for more HMC investment) followed by a long-term decrease, as interest repayments accumulate. Typically, the shift from net positive to net negative effects will take an order of one or two decades to manifest.

In addition, the invisibles balance contains a mechanism representing inflows of wealth associated with in-migration. The user may select the average incoming wealth taken into the national economy by an in-migrant, hence allowing the effects of migration of different types to be modelled.

The balance of payments sector will reflect changes in policies implemented in the dynamically linked sectors such as mining and agriculture. In addition, different international trading scenarios may be generated by altering data tables for international debt and invisibles balance terms.

This simple balance of payments sector serves to account for embodied energy imported and exported. Many parts are driven exogenously, and new data input from1995 onwards must be derived from a logical and consistent sets of scenarios. Dynamic interactions occur only in connection with some visibles exports, debt interest and the effect of immigration.

5.1.1.9 Agriculture & Forestry

The agriculture sector has been simplified to incorporate all agricultural and fishing activities, and is re-sectorised in terms of animal and vegetable protein acquisition. The driver for the development of both animal and vegetable sectors is the desired nutritional level and mix for the indigenous population, and the desired self-sufficiency in foodstuffs. In the case of animal protein, this latter factor has risen considerably over the validation period, and exceeds unity (i.e. Australia is a net exporter of animal protein). Output of vegetable protein is also driven by the need to supply feeds for the animal sector. Output and demand is measured primarily in tonnes of protein. The rationale for this is that protein is the limiting (bulk) factor in a diet; it is very hard to meet protein requirements without also consuming sufficient carbohydrates.

Wool production is computed in a highly empirical fashion, from the fraction of meat production as sheep, and average wool yield data derived from validation period statistics. This is done primarily to serve the balance of payments sector.

The forestry sector focuses mainly on plantation forestry, divided into eucalypts and pine. Plantations are represented by land areas, from which timber yields are calculated on the basis of an average marginal stem volume increment for a regular rotation management scheme assumed to maximise steady-state yields of timber over the long term. Native forests are also represented, with land-use changes being treated as exogenous, again. Cleared native forests may or may not contribute towards timber supply, at the user's specification.

The energy inputs to agriculture are calculated using a generic set of process analysis equations derived in the mid-70's for energy inputs to agriculture (Slesser, 1975). Inputs are seen to rise exponentially as a function of land-intensity of yield. The amount of land available to agriculture is determined by the user. The logarithmic equations used to determine total process energy requirement are:

$$\mathbf{per_v = 60 \times 10^{-5} \times (int_v - p_{zero})^{1.4}}$$

$$\mathbf{per_a = 18 \times 10^{-3} \times (int_a)^{1.6}}$$

where **per** is the total process energy requirement per hectare (PJ/ha), **int** the intensity of output per hectare (tonnes protein/ha), and subscript **v** and **a** denote vegetable and animal production respectively. The term $\mathbf{p_{zero}}$ is the output of vegetable protein available with no exosomatic energy input. The process energy requirement is then allocated between thermal fuels, electricity and fertiliser (for which average embodied energy values are known).

In the case of animal agriculture, much of the protein is grown extensively, with little exogenous input. This is reflected by the term FANINT, the fraction of animal protein grown intensively. This term is estimated at roughly 5% on the basis of historical protein yields and energy demands.

The self-sufficiency terms (effectively denoting export targets) are sensitive to changes in water availability for irrigation, and to the energy requirements of water supply. These mechanisms are discussed in greater detail in section 5.1.1.11.

Timber growth rates are calculated as an average value, representing the average value on the logistic growth curve used by most forest growth-age profiles. That is, a steady-state simplification is assumed, for a given age of felling (i.e. rotation cycle length). These data are taken as average values for eucalypt and coniferous species, from the literature. Note that marginal growth rates refer to growth of potentially harvestable timber, not total biomass accumulation. A wastage factor of 30% for timber production is assumed. Plantation forests are assumed to be run on a regular rotation regime over a course of decades, approximating to a steady state for a large number of individual plantations out of phase with one another.

Timber is used as a fuel in Australia. This sector also summarises the fuel wood demands of various sectors, using data from ABARE total biomass fuel demands (which also includes bagasse i.e. sugar cane residue).

Policy levers to date have been used to assess the energy implications for the agricultural sector of retiring major portions of intensively used agricultural land, under different levels of export maintenance and changed dietary levels.

On the forestry side, the user may experiment with different forest management policies via changes in planting rates and expansion of native stands (which are then left to mature until specified otherwise). These changes are specifically policy-relevant in connection with the carbon cycle, as described below in section 5.1.1.17.

The steady state harvesting assumptions for forestry are suitable for long-term projections such as these, but would require back-up from more detailed temporal simulation models such as those of Nabuurs & Mohren (1995), in which the fluxes during a rotation cycle are represented in greater detail, rather than averaged out, as here.

Wool production is simplified, ignoring short-term changes occurring over the validation period with the collapse of the Special Reserve Price for wool. In reality, prior to 1991, stockpiles of wool were accumulating, and many of these were sold off cheaply after the market liberalised. Hence WOLPRIC data from validation gives a poor match to exports, as the model doesn't account for stockpiling behaviour. Long-term behaviour is, however, satisfactory for balance of payments purposes.

A more serious shortcoming of this module is that the hydrological implications of large-scale plantations are not modelled. The evapotranspiration rates of native tree species is of an order higher than typical European species, and large-scale changes in vegetation cover have resulted in marked rises in the water table in some regions, followed by salination of the groundwater supply. Obviously, the severity of this situation occurring again in the future depends upon a range of geomorphologic and hydrological factors peculiar to each location, but the consequences could be considerable in some areas. A serious study of the effectiveness of forests as carbon sinks should aim to take these factors into account: any carbon stored by a forest responsible for such a process would be outweighed many times by the requirement for capital- and energy hungry desalination technologies!

5.1.1.10 Mining

This part of the model accounts for the human made capital involved in all mining activities, with subdivisions into three energy and one non-energy resource sectors. Both are driven dynamically by demand terms, although the demand for non-energy resources is largely composed of simple linear empirical data. The energy part tracks three separate capital stocks, extracting oil, gas and coal respectively. Estimates of the initial capital stocks are based upon the total stock of energy mining capital recorded in ABS data, disaggregated on the assumption that the output-to-capital ratio of all three stocks are similar. A thorough evaluation of this sector would require more detailed data, but the user is free to test other capital desegregation patterns by altering the terms FNEN, FMINOIL, FMINGAS and FMINCOL.

The structure of each sector is identical, following the depleteable resource model used in ECCO. The relationship between resource and cumulative extraction is modelled in section 2, natural resource bases. The rate of capital investment into each sector can be set to follow one of two patterns. The first, default behaviour is to determine RCF by an empirical coefficient and the indigenous demand for the resource. The coefficient is calibrated to match the overall pattern of extraction over the validation period. This structure allows the user to alter the coefficient in order to simulate policies involving faster or slower depletion of the resource, trading export revenue for future indigenous use. Effectively, this option represents a free-market exploitation of the resource base, and tends to result in considerable net exports.

The second option allows the user to exogenously determine the size of the overseas market, and investment is then constrained to match that plus the local demand (provided that the cut-off ERECUT parameter described below is not exceeded). This mechanism was initially introduced to the coal extraction sector to prevent the model from exporting too large a quantity of coal, but has been extended to oil and gas to allow a resource conservation policy, where export limits are set to zero, and the energy resources are used solely for domestic demand.

Investment in gas and coal capital stock is set to stop at the point where the ERE of the resource becomes uneconomically large, as determined by the ERECUT parameter in sector 2. A similar algorithm applies to the oil sector, but is based on the difference in ERE between Australian and Middle Eastern oil (i.e. the competitiveness of the Australian resource), rather than the absolute value of ERE.

A limited number of policy interactions are available with this section of the model. A key one might be to limit the overseas market for coal, and run down the capital stock for the coal sector, when we make a transition to a natural gas economy. Similar limitations may be applied to oil and gas sectors, in an effort to eke out the resources.

Energy mining sectors are modelled in an appropriate amount of detail as they supply the basic energy that fuels the modelling paradigm. The other mining sectors could be disaggregated into major and minor energy users in a later version of the model. For balance of payments purposes, a distinction between bulk materials (where market price correlates closely to embodied energy) and precious materials (where it does not) would be desirable.

5.1.1.11 Industry

The industrial sector is modelled as a single capital stock, producing a single stream of output of human made capital. All manufacturing and construction activities are subsumed within this sector. Investment in industry is calculated using the residual theory described already. The main influences in the OzEcco model are given below in figure 5.2. Note that the growth model attains a degree of stability through the addition of negative feedback loops to the central growth loop's positive feedback.

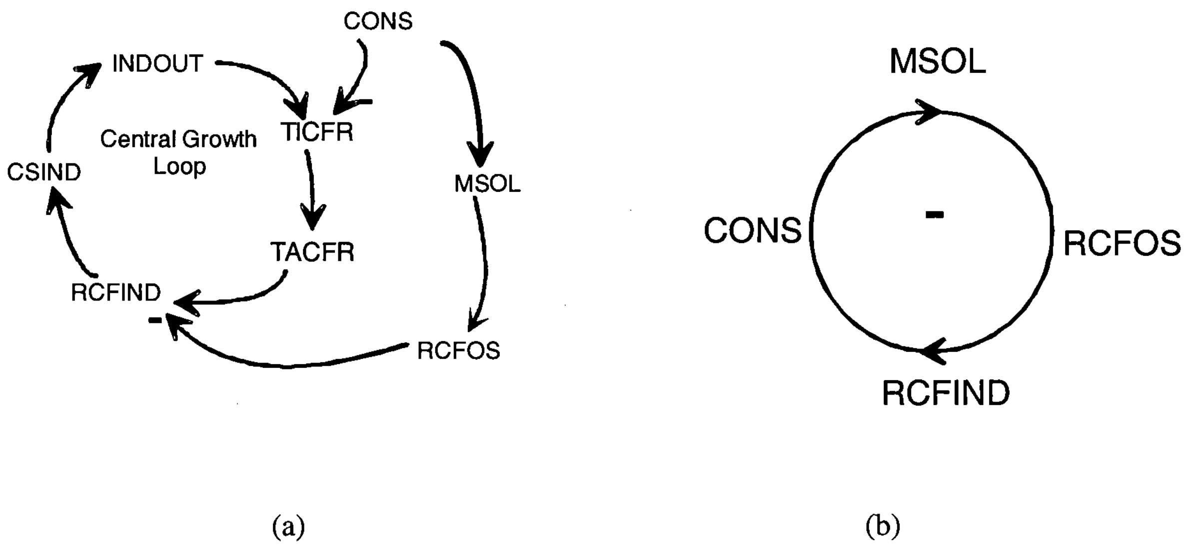


Figure 5.2. Key influences on the rate of capital formation in industry within the OzEcco model (a) full model structure of key components, comprising of one main positive feedback loop and one negative 'braking' loop (b) simplification of main negative feedback loop: increasing growth drives up affluence, which 'brakes' further growth.

5.1.1.12 Utility Sectors

Three utility sectors are identified within this sector; electricity generation, water supply and gas distribution. Water and electricity generation are modelled in some detail in the current model, with water distinguishing between three urban and three agricultural sources of demand, and electricity distinguishing between fossil-fired, hydro-electric, biomass-fired and renewable technologies. The gas distribution sector has a simple structures in place, but lack of hard data and a spatial element prevents further expansion at present.

5.1.1.13 Electricity Generation

Four electricity generating technologies are modelled here; fossil-fuelled, hydro-electric, biomass-fuelled generation and other renewables (the latter based on a mix of photovoltaics and wind turbines). Each sector is modelled primarily in terms of a generating capacity (expressed in MegaWatts), from which secondary data on capital stocks are derived.

The generation of electricity is determined as a function of the generating capacity and the load factor, which is based on average values for the technology at present. In the case of fossil-fired plant, a thermal efficiency rating is also assigned, allowing calculation of the required fuel inputs.

The hydro-electric sector is assumed to be static as a default, i.e. investment is made only to maintain existing stock. This follows an assertion in the Australian Year Book (ABS 1995c) that Australia's large-scale hydro-electric potential is largely saturated. There is currently 7441 megawatts installed capacity and a possible 200-250 megawatts awaiting installation on small dams (ABS, 1996b). A table function is provided to allow the user to provide exogenous hydro-expansion policies.

The biomass & renewables sectors are inactive unless activated by user policy. Australia currently has 5-7 megawatts of photovoltaic solar power units with a production of 36 megajoules a year (ABS, 1996b). Theoretically 2500 square kilometres of solar arrays with a capacity factor of 25% would be able to meet Australia's current electricity consumption of 570 petajoules. This area could be reduced to 1550 square kilometres for solar thermal systems. There are currently 3-4 megawatts of wind farms installed. All renewable systems have a considerable capital requirement, and the transition through to a renewable energy economy would produce a large stimulation to the industrial economy, and a lag phase before the real efficiency gains were evident.

Changes in electricity demand are therefore largely met by expansion or contraction of the fossil-fuelled sector, and one of the major challenges is to find a pathway which effects a transition from coal to natural gas, and then to renewables.

The generation capacity of electrical plant is measured primarily in power terms (power in the physics sense e.g. MegaWatts). The declared net capacity of a power station refers to the rate at which it can convert fuel (or wind, water, etc.) energy into electricity when operating at full load. In order to determine the actual potential for generation, the load factor must also be taken into account; load factor accounts for a range of factors; coal-fired plant need to be stoked up with fuel, wind farms face an unreliable and variable source of energy, and individual machines may operate at less than full peak due to age, defects or other factors. The theoretical upper rate of electrical energy production, based on declared net capacity alone, would be:

$$\mathbf{E_p = DNC \times 8760 \times 10^{-3}}$$

where Ep is measured in GWh/y and declared net capacity in MW. (There are 10-3GW in a MW, and 8760 hours in a year. The load factor corrects for various 'real world imperfections' and operating conditions, giving the formula used in the model:

$$\mathbf{E_p = DNC \times 8760 \times 10^{-3} \times lf}$$

Load factors are crucial in determining the capital costs of different technologies. Wind farms, for example, have a load factor roughly one-fifth that of coal-fired plant, and so five times the DNC of wind farms would be required to meet a given demand.

The policy levers shown below must be used in a mix to introduce efficiencies and decrease greenhouse gasses that come from fossil fuels usage. The size of the capital stock in electricity generation is considerable, and turning it over to make way for new technologies is difficult because of the large amount of redundancy built into the electricity system as load factors i.e. the ability to respond to peak loads, means a large generating capacity waiting for winter and spikes in demand. thus a trade in generating technology will mean a mix of the following:

1. Changing the fuel mix from coal to natural gas while altering the capital stocks of those two resource extraction industries. Also in some scenarios decreasing coal export trade.
2. Increasing the efficiency of current thermal plant from 30% to 40% over time
3. Capping electricity demand through several other sectors while gradually increasing investment in renewables while decreasing the life time of fossil plant.
4. Watching for the rebound effect where resources "saved" are taken up by another sector.

This is one of the more complex sections in the model. As electricity generation is a major producer of greenhouse gasses, and is the key to the functioning of a modern economy, changing fuel mixes, introducing new technologies and reducing the demand from other sectors of the economy produce a difficult mix of interactions which have to be managed. A technological fix for coal-fired CO2 emissions is included in the model, but can be seen to be limited in its effect due to its requirement for carbon-free electricity.

5.1.1.14 Gas Distribution

Supply of natural gas requires a large infrastructure of pipelines from distant gas fields, to distribution within urban and industrial areas where the fuel is used. The past 15 years has seen a rapid increase in gas infrastructure with electricity conversion, industry and domestic all being major users (ABS, 1996b). Natural gas will be a key fuel underpinning Australia's transition to a lower carbon economy, and it will also buffer the possibility of declining supplies of indigenous petroleum fuels as the vehicle fleet makes the transition to natural gas powered vehicles

A relatively simple set of equations keep track of the capital stocks of gas pipelines and infrastructure.

5.1.1.15 Water Supply

This sector models the capital infrastructure required to extract and transport water. Because Australia is a dry continent in world terms, the last century has seen a major effort made to harness Australia's water supply for urban, industrial and irrigation purposes. The capital stock in 1995 was $72 bn. The water available for human use in urban areas is not necessarily constrained, although the capital investment needed to deliver it where it is wanted, at the desired quality standard, is more of an investment capital limitation, rather than a natural resource constraint. As Davidson (1961) noted, *"Australia has more water available to it than people or capital to develop it"*. This becomes especially apparent when considering the fixed capital requirements of a widespread desalination program.

Approximately 70% of water used in Australia is used for irrigation, and the reallocation from agriculture to urban usage is therefore open to a range of political and economic instruments.

Water resources are modelled as six stocks: fresh, marginal and saline for each of surface and ground-water. The fresh and marginal categories cover the range of resources listed in the Australian Yearbook series and other sources; saline is reserved essentially for seawater and other extreme capital-intensive reserves. Using an analysis of state-by-state water demand and reserves, the fraction of surface and ground water falling into each category (fresh, marginal, saline) under increasing overall demand profiles has been calculated. This state level analysis is intended to reflect the geographical distribution of water and economic activity; although Australia as a whole has resources equivalent to five times the current demand for surface water, many highly-populated areas currently use over 90% of available supply (Heathcote & Mabbutt, 1987).

In practice, the allocation of resource grades is calculated in two stages, the second stage making a correction for any reductions in irrigation demand made to avoid investment in desalination.

Transitions from fresh to marginal to saline water resources imply a change in capital and energy requirements of extraction. Most notably, the shift to saline water use implies a large increase, estimated as a factor of 40-50. Given the optimistic tone of some recent literature on desalination technology, these data are supplied as user-definable tables, in which technological improvements can be entered. This is a similar structure to the depleteable resource model for fossil-fuels: the terms ACCAWT and ACCUWT (accessibility of agricultural and urban water supplies) offer a similar indication of resource grade to the ERE terms. Water is, of course, renewable, unlike energy, but the existence of a range of grades of resource merits the use of the present structure.

Demand for water is modelled as default in a simple linear fashion, assuming that water use by end-use sectors will rise in line with the activity of those sectors (measured as capital stocks or similar). Major users of water are agriculture, industry and mains (driven by domestic and services sectors) as identified by Input-Output studies and Australian Water Resources Council data (AWRC, 1987). Domestic water demand is driven by a per-household demand term, using exogenous data series for demand factors and average household size.

Because a large part of Australia's water demand is for irrigation, it might be seen as unrealistic to opt for expensive desalination policies when widespread irrigation is still practised. The model therefore allows two policy options: unlimited expansion of demands of all types, or a reduction in irrigation water as urban demands increase specifically to avoid the need for desalination technologies (as might occur under tradable permits, for example). This may trigger decreases in export targets for agricultural sectors (see section 6). Urban demand-side management can also be explored through the per-household demands for domestic use, and a simple efficiency-of-use coefficient for other urban uses.

This section used mainly to account for water infrastructure requirements rather than major questions of water policy. Demand-side management issues can be explored in a relatively simple way, provided that exogenous data series for urban demand are available.

As noted in sections 3 and 6, no attempt has been made to model Australia's hydro-geological cycle in detail, and so the potential pitfalls of applying 'European' practices and solutions has not been fully explored here.

5.1.1.16 Dwellings

Australia's built dwelling stock is the largest item in the capital stocks of the nation, being valued at $524bn in 1993/94, three times that of the capital stock of industry and about one half of the national total. While nations do allow their built infrastructure to deteriorate, within OzEcco the investment needed to cover the depreciation alone (i.e. to maintain existing housing stock) represents a hurdle for reinvestment in the industrial sector (refer to RCFOS in Fig. 5.2 section 5.1.1.8).

This sector tracks the capital stock of dwellings, covering both private and local government housing stocks. Investment is empirically determined as a log-linear function of the average physical affluence of the population, via the driver MSOLF (see section 5.1.1.15).

The age class structure of the housing stock is a key determinant of likely rates and requirements of turnover during the next 50 years. Without the inclusion of this important variable, some key timing dependencies might be missed. Nevertheless the current structure is appropriate for the current model.

5.1.1.17 Services

This section brings together services under wholesale and retail trade, transport, storage and communications, finance, property and business services, community services, recreation, personal and other services. Services by private and government concerns are all aggregated into single sector

Development of this sector is driven by a number of major end-user sectors, as determined by input-output analysis. The sectors identified are industry, services themselves, domestic dwellings and exports. Changes in composition of end-use between 1981-2 and 1992-3 are accounted for in the model.

Services output destination is explicitly recorded for all sectors which purchase more than 5% of output in 1981 or 1993 combined use matrix of the input-output tables (ABS, 1996a). In addition, desired indigenous output is determined by FSERIMP, the fraction of services output bought in from abroad (0 - 2.5%; negligible). These sectors are tabulated below.

%age	1981/2	1989/90	1992/3
Industry	6.5	13.3	17.6
Services	34.3	43.0	35.3
Domestic	15.4	35.8	25.4
Exports	39.4	2.8	14.0
Other *	4.4	5.1	7.7

* The small 'other' category is eliminated in the model structure, and reallocated to the four major users. This may introduce some errors, but aids model clarity.

Note the considerable structural change in services output occurring over the period 1981-93, specifically in the exports term. This has been analysed in greater detail using IO tables for intermediate years where available, and the drop in export volume appears to have occurred in the early 1980's, mainly affecting wholesale, retail and government services (education, health, etc.) rather than banking & finance. The change does seem somewhat dramatic, but is borne out by the figures.

Services are an important and growing component of the national economy and because of the high embodied energy in a service (the layers of organisation, infrastructure and people behind the shop front), services are quite energy intensive. All simulations should question the BAU policy settings within the context of increasingly globalised demand for services.

The aggregation of a diverse range of service activities into one sector inevitably loses the different potentials and dynamics beholden to any particular service enterprise. Subsequent version of the model might have to consider some more disaggregation of the services sector.

5.1.1.18 Personal Consumption of Goods

This is the first of the next three sections of the model which account for additional demand-side activities not associated directly with a fixed capital stock. These are consumption of goods by individuals (5.1.1.14), the material affluence that results from that (5.1.1.15) and transportation (5.1.1.16). The rate of consumption is linked to the rate of reinvestment in industry, which is viewed as a broad indicator of economic activity.

Put another way, residual human made capital availability is split between consumption and reinvestment in industry, on the basis of the 'RGCT' term. While rather crude in many ways, this consumption function generates a tight feedback between increased wealth creation and consumption, both directly through CONS, and less directly through MSOL (see 5.1.1.15). Growth of the system is sensitive to RGCT, as it diverts human made capital between long-term interests (reinvestment in industry helps to secure future output and hence future capital maintenance) and short-term interests (enjoyment of current human made consumer durables).

This sector directly models the fraction of output that is directed towards personal consumption, rather than being reinvested in a fixed capital stock (see). Consumption is modelled as a function of re-investment in the industrial sector, effectively treating the two activities jointly as the residual flow of human made capital (see figure 5.2 for the relationship between INDOUT, TICFR, TACFR and RCFIND1).

The split of this residual is determined by the ratio RGCT, set as a linear function in the pilot model, following examination of the relationship over the validation period. The pilot model formulation is simplistic, but important in setting up this feedback between long- and short-term interests. Other more sophisticated ECCO models have successfully used equally simple formulations.

5.1.1.19 Physical Affluence Per Capita

This sector calculates an important model driver, the material standard of living, MSOL. MSOL is not a welfare indicator, as it incorporates only physical throughput, with no reference to quality or distribution of living standards. As such, it is perhaps best thought of as a measure of average physical affluence. MSOL is thus defined on a yearly basis as the average embodied energy available to a member of the population as consumer goods and services to individuals.

In traditional economic reporting the measure of gross domestic product is used. However this describes the absolute level of economic activity, rather than whether that economic activity is useful to the individual e.g. it may all be spent constructing aluminium smelting plants for export or for the defence services. Particularly with the globalisation of trade, and large direct investment terms passing through national balances of payments, the decoupling of overall growth and growth of affluence is a genuine possibility.

As an indicator of physical affluence, MSOL has two main uses. Firstly it relates (imperfectly) the country's overall performance to benefits accrued to the average citizen. Secondly it is often (but not always) correlated to many efficiency gains in the country's metabolism i.e. part of what is left over after maintaining the basic life support services given to average per capita physical affluence. Under some scenarios however, physical affluence may be judged to be already too high and some of that may have to be reallocated to reinvestment into environmental quality.

MSOL is calculated from the a summation of the consumption terms CONS (from 5.1.1.14) and the services allocated to domestic housing DSOTDOM (section 5.1.1.13). If industrial output is insufficient to meet all these demands being made on it, the model sacrifices export goods (XPGDS from section 5.1.1.5) to ensure that there is enough human made capital available each year to maintain the rest of the infrastructure, i.e. that requirement for rate of capital formation in other sectors (RCFOS) can be satisfied. This level is the minimum rate of investment which will maintain the national life support system. However if there is a fall in RCFIND, that reduces CONS, and eventually affects the Material Standard of Living (MSOL), which in due course diminishes the growth in services and infrastructure, and so reduces RCFOS. These two negative feed backs (see also figure 5.2) bring the economy into balance, and so determine its potential for growth. In order to implement a policy action that would halt any falls in material affluence, there is a BENPOL switch, which when implemented, maintains MSOL at the highest level. This functions by further constraining reinvestment in industrial and other sectors. This in turn can slow transitions to renewable energy policies, for example.

It must be noted again that this section emphasises material affluence, and does not deal with the equity and distributional aspects of material affluence, nor the existential angst that comes in time to the middle class consumers.

5.1.1.20 Transportation

Transportation is, of course, an activity that does require a capital stock. No human made capital is attributed to this sector because of the fixed capital sectorisation used by the national accounts (ABS 1995 b). The total Australian fixed capital is divided there into sectoral categories and by function (e.g. equipment, transport, dwellings, other buildings). Hence, the stock of Australian vehicles are implicitly accounted for across the sectoral divisions, and to model them separately here would involve double-counting of vehicles. This being the case, the pilot model directly accounts only for energy use by the transport sector. These terms are driven directly by expansion of the transport end-use sectors, as identified by input-output analyses. Four types of transport are identified; road, rail, air and water, with major end-users being identified as industry, services, domestic and mining sectors. Demand for domestic sector transport is driven by the MSOLF term (see sector 5.1.1.15) rather than the stock of dwellings. A simple stock of vehicles is recorded to help account for the transition from petrol to natural gas powered vehicles, for which an exceptional capital investment (RCFNGV) must be made.

Demand for transport in the different sectors is driven by indices of activity in those sectors e.g. MINDEX (mining), INDEX (industry), SERDEX (services), MSOLF (private). As such the activity in those sectors must be capped or scaled back to manage energy use in the different industries and transport types. Because industrial output is such an important driver of endogenous growth within the model, changing the fraction of transport used by industry will help to reduce overall energy use in transport.

This module contains policy levers both to reduce overall transport demand, and to change the fuel mix (i.e. trading the car fleet from oil to natural gas). Alteration of the relevant terms may also allow examination of the effects of changes in modal split between the major transportation types.

As with the housing sector the age class of vehicles is an important consideration for transitions to new more fuel efficient technologies. The levels for changing transport demand are fairly diffuse and indirect. The strength is that transport demand and energy usage is tied to activity in the related sectors of the economy.

5.1.1.21 Environmental Pollution

This final sector of the model tracks the rates of emissions of pollutants generated by the economic system. In general, these are determined from first principles as a function of the fuel used by the economy. Within the pilot model, emissions of carbon dioxide and sulphur dioxide are estimated.

The carbon dioxide model has been expanded to account for other sources and sinks of CO_2 emissions, including fugitive emissions from fossil fuel extraction, a range of forestry-related fluxes, and technological options for extracting carbon from stack gases of coal-fired electricity generating plant.

Simple calculators multiply the fuel combusted in petajoules with the CO_2 and SO_2 content per petajoule to determine basic generation rate of pollutants.

For CO_2, the emissions are then calculated by subtracting abstraction by MEA technologies, modelled in section 5.1.1.1 of the model code. Monoethanolamine (MEA) technology is discussed by Hendricks (1990), and is included here as an example of a techno-fix policy. Other technologies, such as dolomite rock-based abstraction, could also be modelled given suitable capital- and energy requirements data. The MEA option is followed by injection of CO_2 into ground cavities such as disused mines. The entire process uses a considerable amount of electricity, and is hence limited in scope by the availability of non-carbon based electricity generation. A switch function in the model automatically cuts out investment in MEA if additional coal-fired capacity would be required to power it!

Further calculations (model code section 4.1.2) account for the carbon storage and releases associated with forestry (both native and plantations). The structure here follows that of the National Greenhouse Gas Inventory for 1990 (and subsequent years), covering (slow) soak-up of carbon by mature native forest, rapid soak-up by plantation timber (which is immature and growing more vigorously), plus the storage of carbon as ground-level waste from felled trees and in human-made structures as timber. The former storage includes cleared native forest & wastage from plantation trees. The latter includes commercial timbers, particle boards and paper/pulp products, using average residence times estimated by Nabuur & Mohrens (1993). Release of carbon in biomass burning is treated separately. Expansion and contraction of native forest areas is also accounted for. Reforestation involves a relatively slow accumulation of carbon as the stands mature, whereas deforestation involves a rapid release of cut timber (possibly delayed in storage as timber products if the wood is used economically) plus a slower release of waste biomass as it decays at ground level. Both processes are incorporated here. An estimate of lost carbon storage (technically a release) from scrub vegetation displaced by new forests is also made.

Model calculations agree broadly with estimates from the national greenhouse gas inventory, although the model predicts slightly higher CO2 generation rates. This is because it bases its calculation on fuel demand terms calibrated to ABARE data, which does not exactly match NGGI estimates of 'total apparent consumption', especially for coal. The discrepancies for 1990 are tabulated below.

PJ	NGGI	ABARE	difference
Oil	1478	1450	-28
Gas	704	682	-22
Coal	1586	1663	+77
Total	3768	3796	+28

A wide range of fuel types and even sources of each type are subsumed in a series of average pollution value above, but calibration has reasonably good agreement with greenhouse gas inventory (NGGC, 1996)

5.1.1.22 Whole System Indicators

A number of whole system indicators of different interpretations of sustainability developed by Slesser et al. (1994) are included here.

STES1 (short term economic sustainability) is the key indicator of non-monetary measures of sustainability according to Slesser et al. (1994). It reflects the balance between wealth creation and wealth consumption in the context of any set of user imposed policies, technologies and environmental objectives. A sustainable economy maintains and index value greater than 1. It is a ratio of the total available capital for capital creation (TACFR see 1.4.8) divided by the sum of the depreciation in industrial capital (RDCIND) and the rate of capital formation for other sectors apart from industry (RCFOS).

VAINT is a per capita of the intensity of arable agriculture and is obtained by dividing on a yearly basis the land used for cereals, vegetables and fruits by the total population.

POTFCH1, the potential for change, multiplies STES1 by VAINT and if the resulting number is greater than one, then a country should have the ability to look after itself economically as well as feed its population.

This concludes the general overview of the simulation model. The structure and calibration of the water supply sector is discussed in further detail below, as a prelude to the water policy case studies.

5.2 Australia's Water Resources

Australia's water resources are characterised in official data sources (AWRC, 1987; ABS 1995) as fresh, marginal, brackish & saline, for ground and surface water respectively. In analysing water resources at the state level, the marginal, brackish and saline categories were combined, so as to simplify the analysis. Tables 5.2 and 5.3 show the state of Australian water resources relative to current (1987) demand.

Table 5.2: Australia's Surface Water Resources relative to current demand (Gigalitres)

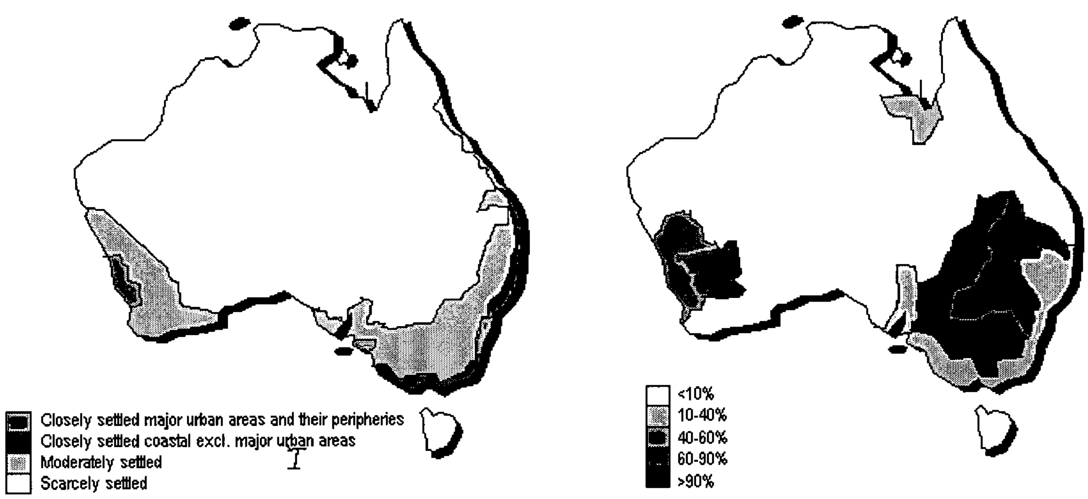
State	Population	Fresh	Total	Developed	%fresh dev	%tot dev
WA	1.5	10200	11700	2340	22.94	20.00
NT	0.16	17700	17700	59	0.33	0.33
SA	1.39	193	384	124	64.25	32.29
QU	2.68	32700	32700	3840	11.74	11.74
NSW	5.62	17300	16900	7970	46.07	47.16
ACT	0.26	175	175	106	60.57	60.57
VIC	4.21	9050	9810	5990	66.19	61.06
TAS	0.45	10800	10900	1020	9.44	9.36
Total/average	16.27	98118	100269	21449	21.86	21.39

The states of Australia are: **WA** Western Australia; **NT** Northern Territories; **SA** South Australia; **QU** Queensland; **NSW** New South Wales; **ACT** Australian Central Territories; **VIC** Victoria; **TAS** Tasmania
All populations are quoted in millions of people.

Table 5.3: Australia's Ground Water Resources relative to current demand (Gigalitres)

State	Population	Fresh	total	Abstracted	%fresh abs	%tot abs
WA	1.5	578	2740	355	61.42	12.96
NT	0.16	994	4420	24	2.41	0.54
SA	1.39	102	1210	504	494.12	41.65
QU	2.68	1760	2840	962	54.66	33.87
NSW inc. ACT	5.88	881	2180	962	109.19	44.13
VIC	4.21	469	862	146	31.13	16.94
TAS	0.45	47	124	5	10.64	4.03
Total/average	16.27	4831	14376	2958	61.23	20.58

The states of Australia are: **WA** Western Australia; **NT** Northern Territories; **SA** South Australia; **QU** Queensland; **NSW** New South Wales; **ACT** Australian Central Territories; **VIC** Victoria; **TAS** Tasmania
All populations are quoted in millions of people.



(a) (b)

Figure 5.3 Geographical distribution of (a) population (b) water demand in Australia (*source: Heathcote & Mabbutt (1987) pp.21 & 195*)

Note the importance of the geographical disaggregation. Australia as a whole uses only 20% of available surface water, but some individual states use up to 60% of reserves. For groundwater, the situation is even more dramatic; some states' demands exceed current supplies of fresh ground water. Figure 5.3 illustrates the geographical disparity between population density and water resources.

Using a linear extrapolation of current water demand for each state, the pressure on future water resources was calculated, in terms of the fraction of demand met by fresh & marginal-saline categories shown in tables 5.2 & 5.3. A further third category of 'sea water' was added to cover demand exceeding all currently identified resources, whereby desalinated sea water could be used as a last resort. The 'mix' of water grades available for surface and groundwater as the demand triples present levels is shown in figures 5.4 & 5.5 for surface & ground water respectively. (These data are derived from the statistics fed into the model, and are essentially a static analysis. They are not results *of* the model.) Note that surface water effectively moves straight from fresh to seawater categories, whereas groundwater has considerable marginal reserves.

The grades of water are not dynamic in the current model, beyond responding to demand. There is no representation of water pollution here (such as salination of the water table, as discussed in sections 1.1.6 & 1.1.11 of the model overview).

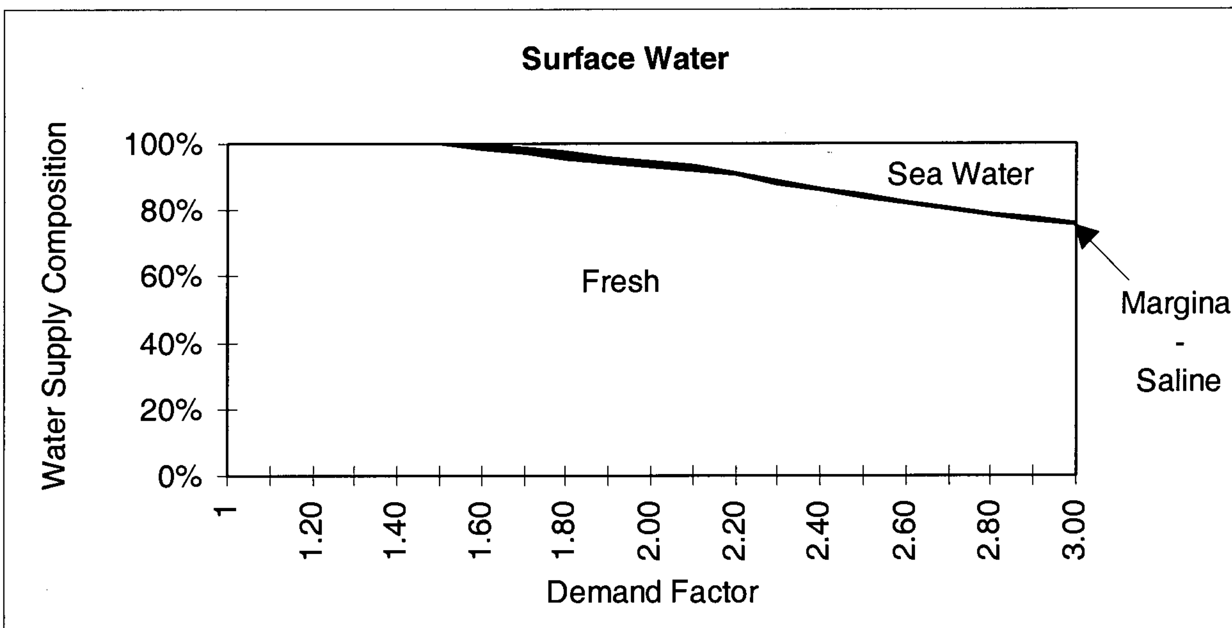


Figure 5.4: Relationship between resource grade and increased demand for surface water

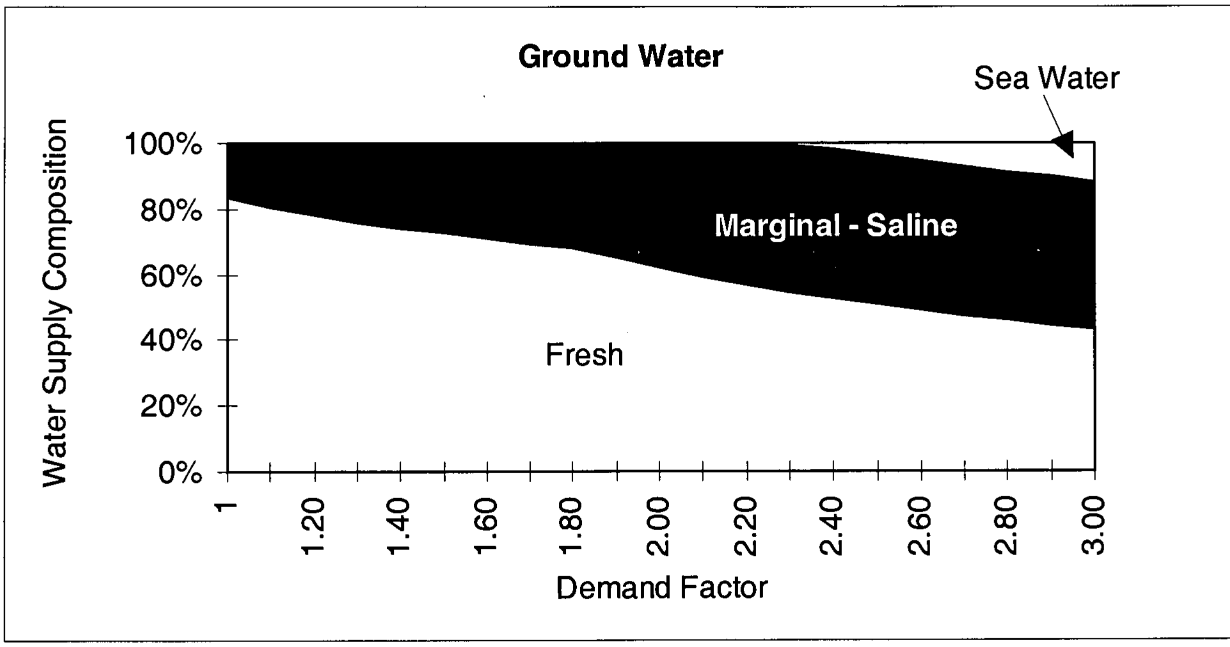


Figure 5.5: Relationship between resource grade and increased demand for ground water

The capital costs of water supply are based on historical data, for current technologies. Relative costs of supply for fresh, marginal and saline water are based on energy analyses of water supply types, with a very high value attributed to desalination (roughly 30 times current costs). Desalination technologies are, of course, immature at present, and one would expect costs to reduce, either by improvement of current reverse osmosis or temperature-based techniques, or through new methods (Childs & Dabiri, 1992; Hauge, 1995).

There is considerable hype surrounding some newly emerging technologies, suggesting reductions of energy and capital costs by factors of tens and hundreds already. Rather than entering these values into the model as defaults, they are left to the user as a table function.

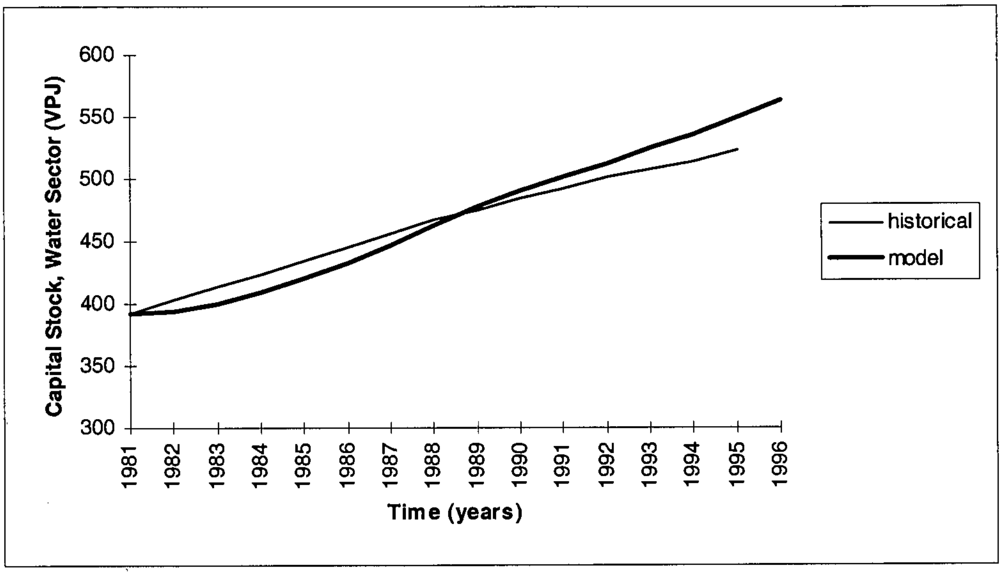


Figure 5.6: Capital Stocks of Water Supply The unit VPJ refers to 'volume-corrected' embodied energy units (see Chapter 4).

The current water supply sector makes a reasonable fit to historical data on capital stocks and investment rates (figure 5.6), although the rate of investment is somewhat higher in later years than the historical value. Whether this represented a genuine technological change or a short-term under-investment in water is unclear from the data, and no technological change has been assumed in the default model data set.

5.2.1 A Simple Scenario Analysis: desalination versus irrigation cuts

The linear analysis of water supply and demand above assumed a proportional growth of water demand by all regions, and by all sectors. The latter is somewhat unrealistic; as water becomes scarce, it is likely that irrigation water would be cut back on in favour of urban demand, rather than expanding the supply via desalination. (Tradable permits offer one means of promoting such a transition economically.) Either option can be explored in the model; the default is the cutback on irrigation.

The two options are both presented below; for the desalination option, both a default technological change and a more considerable decrease in costs (halving every ten years from 2011 onwards).

The investment required by desalination is considerable (figure 5.7) showing up in the total non-industrial investment of the entire economy quite clearly. Use of desalinated water raises water energy- and capital intensity considerably (figure 5.8) and has a noticeable negative impact on industrial output (figure 5.9).

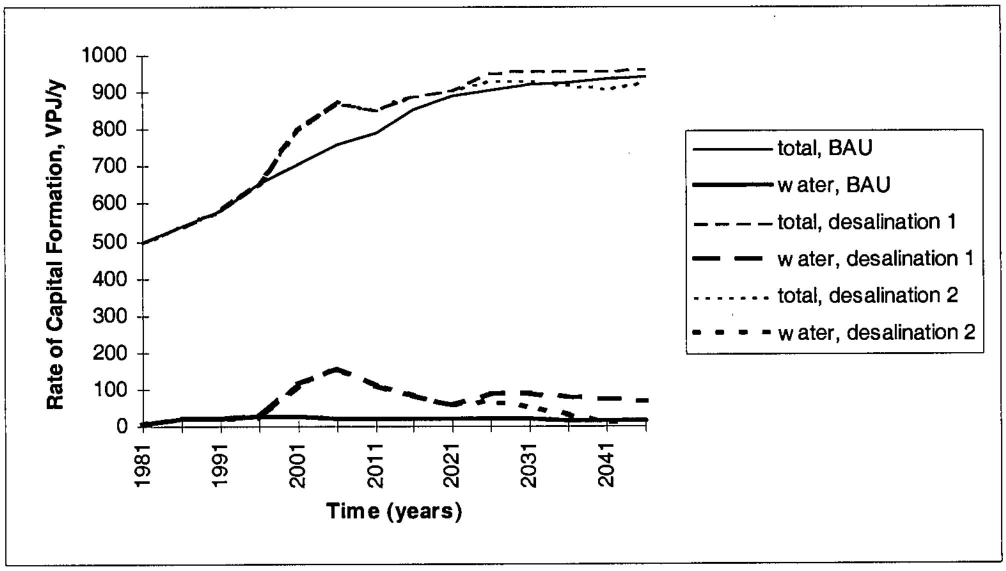


Figure 5.7: Investment Requirements of Water Sector, in relation to total non-industrial investments ('desalination 1' = default costs; 'desalination 2' = reduced costs)

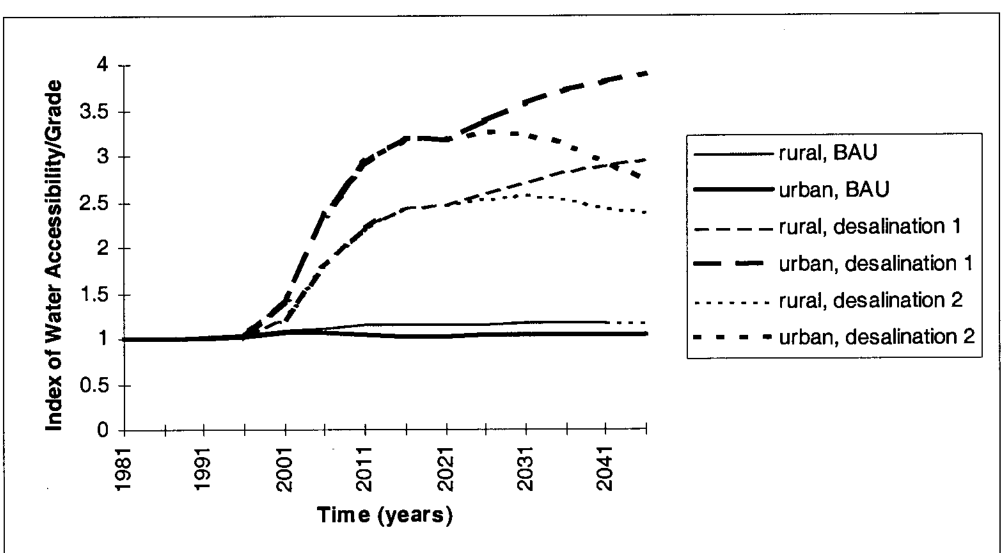


Figure 5.8: index of Energy/Capital Requirements for Rural & Urban Water Extraction

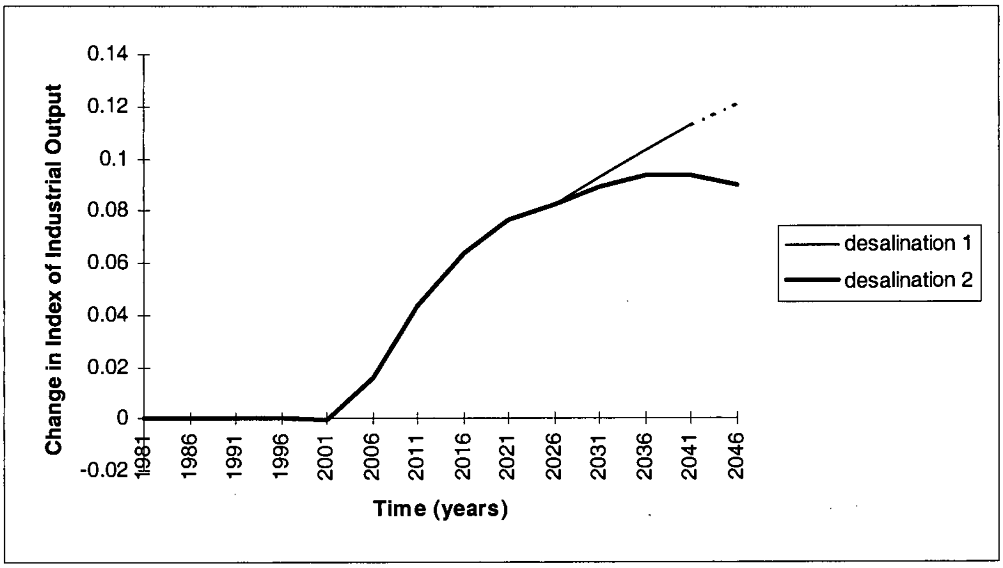


Figure 5.9: Effects of Desalination Programs on Industrial Sector Growth (expressed as a cost)

Even a relatively simple scenario exercise such as this brings out the interplay between technology, resource supplies (water and energy), capital accumulation and behavioural options in determining growth. The water supply sector in the simulation model is detailed enough, though, to allow a more structured investigation into the relationships between the various factors.:

- The resource base is characterised in terms of both volume and quality.
- A range of technology options are represented - the transition in water supply technologies from simple run-off collection to desalination technologies has been included, and related to the available resource base and quality.
- Economic reactions to scarcity have been included as a user-defined policy, with cutbacks to irrigation in the face of resource scarcity being seen as a likely option. Rather than opting for costly desalination technologies straight away, water demand may be reallocated from irrigation to urban uses. Given Australia's considerable agricultural surplus, this primarily affects balance of trade and peoples' livelihoods. The degree of cutback can be imposed so as to avoid desalination technologies altogether for as long as possible (the default) or as a partial substitution controlled by a coefficient varied by the user.

- Behavioural reactions may be imposed on the model for urban water use: the average amount of water use per household can be altered to reflect increased parsimony, whether this is realised through water-efficient technologies, changes in lifestyle, 'hosepipe bans' or whatever.

A set of 18 scenarios were run to reflect the variety of these factors. The scenarios are listed below in table 5.4.

Table 5.4: Specification of Scenarios for Water Policy: specification follows three factors; firstly, the average household water usage rate, set at 300kL/y as default, is either maintained at that level throughout the simulation, or reduced by a factor of four over the period 2000-2020. Desalination Technology is assigned a default Gross Energy Requirement of 100GJ/Ml (c.f approx. 4GJ/Ml for dam & pipe technology); again, this value is either held constant throughout the simulation, or allowed to decrease by a factor of four from 2000-2020. Finally, the response of irrigation use to water scarcity is modelled either by cutting back on irrigation altogether in order to avoid desalination (the model default) or calculating a reduction in agricultural self-sufficiency factor r as a power of the ratio between desired and feasible water supplies. In the latter case, the power coefficient has no intrinsic meaning, but varying it can generate a range of responses, termed here 'weak', 'medium' and 'strong' for three chosen values.

Ave. Water Usage per Household	Desalination Technology Cost	Responsiveness of Irrigation to Water Scarcity
declining (x4)	constant	complete avoidance of desalination uptake
constant	constant	complete avoidance of desalination uptake
declining (x4)	constant	none
constant	constant	none
declining (x4)	constant	slight (coefficient=1)
constant	constant	slight (coefficient=1)
declining (x4)	constant	medium (coefficient=2)
constant	constant	medium (coefficient=2)
declining (x4)	constant	strong (coefficient=4)
constant	constant	strong (coefficient=4)
declining (x4)	declining (x4)	none
constant	declining (x4)	none
declining (x4)	declining (x4)	slight (coefficient=1)
constant	declining (x4)	slight (coefficient=1)
declining (x4)	declining (x4)	medium (coefficient=2)
constant	declining (x4)	medium (coefficient=2)
declining (x4)	declining (x4)	strong (coefficient=4)
constant	declining (x4)	strong (coefficient=4)

The three factors varied above are linked. Water demand will drive resource scarcity, which will drive the adoption of the desalination technology and/or cutback in agricultural surplus. Both factors will impact upon the model-determined growth rate; the former through increased diversion of available HMC into costly technologies, the latter through a reduction in export revenue. Water demand will be driven by the rate of growth of HMC stocks and by the household demand for water, and also by the policy or irrigation reduction (in 1987, irrigation is estimated to have accounted for around 70% of total water demand in Australia). The influences are summarised in figure 5.9 below.

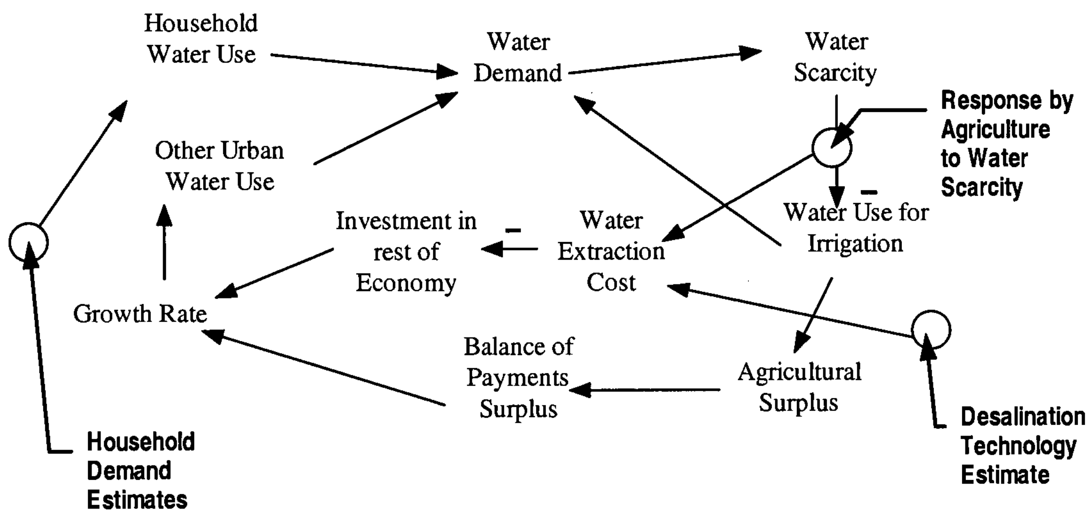


Figure 5.10: Interactions between technology, behaviour and resource scarcity as represented in the OzEcco model water sector. Points of entry of the policy options explored here are represented as white circles. All influences are positive in nature (in the technical sense) unless indicated by a negative sign at the arrowhead.

Note that there are negative feedbacks stabilising the water demand under both responses to scarcity. Where desalination is opted for, demand is reduced by the slowing-down of the economy under the burden of constructing the technologies (see figure 5.8 for an estimate of typical magnitudes). Where irrigation cutbacks are implemented in the model, projected growth is reduced through a less favourable international trade position (Australia's trade position rests strongly on agricultural produce).

The effects on growth posited by figure 5.9 are, then, liable to result in 'intersectoral rebound effects' of the type discussed in chapter 4. In other words, the decrease in water demand experienced by the change in household usage will be less than 'expected' (if one expected the result to be equal to the household water demand under the no-reduction scenario multiplied by the change in the coefficient).

By comparing the nine sets of policies with and without household reductions, the rebound effect associated with each irrigation policy under both desalination cost assumptions can be determined from the model. The results are shown in figure 5.11.

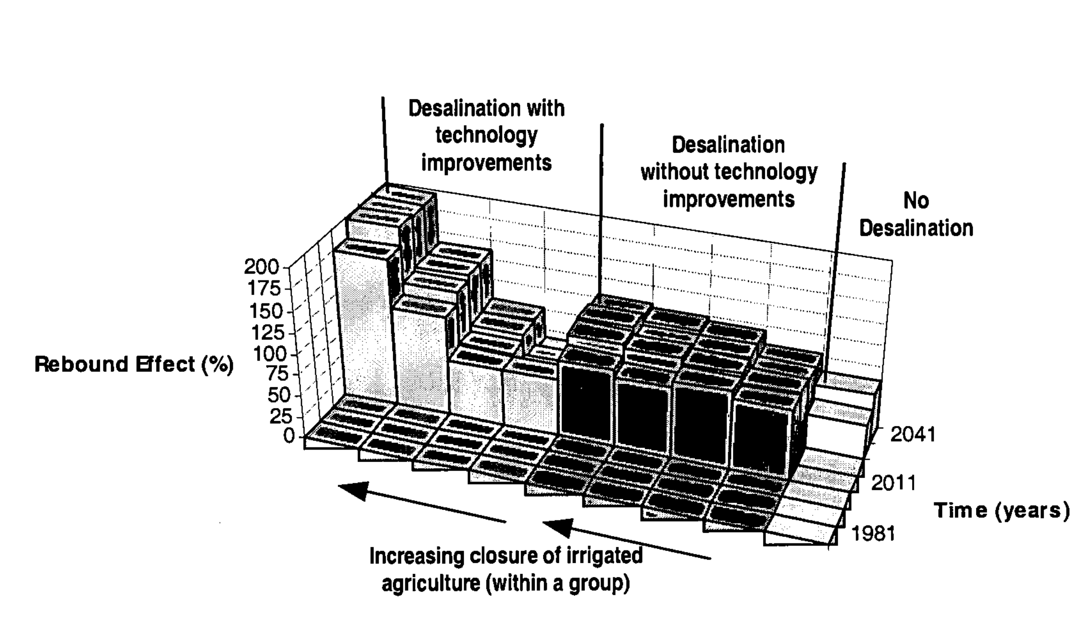


Figure 5.11: Calculation of Rebound Effects for a Range of Water Policy Scenarios. Values are calculated at ten year intervals from model time-series outputs. Note that rebound effects increase after desalination technology has been adopted, at around 2011 in most scenarios, and hence not in the 'no desalination' scenario, where the smaller, later rebound effect follows full exploitation of 'marginal' water sources.

A number of things can be seen from the rebound calculations. The most striking thing is that the values determined here are high - starting at around values of 50% and rising nearly to 200% (i.e. demand *increases* by twice the expected loss). Given that the overall capital cost is a significant part of the overall HMC demand by non-industry sectors (e.g. figure 5.7), this is not surprising; the UK economy rebound effect for energy discussed in Chapter 4 was small because investment in energy supply is a small proportion of overall investment patterns.

The larger rebound effects evident in the earlier parts of this century (figure 4.9) may have reflected the much larger capital-savings made at the time as more significant improvements were being made to immature technologies. Similarly, it is not surprising that the rebound effects for the scenarios where desalination is adopted are larger than for the one where it is not (although by any other measure the latter is very big).

What is more counter-intuitive is that the rebound effects are greater for the scenarios in which desalination technology costs decrease. Figure 5.12 plots the relationship between rebound effect magnitude and the accessibility index of agricultural water, as measured by the average HMC cost per unit water delivered for the mix of conventional and desalination techniques. As would be expected, the average cost has risen only slightly where no desalination has been adopted (roughly 16%), and several-fold where it has been. The increase has been noticeably greater where no improvements in the technology (reflected in the model as decreased capital costs) have been assumed.

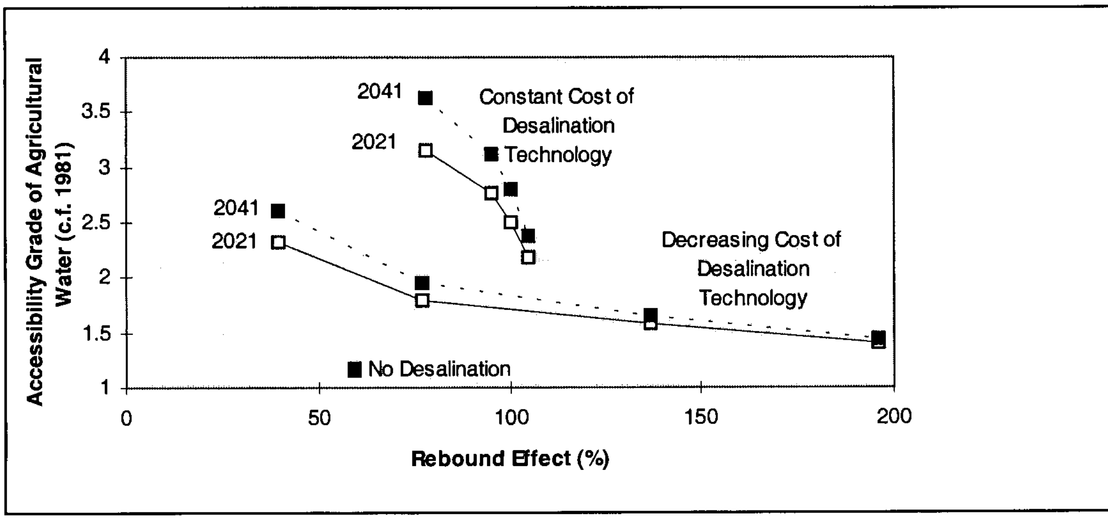


Figure 5.12: Relationship between Resource Acquisition Cost (in HMC terms) and Rebound Effects. Estimated values for the years 2021 and 2041 are plotted for each scenario. Results are grouped on the basis of technological assumptions and uptake.

Both technological assumptions give similar decreases in the resource scarcity parameter, with the strongest cutback on irrigation activity yielding a resource accessibility of roughly 60% of the 'no cutback' scenario. Covering the same range using the more optimistic assumptions about technological progress results in a much greater rebound effect, though.

The rebound values are bigger and cover a wider range for the case of the less-capital intensive desalination technology because under those conditions the economy's physical capital stocks are growing more rapidly, as shown in figure 5.13 below. Under faster growth conditions, differences introduced by the household decrease in water are amplified to a greater extent, resulting in greater values for the rebound calculation. In comparison, capital growth under the constant-cost desalination technology is sluggish to the extent that releasing extra investment potential by decreasing household water usage will only result in small increase in growth rate. The range of growth rates, expressed as average p.a. increases is small (and in all cases, this growth is quite smooth; the averaging process is not masking marked changes in trends). The 'rebound effects' observed here are, then, very sensitive to changes in growth rates in the output of HMC.

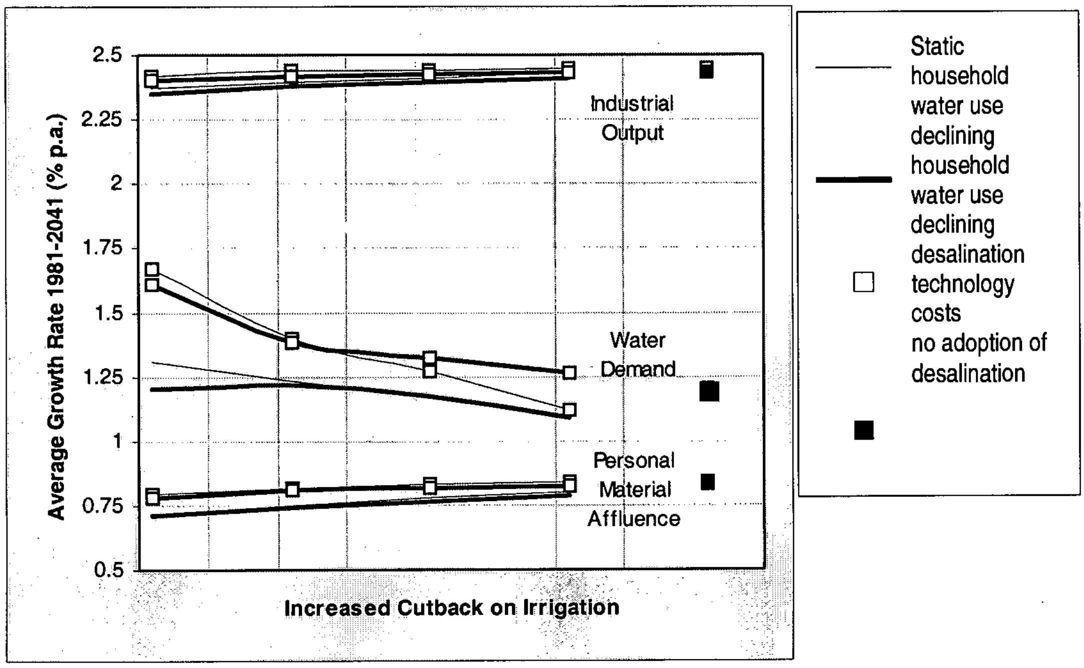


Figure 5.13: Average growth rates of Industrial Output, Water Demand and Average Personal Affluence determined by OzEcco model under different scenarios: as in figure 5.11, scenarios are grouped in terms of irrigation cutbacks versus desalination technology adoption. The individual points shown on the far right are the 'no desalination' policies.

5.2.2 Conclusions

The results presented here compound a number of speculative mechanisms in order to create a wide range of complex behaviour. The mechanisms followed by the model are greatly simplified representations of reality, and a number of additional feedbacks and caveats could be postulated.

Within the framework of the broader growth debate, however, the results here are important. At the simplest, they demonstrate that the interactions between technological progress and resource scarcity, when considered as a whole rather than as two opposing arguments, are significant and complex. Few of the behaviour patterns observed here could have been understood without the aid of this or a similar model.

Further, the results point in a certain direction. The rebound effect is not a universal mechanism, and, even within the subset of economies limited primarily by investment constraints, the rebound effect is not always significant. The pre-conditions for a large rebound effect appear to be that:

- the production of the resource being used more efficiently is capital-intensive
- the increase in production efficiency is large and rapid
- the economy is growing rapidly anyway at the time of the resource change

Note that these conditions describe the early 20th century, where technological change in the direction of resource efficiency did occur rapidly at the same time as rapid increases in resource use. Ironically, these latter two conditions, of rapid technological change and rapid economic growth, are those cited by the technological optimists as being evidence of a lack of resource constraints. Under the sluggish, ailing conditions predicted by the "ecological Cassandra's" (Simon, 1998), rebound effects would be unlikely to manifest at all, and eco-technology could provide a cure to resource scarcity issues. One is never so confident as before a fall, it seems.

The effect of a 'techno-fix' to environmental issues depends heavily, then, on the economic climate in which they occur, and, stepping beyond the model, on a range of cultural and social factors that would influence the stylised and distilled parameters discussed here. Given these results on 'rebound effects', it seems highly necessary to consider the interactions between technology, nature and human behaviour as the key to understanding economies, rather than the three in isolation from one another, or even as separate disciplines to be addressed side by side.

It is unlikely that understanding of these interactions can be developed much further solely by using the ECCO model. While it has served well up to this point in allowing a characterisation of different qualitative dynamic regimes (small rebound and big rebound), it is not well equipped to deal with a more detailed disaggregation of the factors involved. Specifically, technological change has been represented so far in a highly empirical way, as external changes to sets of resource use coefficients. The IPSO Model developed in Chapter 8 addresses some of these shortcomings.

Chapter 6 Naïve Realism in Models of Urban Form

This chapter presents a second policy-relevant modelling case study, this time of a spatial simulation of the factors that affect urban form. CarteSim is a constrained cellular automaton model operating on a stylised rectangular grid representation of urban space, using a stylised set of land-use types. In terms of broad family, CarteSim is a Complex Adaptive Systems model of a fairly simple type. It is introduced at this point in the thesis as a contrast to the conventional System Dynamics of the ECCO model described in Chapters 4 & 5.

Although these models take a somewhat different approach and subject matter to the ECCO models of the previous two chapters, there are significant overlaps, enabling each to 'learn' from the other. The potential for this is discussed in Chapter 7, and an example given in Part 3 of this thesis. The structure and dynamics are presented in this chapter, along with a discussion of the tension between realism and tractability in mathematical modelling.

Two sets of experiments are carried out using CarteSim. The first reduces the realism of the model by substituting a one-dimensional grid for the two-dimensional one, without significantly altering the fundamental dynamics of the system.

The second experiment increases the realism, by allowing a differentiation between spatial distance and journey time, giving a possibility of generating a variety of new types of urban form.

Both of these experiments are designed to illustrate the complexity of the relationship between what a model represents, and the insights that it can offer. It is not always the case that adding additional detail increases the usefulness of the model, nor that reducing detail results in a less useful model.

6.1 Models of Urban Form: A Brief Overview

A comprehensive treatment of the theory of urban form lies outside the scope of this thesis. A brief overview of significant work will be presented here, to set the context for the discussion of the CarteSim model.

The term 'urban form' refers to the shape, size and structure of urban regions. It can be interpreted to cover a range of topics, taking in land-use patterns in addition to simple morphology. Further, it can be interpreted to cover both the structure of a single urban region or of a series of towns and cities taken as a whole. The key requisite for the classification is a spatial element; hence a theory of size ranking (e.g. Zipf, 1949), income disparity or housing stock (e.g. Forrester, 1968) would not qualify as 'urban form' theory. It must also contain an element of causal explanation; hence purely cartographic exercises are also discounted.

Urbanisation and urban form issues are a prime example of a discipline in which a wide and varied range of factors interact (i.e. a 'complex human policy issue'). The processes underlying the urbanisation process are at once physical, social, economic and political, and draw upon influences from the individual, the city's internal structure, and regional, national and international context. Any attempt to numerically model urban form must, then, be highly selective in those aspects that it chooses to represent, if it is to mathematically tractable and amenable to interpretation.

The acknowledged starting point for theories of urban form is the 'urban ecology' of Burgess (1925) and later Hoyt (1939). Both these studies developed from what might be termed a 'holistic' outlook, as they attempted to understand the distribution of individual components by reference to the whole system.

Burgess developed a zonal model of city growth in which different land-use functions were radially distributed about a central business district (CBD). The key determinants in his explanation were population growth, and the ageing of inner areas leading to a 'colonisation' by lower income groups. Through a 'sifting' process, five idealised bands of activity would develop:

- a central business district, almost exclusively commercial

- a transition zone with mixed land-use and low rents, about to be invaded by the CBD
- worker's homes, dominated by sound but inexpensive housing
- residential homes for more affluent groups
- affluent and exclusive suburbs

Burgess was not the first to describe land-use patterns as concentric circles; the agricultural economist von Thunen[9] had described a very similar process to Burgess' regarding the distribution of agricultural land uses around an isolated city. The novelty of Burgess' approach lay in his adoption of an explicitly ecological approach, and on the dynamic properties of the system.

Burgess' model was based theoretically upon ecological concepts of (linear) vegetative succession, and on empirical studies of Chicago and other cities. Although highly stylised, and based upon a now outdated equilibrium view of ecological science, it does represent an early attempt to treat the city as an interacting systemic whole, and, within the limited context of industrialised America, it served as a reasonable approximation.

Hoyt followed Burgess' studies, again validating on a series of US cities. While recognising the zonal patterns defined by Burgess, Hoyt emphasised 'sectoral' patterns, by which is meant radial 'slices' of concentric circles. Hoyt saw high-class residential areas as the key determinants of urban land-use, as they could pre-empt the most desirable areas. His emphasis on sectoral zones within cities arose from empirical studies of high-income groups.

While both Hoyt and Burgess based their explanations upon equilibrium concepts, both also stressed the role of change over time, and attempted to explain the changes in land-use patterns rather than static analyses. The human ecology school of urban form continued to develop, mainly via more sophisticated statistical analyses such as the Factorial Ecology methods of Shevky & Bell (1955) among others. Shevky and Bell argued that both Burgess and Hoyt presented partial explanations, and derived through multivariate analysis four main explanatory variables for static analyses of urban form,

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[9] who also acted as a major precursor to Leon Walras in determining the marginalist revolution in mainstream economics - see Chapter 3.

namely social class, stage in the family life-cycle, ethnic grouping and mobility characteristics.

Later, much of the theory was re-interpreted by the development of bid-rent theory (Alonso, 1960; 1964). This benefited from the work in equilibrium analysis gaining prominence within the economics profession, and is strongly influenced by the concepts of rational optimisation.

Bid-rent theory describes urban form as a trade-off between land-use costs and the revenue that can be generated by use of the land (various studies measure the budgets in either money terms or travel-to-work distances). Activities such as commerce can command a much higher revenue per acre than housing, which, in term commands more than agriculture, say, and so can gain access to land much closer to the city centre. Given a variety of activities, an equilibrium is posited at which all groups have maximised their gains as far as possible. Again, the idealised outcome is seen as a concentric circle pattern, with the local peculiarities of real cities being explained through reference to external 'complexities'. The key difference in bid-rent from the ecological approaches is the greater emphasis on equilibrium rather than change, and more emphasis on rationality in the stylisation of the actors involved.

Physics, as well as economics, has played a part in influencing the development of urban studies, most notably in the 'gravity models' of population distribution, which borrowed initially from the mathematics of Newtonian mechanics, although later developments (e.g. Wilson, 1970) moved on to statistical mechanics, and an introduction of the concept of entropy (see Chapter 3)into urban form.

The above theories of urban form can all be characterised as structural, in contrast to a historical school, which sought more specific explanations based on empirical studies. Further, all share a common property of proposing a simplified idealised pattern far removed from actual urban forms, and call upon external complexities to account for the difference (figure 6.1).

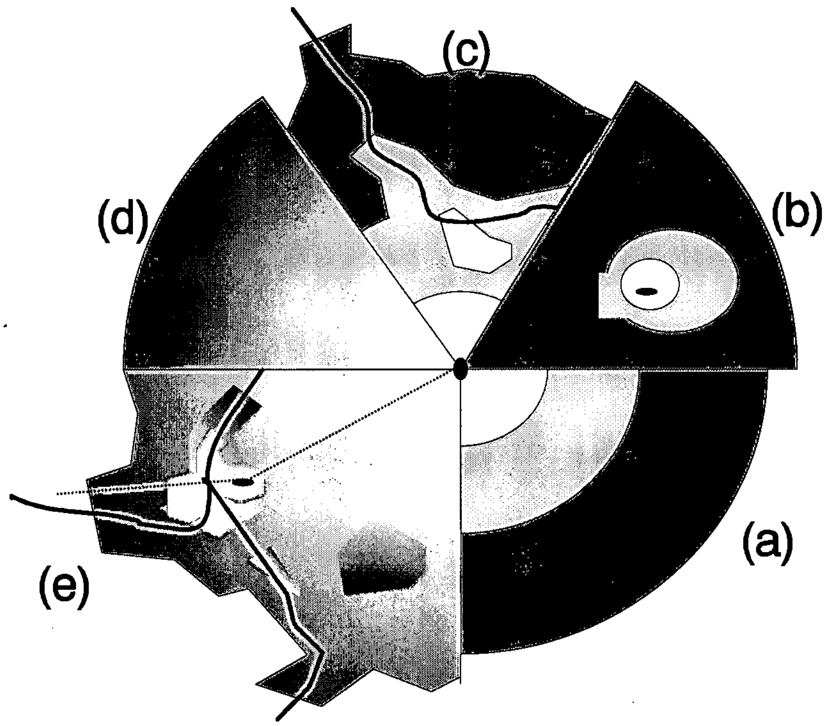


Figure 6.1: Classical view of urban form resulting from (a) an idealised equilibrium pattern distorted by external complexities such as (b) influence of a subsidiary nucleus (c) natural features such as mountains, coastlines or rivers (d) imperfect information (e) a combination of these.

More recently, the general move away from equilibrium explanations towards a complex systems approach has played a prominent part in the development of urban form theory. Allen & Sanglier (Allen & Sanglier, 1981; Sanglier & Allen, 1989) developed complex simulations of 'self-organising' urban systems, in which transient periods of stability would develop within a dynamic pattern of migration between urban centres. Changes could be triggered by externally imposed events, such as development of transport systems, but could also occur through internal amplification of random elements. A number of authors have taken up this approach (e.g. Haag et al., 1992; Engelen, 1986).

Non-equilibrium explanations for internal city structure also developed around the same time. Early studies (e.g. Engelen, 1986) followed the regional model structures, but, more recently, the adoption of cellular automaton techniques (White & Engelen, 1993, 1994; Batty & Xie, 1994, Clarke et al., 1994; Kirtland et. al, 1996) have allowed a considerable increase in scale of resolution. The model presented here is a close relative of that described in White & Engelen (1993).

The key importance of the non-equilibrium school of urban form lay not so much in the access to high spatial resolution, but in the fact that it challenged the concept of an ideal regularly-shaped system being distorted by external 'complexities'. Within an equilibrium-based explanation, these complexities are mere anomalies that intrude upon the present moment, but serve no long-term role within the dynamics. The underlying driving forces and the complexities, in the classical mode, are independently determined, and can be modelled independently then superimposed to create a snapshot of the present. Complex systems theory presents mechanisms that challenge this notion of independence; indeed, historical accidents have been elevated to the position of a major driving force, in those cases where they are amplified through micro-level feedback structures in the system. As such, they can no longer be separated out in order to leave a stylised model that makes any sense.

The policy implications of this are potentially significant, if only because there had been a shift over time in the emphasis placed on the equilibrium explanations. What were originally methods adopted for convenience or tractability's sake came over time to possess prescriptive force. As with economics, there was an identification of equilibrium with optimality of welfare, a viewpoint under which complexities became undesirable deviations (see Kivell, 1993). This viewpoint can perhaps be seen most clearly in the regular layout of UK New Towns, or the development of high-rise housing blocks.

The non-equilibrium approach offers an opportunity, then, to reclaim diversity as a desirable, even necessary, thing. Further, because it offers an unpredictable description of change, the emphasis on forward planning has shifted from prediction towards monitoring, or 'adaptive management' (Walters, 1987; Carpentier & Bosch, 1994).

6.2 The CarteSim Model

In this section, a simulation method for understanding the evolution of urban form is presented. The model structure and assumptions are described below, and subsequent sections assess the extent to which it functions as a quantitative and a qualitative tool. The CarteSim model was developed using MicroSoft Visual Basic v3 for 16-bit Windows. A description of the program is given in Appendix 2.

6.2.1 Cellular Automata

Cellular automaton computations techniques (Langton, 1986; 1990; Packard & Wolfram, 1986; Wolfram, 1984 a.o.) have found favour with urban modellers in recent years, because of the obvious analogy between the regular grid on which the calculation is implemented and the spatial surface upon which the city develops. Recent applications of these techniques in city modelling (Batty & Xie, 1994; White & Engelen, 1993; 1994; Clarke et al., 1994; Kirtland et al., 1996) deal with the development of city models in a rather abstract way, generally reporting on broad principles of pattern formation rather than locationally specific applications. (Engelen & Uljee, 1997 is a recent development of a specific case study, of Cinncinati, Ohio, and Kirtland et al.,1996 present a case study of the development of San Francisco.) As such, the emphasis is clearly on generic insight rather than numerical accuracy, and the insights gained are in many cases far-reaching. Nonetheless, the level of detail in the model implementation is considerable, and their operation is computationally intensive.

CarteSim is a variation on the model presented in White & Engelen's 1993 paper (ibid.), in which a further simplification to the representation of urban systems is suggested; that of the representation of space. Cellular city models have typically been implemented on two-dimensional grids of cells.

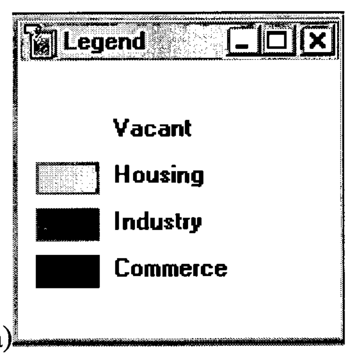
Much of the pioneering work on basic cellular dynamics was implemented on one-dimensional surfaces, and Packard & Wolfram's (ibid.) review suggests that most of the dynamic regimes of two-dimensional cellular automata can also be found in one-dimensional analogues. Obviously, the two-dimensional pattern generated by a two-dimensional automaton can't be reproduced in one dimension, but the higher level organisation can e.g. 'phase changes' between frozen, random and semi-ordered states as particular parameters are varied over a range of values.

CarteSim is designed to operate the same rule-sets upon one- or two-dimensional surfaces. To move from a planar to a linear representation of a city is clearly a move away from realism. As the current generation of models are targeted at elucidating general principles, there is a strong argument to suggest that this is an acceptable reduction. Certainly, the model is no more realistic in many other ways, e.g. the mutually exclusive nature of the land-use functions, and the regularity of the (linear or planar) spatial grid. The advantage of reduction to a linear grid is two-fold; firstly, it reduces the computation time of the model significantly, and, secondly, it makes visualisation of the model dynamics easier.

6.2.2 CarteSim Structure

The specification of the model is relatively simple. Each cell on the grid can exist in one of a number of states at any given time; the examples in this chapter follow White & Engelen's four-fold classification of vacant, housing, industrial or commercial (figure 6.2a). Cells can change only from a 'lower' to a 'higher' state, in the increasing order vacant, housing, industrial, commercial (figure 6.2b).

(This is not realistic; urban decay, for example, cannot be represented here, but it prevents the model from entering into very long repetitive organisation processes whereby the city structure is 're-shuffled' at an unrealistic rate. It is a simplification undertaken solely for the sake of tractability - a more complex algorithm may be able to represent decay processes without risking infinitely long calculations, but time precluded development of such an algorithm within this thesis. The models presented by White & Engelen, upon which CarteSim is based, enforced similar restrictions.)

(a)


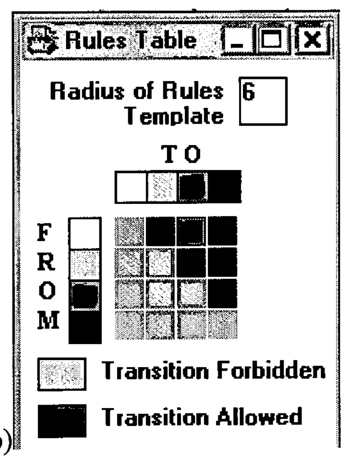
(b)


Figure 6.2: Hierarchy of land-use states in CarteSim model: (a) the editable legend panel allows specification of an 'alphabet' of land-use classes (b) transitions are specified as allowed or disallowed. The scheme shown here allows only transitions from a 'lighter' to a 'darker' colour of land-use, i.e. only downwards in the order given on the legend.

The overall rate of growth of the city is determined exogenously, but the spatial allocation of new activity is determined by a series of ‘attractiveness’ functions calculated as cellular automaton rules (figure 6.3a). Attractiveness is based on semi-qualitative numerical weights representing the ‘push’ and ‘pull’ factors between individual land-use categories (e.g. new housing development will be attracted to nearby commerce and housing, but repelled by nearby industry or very close commerce). The weighting values are recorded as radial profiles that can be interpolated in order to create non-integral values for two-dimensional surfaces that are numerically as close as possible to the ruleset used by the one-dimensional simulations. From these, ‘attractiveness maps’ for the entire grid are calculated (figure 6.3a), a separate map being generated for each ‘active’ land-use category (i.e. each category that may grow in size during the simulation).

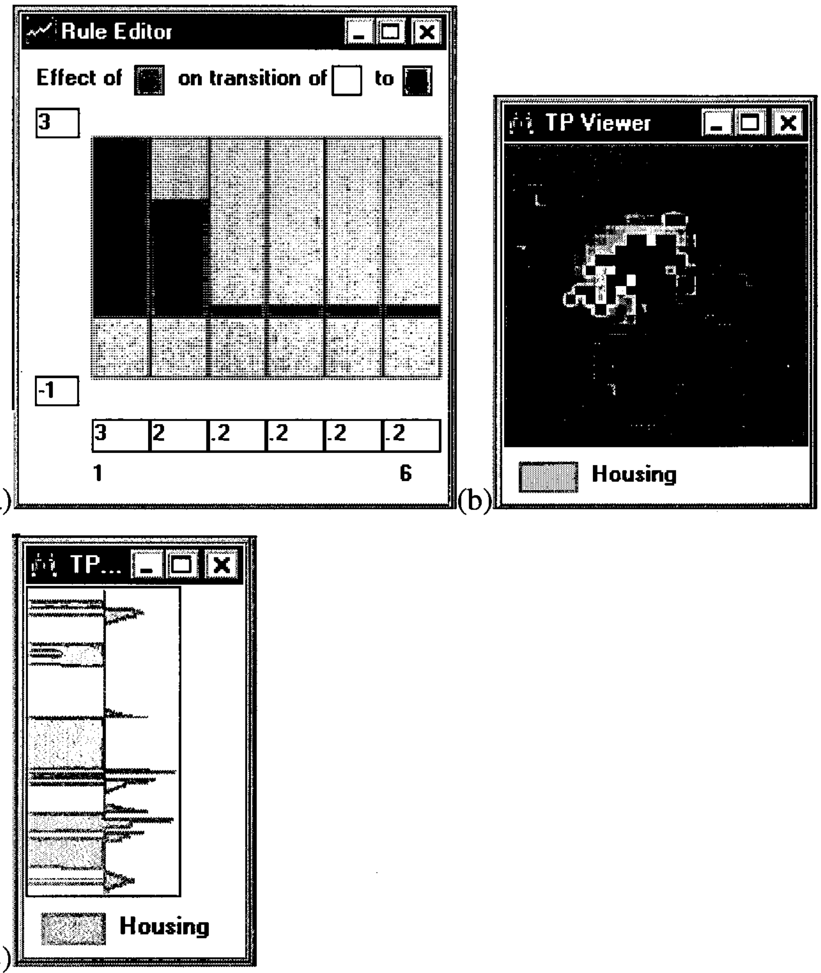


Figure 6.3: Calculation of attractiveness functions in CarteSim: (a) the user inputs attractiveness functions as radial terms representing 'push' and 'pull' factors. In the example given here, existing nearby housing sites will increase the attractiveness of a site for more housing, the attractiveness diminishing strongly with distance. (b) & (c) By summing these functions across the full grid, the attractiveness surfaces can be computed for each time step of the model. Changes in these surfaces will influence the future pattern of growth, and vice versa. Attractiveness surfaces are shown here for (b) 2D and (c) 1D models.

This representation of the determinants of urban growth is interesting, in that it uses numerical data to represent a range of complex information of varying degrees of 'hardness'. A lot of assumptions are embedded within the radial profiles, regarding individual preferences, physical limits to noise and pollutant diffusion, willingness to travel, and planning regulations, amongst other things. In the terms discussed in Chapter 2, the CarteSim model might be accused of falling within the category of implicit formal representation of some of these aspects, as it is not clear how individual changes, such as a new set of noise pollution laws, would be represented within the rule set. Alternatively, it can be argued that the model is not capable of separating out the various issues compounded within any single radial profile, and that they should be thought of as representations of 'the gut feeling' of the individual actors, who do not make these distinctions either in their daily routine.

There is certainly scope for further examination of the way in which the rulesets are represented. It would be technically possible to separate out radial profiles (e.g. in the case of the effect of nearby commerce on attractiveness to housing, separate out a 'convenience of having shops nearby' term from a 'disincentive due to noise and lack of calm' term when presenting the ruleset to the user, and combine them when running the simulation. Given that there are already twenty-four active rules in the simple four-category model, it is a moot point as to whether further disaggregation would increase or decrease the clarity of the model. If such an option were pursued, the design of an easy way of 'navigating' the rule set would be a key issue.

6.2.3 Cities at the Edge of Chaos

White and Engelen (1994) derive a number of interesting insights from their work, relating to the non-deterministic nature of city development. These link in to recent theories of self-organisation, fractal geometry and chaos/bifurcation theory. Chris Langton's 'edge of chaos' concept (Langton, 1986, 1990) is quoted as an important principle in understanding their model (and therefore real urban systems).

Langton derived his concept from a thorough examination of very simple cellular automata. Using a statistical metric, he grouped the wide range of dynamics exhibited by CA calculations into three basic groups. 'Frozen' systems exhibit little structural change, and tend to create static patterns. 'Chaotic' systems create continually unstable patterns in which no regular structure develops. Between these lie the 'edge of chaos' class, which support sufficient variability to allow the development of structure, and sufficient regularity to allow complicated patterns to persist over time. the dynamics of these 'edge' classes can be very complex, allowing for the representation of highly detailed patterns and forms, and development of phenomena such as reproduction and universal computation.

Langton's classification has been repeated in complex systems theory elsewhere (e.g. Kauffman, 1990) and called into question from an early stage (e.g. Mitchell et al, 1994). Nonetheless, the 'edge of chaos' has passed into complex system lore, and served to inspire speculation about a number of real systems e.g. organisational management (Shaw, 1997; Leach, 1996), cognitive psychology (Garson, 1996) and retailing dynamics (Krider & Weinberg, 1997). White & Engelen (1994) claim to have discovered a similar tripartite division of dynamics in their urban model, by controlling the amount of random perturbation introduced into the system. A medium range of randomness allows realistic urban patterns to emerge, supposedly exhibiting complex stochastic fractal properties.

White & Engelen's experiment have been repeated for both the linear and planar models, using the attractiveness parameters that they report in their paper. These values are merely 'common sense', as they state, "intuitively plausible transition rules generated realistic looking cities, and unreasonable rules did not." (p.1180)

A similar range of dynamic behaviour has been found in both cases. The results are not identical; notably the experiments reported here observe a single fractal structure for 'edge' patterns, rather than the bifractal pattern that White & Engelen identify, but this may be simply due to a difference in the method of measuring the fractal dimension. Further, the value for the randomisation parameter alpha at which the transition occurs is different for the linear and planar cases, but as alpha's absolute value has no intrinsic meaning, this is not a cause for concern.

Figure 6.4 illustrates typical model runs for the planar and linear models within the frozen, edge and chaotic regimes. Composite overlays of series of simulation runs from a single 'seed' pattern are shown in figure 6.5 to further illustrate the nature of the transition. The transition is relatively evident by eye, but has been supplemented with two statistical measures characterising the changes in the dataset as the parameter alpha is varied.

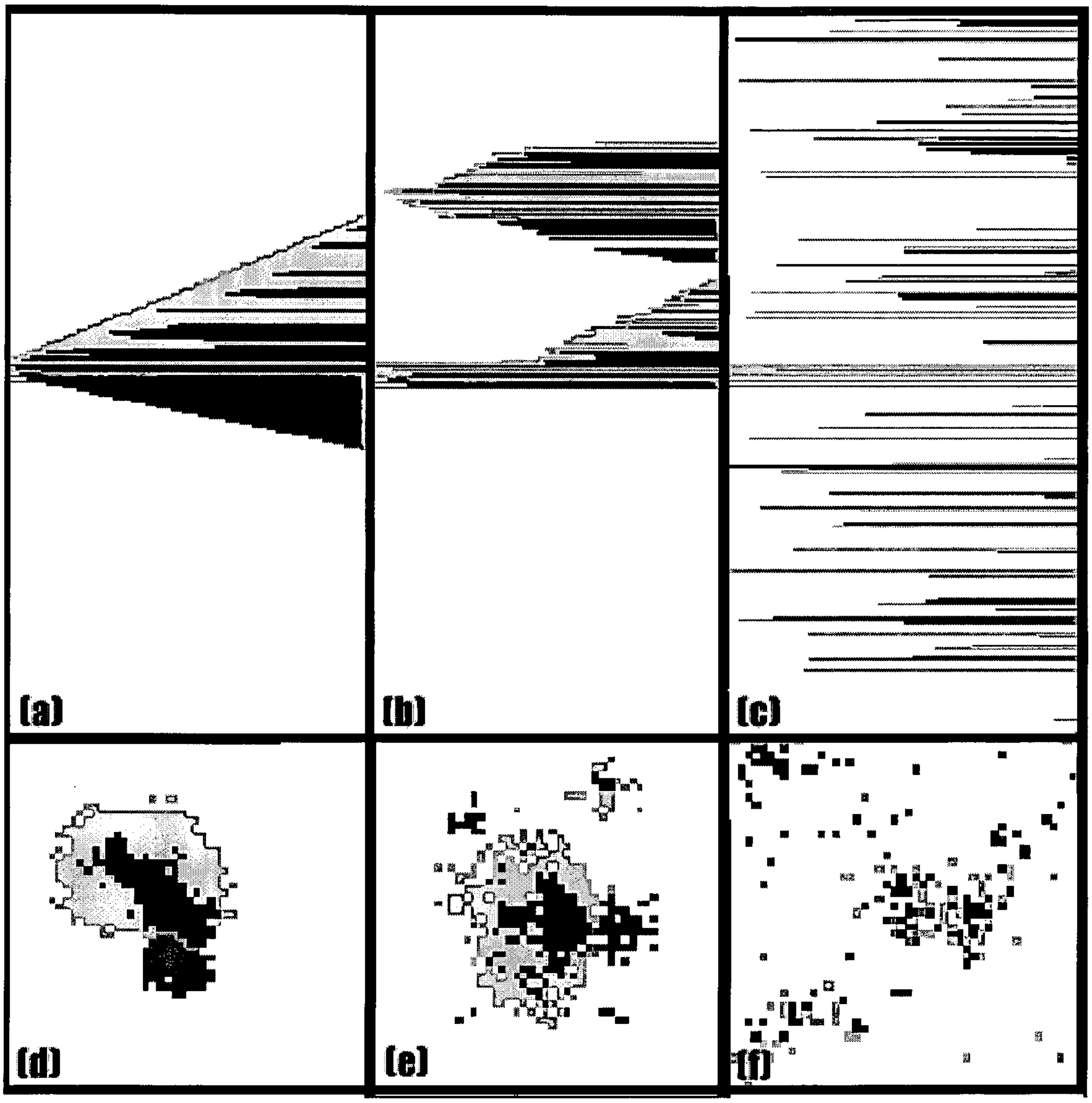


Figure 6.4 Appearance of 'frozen', 'chaotic' and 'edge' type patterns in (a)-(c) one-dimensional and (d)-(f) two-dimensional models, through variation of random parameter alpha. Values used in the examples shown here are (a) 0.2 (b) 0.8 (c) 5.0 (d) 0.5 (e) 2.5 (f) 6.0. The 'middle-range' values of random perturbations, (b) and (e), can be seen to produce structures that possess both the high-level structure of the 'frozen' systems (a) and (d), and the variety found in the 'chaotic' systems (c) and (f).

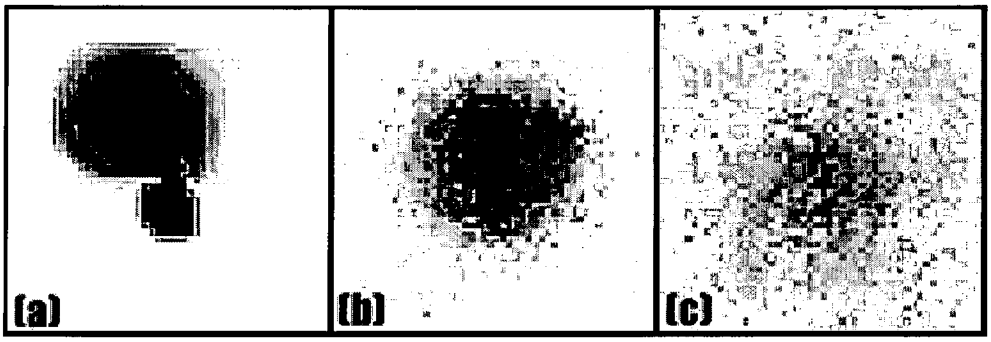


Figure 6.5: Composite overlay maps for the two-dimensional case, showing the transition from 'frozen' to 'chaotic' regimes. The overlay consists of a superimposition of the total urban coverage for twenty-four simulations developed from a common starting pattern, using different random number sequences. Dark areas indicate presence of some urban function in a high number of the cases examined. The sharpness of the edges indicates the diversity generated by the model - very little for the 'frozen' system (a), and a great deal for the 'chaotic' (c). Again, a combination of both properties can be discerned in the intermediate system (c); although a distinct pattern is evident, the edges are blurred, indicating a wide variation within this pattern.

The first measure used is intended to reflect the fractal dimension measured by White & Engelen. Very simply, the fractal dimension of an object is a measure of the extent to which it fills the space that it inhabits. Fractal dimensions of irregular objects can be computed as:

$$D = (\log(B) - c) / \log(r)$$

where D is the fractal dimension, B is the number of occupied cells in the object, c is a constant and r is the radius of the circle required to contain the object.

Thus a solid n-dimensional object will have a fractal dimension of n, and a sparser object a value less than n.

Rather than measuring the fractal dimension of individual objects within the dataset, the radial profile of the average occupancy of cells for the dataset as a whole (i.e. the fraction of cases in which an individual cell is occupied rather than vacant) has been measured, using an 'overlay' feature built into the modelling software (see figure 6.6). The radius is measured from the original centre of the object, rather than the 'centre of gravity' of the finished pattern.

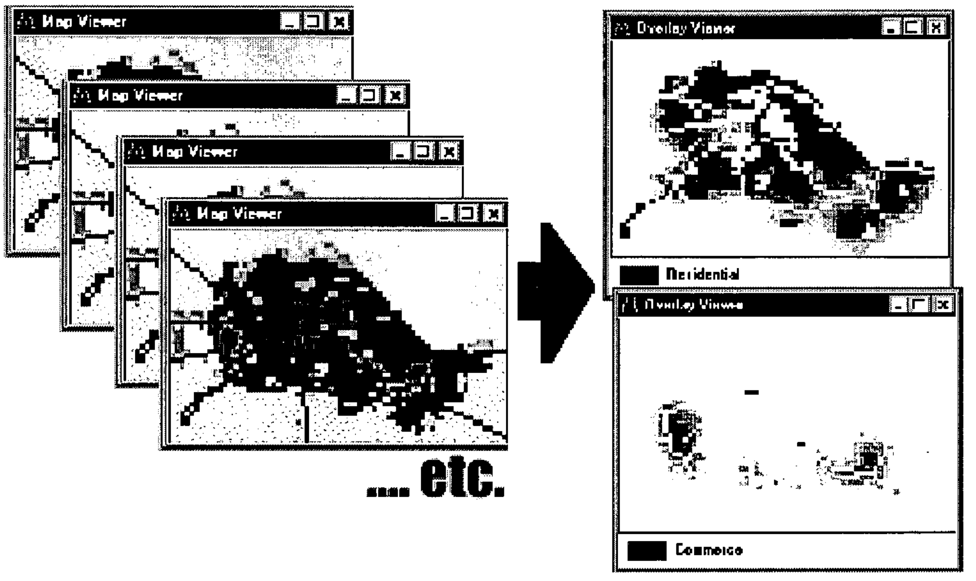
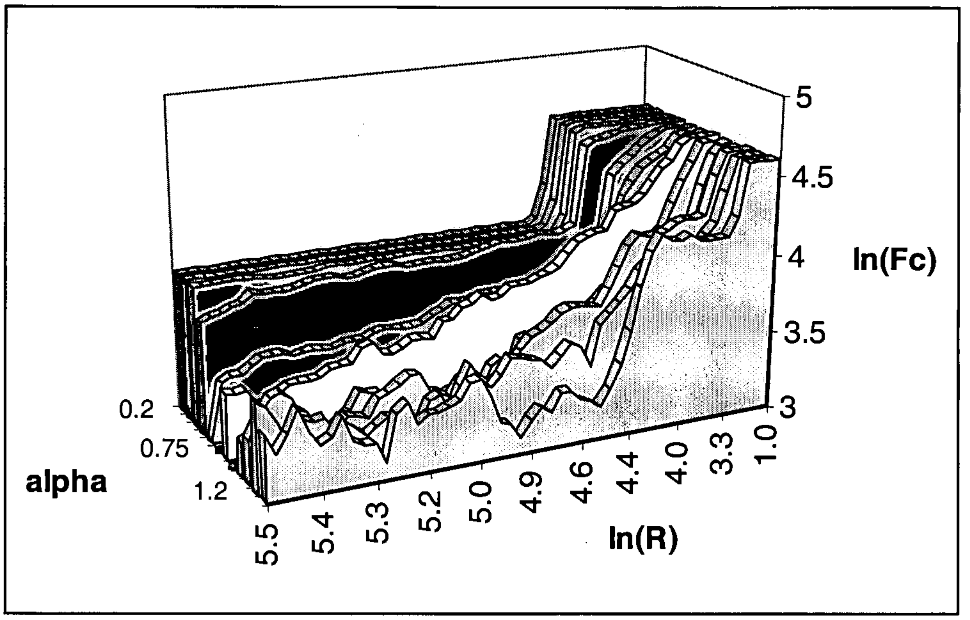


Figure 6.6: Overlay feature in CarteSim model: individual model runs illustrate only one possible outcome for urban pattern using a given ruleset. A better idea of the overall probability of future land-use can be obtained by combining a number of individual results generated from the same initial configuration into an 'overlay' which shows the most probable regions of growth. Graphically, four maps are depicted as being combined here; in practice, typically 20-40 maps would be used. The overlay generated by this process has as many maps as there are land-use categories; the illustration above shows probability distributions for housing (upper) and shopping mall (lower) categories from a pilot study of Edinburgh using the CarteSim software. Two areas along the ring-road can be seen to be favoured for future mall development (the ringroad and radial roads can be seen as disjoint white lines cutting through the residential overlay map in the top left window).

(a)



(b)

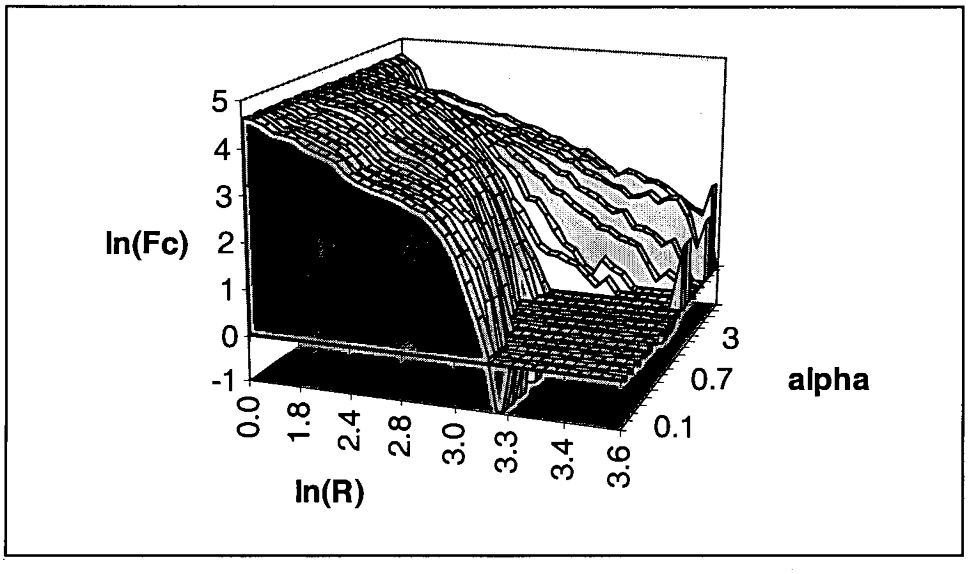
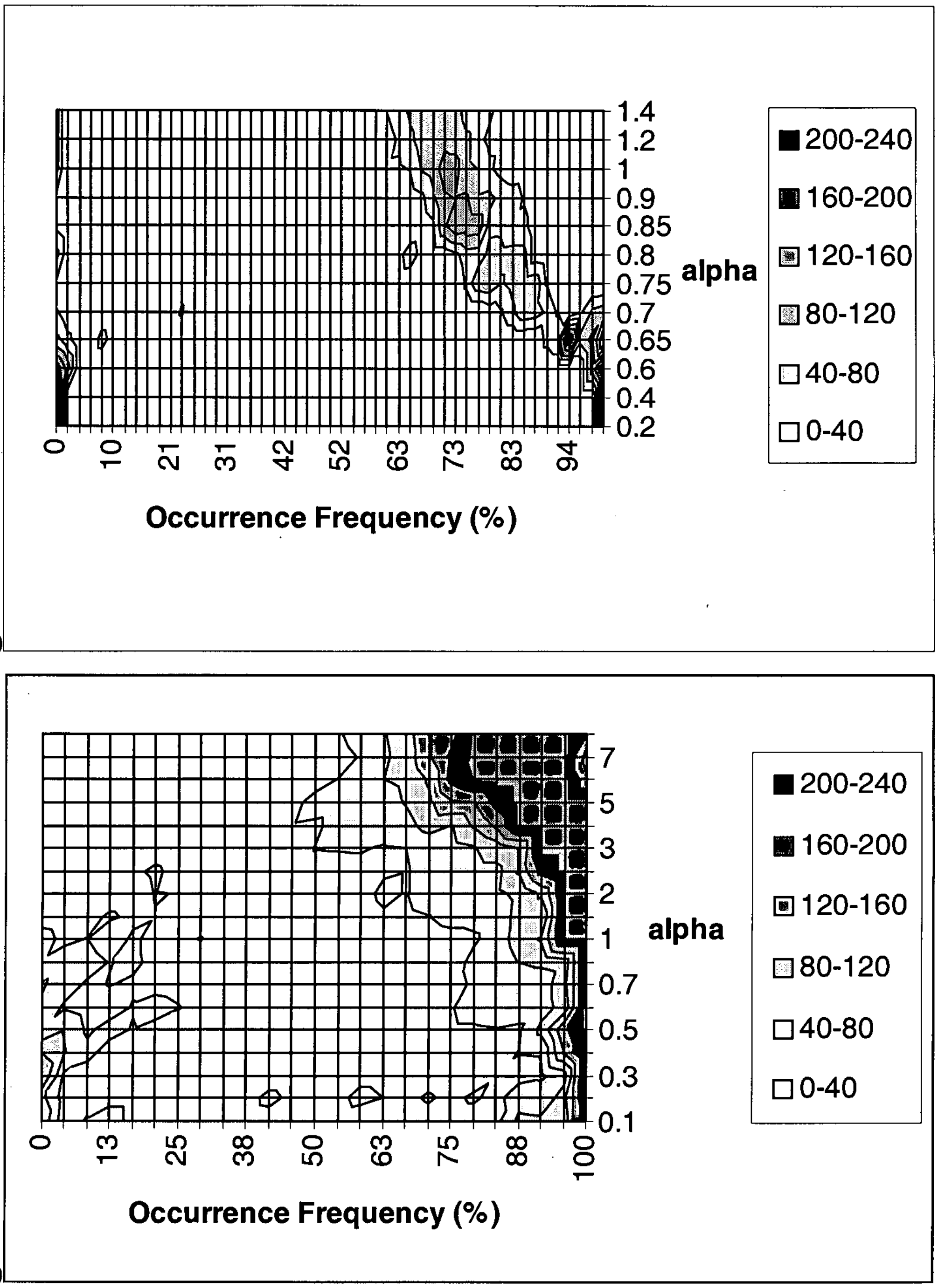


Figure 6.7 Evidence for 'edge of chaos' from radial probability distribution maps for (a) two-dimensional (b) one-dimensional models. Logarithmic radial probability is plotted versus ln(alpha) in both cases, so that gradient of slope for each alpha approximates to average fractal dimension D of the dataset. Although individual patterns of surfaces vary, note that both are characterised by (i) 'frozen' patterns at low values of alpha, with D experiencing a sudden change (ii) 'chaotic' patterns with ln(Fc) decaying irregularly as ln(R) increases (iii) in-between patterns in which ln(Fc) decays smoothly, corresponding to a constant value of D, which suggests fractal properties.

In both planar and linear data sets, a regular gradient (i.e. a radius-invariant fractal dimension) was obtained for a relatively narrow band of values of alpha. Lower values of alpha showed a sudden decrease in occupancy, indicating a sudden shift from mostly-filled to mostly-empty cells (i.e. a frozen regime with very low variability). Higher values of alpha generated radial occupancy values that fluctuated considerably (i.e. a chaotic regime). The critical value of alpha at which fractal patterns were observed was noticeably lower for the linear than the planar case. This is not surprising, as a cell in a linear grid has fewer neighbours around which nucleation can occur, and the change from frozen to chaotic regimes reflects a shift in the net balance between nucleating and randomising factors. Most importantly, the qualitative dynamics of the two grids are identical.

The second statistical measure that was applied was to construct a frequency histogram of the probability of occupancy maps assembled from each data set. This allowed an assessment of the fraction of cells that were always vacant, always used, and sometimes used for different values of alpha. The results of these analyses are shown in figure 6.8.
Both datasets show a similar transition pattern. At low values of alpha, most cells in the map lie at either very high or very low occupancy rates, indicating little variability between individual model runs. At high values of alpha, variability is high, and most cells are active in some cases, passive in others. in both cases, the 'edge of chaos' values of alpha identified from figure 2 lie just above the point at which the main 'ridge' of figure 3 begins to move away from the right-hand side of the diagram. (This corresponds to a move away from repetitive to variable patterns.)
The fact that both measures of the transition indicate the transition from frozen to chaotic regimes at similar values of alpha is encouraging, as it suggests that the transition is not merely an artefact of either statistical metric. Taken together, the results presented in figures 6.7 and 6.8 suggest that the linear implementation of the model is able to generate identical qualitative dynamics to the planar model, and therefore has the capacity to provide similar insights (at a lesser computational cost).

Reproduction of an 'edge-of-chaos' effect in the model cannot, of course, be taken as a guarantee that the model is replicating the dynamics of real urban regions. The question of why real urban form should follow such a narrow regime within the range of possibilities is a difficult one to address, and certainly outside the scope of this chapter. Within the science of complexity, some authors have attempted synthetic analyses of many complex systems (notably Prigogine & Stengers, 1980; Kauffmann, 1993) in an attempt to address such fundamental questions. Specifically within the discipline of urban studies, some attempts at empirical measures of urban form using fractal techniques (e.g. Dendrinos & Sonis, 1990; Frankhauser & Sadler, 1991) have suggested that real urban systems follow complex fractal patterns.



(a) (b)

Figure 6.8 Evidence for 'edge of chaos' from occurrence frequency histograms for (a) two-dimensional (b) one-dimensional models. For each value of alpha, the combined probability of occupancy by any 'active' land-use type (i.e. housing, industry and commerce) has been calculated for each cell on the map, and the frequency of occurrence of each probability for each value of alpha plotted as a density map. Again, the qualitative behaviour for both one- and two-dimensional

maps is similar; sharp definition into high and low occupancy sites at low alpha (corresponding to sharply defined boundaries), leading into a broader range of middle values at high alpha(corresponding to 'fuzzy' or irregular distribution patterns). In both cases, the transition occurs at values of alpha just below those identified as 'edge of chaos' values in figure 6.7.

6.2.4 Discussion

As noted already, a formal model can deliver insights into the character of the situation that it portrays, as well as hard numerical results. Given that the current generation of cellular city models are focussed on insight provision, these results have implications for the further development of these techniques, in addition to demonstrating the argument about realism in models. Even when the development of these models reaches the point of the specific case study, as it undoubtedly will do soon, the linear model may have a useful role to play.

For one thing, the linear model has the advantage of speed. For a relatively simple single-layer computation as presented here, this issue may be trivial, as computation complexity is simply of the order NxT, where N=number of cells on the grid and T=number of cells in the 'neighbourhood template'. Some potentially useful computations have much higher complexity, though; for example, the comprehensive calculation of cell-to-cell journey-times using a 'friction map' has complexity of order N2T, making the savings available from a linear approach more important.

In any case, there is another advantage to the linear representation; it is easier to see what is going on within the confines of a flat computer screen. Comparing the figures 6.4, in the planar case (6.4a-c), only the endpoint of each simulation has been represented, whereas the entire evolution of the linear systems (6.4d-f) is visible. During model development and testing, the ability to visualise the dynamics is important, and hence the ability to switch between linear and planar grids is highly useful. A full migration to the planar grid need not occur until the point of developing actual case studies, and even here, the ability to test modifications and newly added features in a linear mode could be valuable. Models illustrating variation in space and time necessarily generate a great deal of data, and the modeller is increasingly incapable of checking every result individually as model complexity increases. Assessment of overall pattern formation by eye provides a ready check on the model behaviour (coupled to statistical measures of datasets, of course).

If the move from toy model to case study is to be effective, the deep lessons learned from the toy model phase must be carried over. Specific numerical advice can only be useful if it is accompanied by the more general understanding as to what can and cannot be done. (One cannot, for example, use a cellular automaton model of this type to forecast and control city development in an engineering fashion, because the modelling methods rely on an understanding of the balance between structure and unpredictability).

Formal models of complex social systems are relevant in the insights that they provide, as well as the numerical outputs they give. This realisation militates against a striving for unnecessary realism in model design. Considering the case of cellular automaton models of urban form, a useful role is evident for models in which even the basic elements of realism, such as representation of space, are reduced. Further, the degree of realism in a model can be flexible, and changed as appropriate for the different stages of model design and implementation.

6.3 Representing Space & Time

As it stands, the CarteSim model offers a very rigid representation of space, as a fixed grid following Euclidean geometry. In itself, this is certainly a good representation of real, physical space, which does appear to possess these properties. The point to bear in mind though, when modelling a complex mix of physical and behavioural phenomena such as an urban system, is that different aspects in the model will require different things of the representation of space that is chosen. As with the embodied energy numeraire in ECCO, what has been chosen as a good representation for one purpose may require modification when applied in other contexts.

The functions used to compute the 'attractiveness' maps are certainly not rigid physical definitions, and these are defined using spatial distance as the primary axis purely because that is what is offered by the rest of the model structure. The interactions represented here are varied in nature, and arguably some do not occur within a simple Euclidean space.

The most obvious distortion of the simple distance metric comes through variations in transport. Transportation systems are unarguably an important determinant of urban form; Marchetti (1994) develops a persuasive model of urban size based almost solely upon transportation speed.

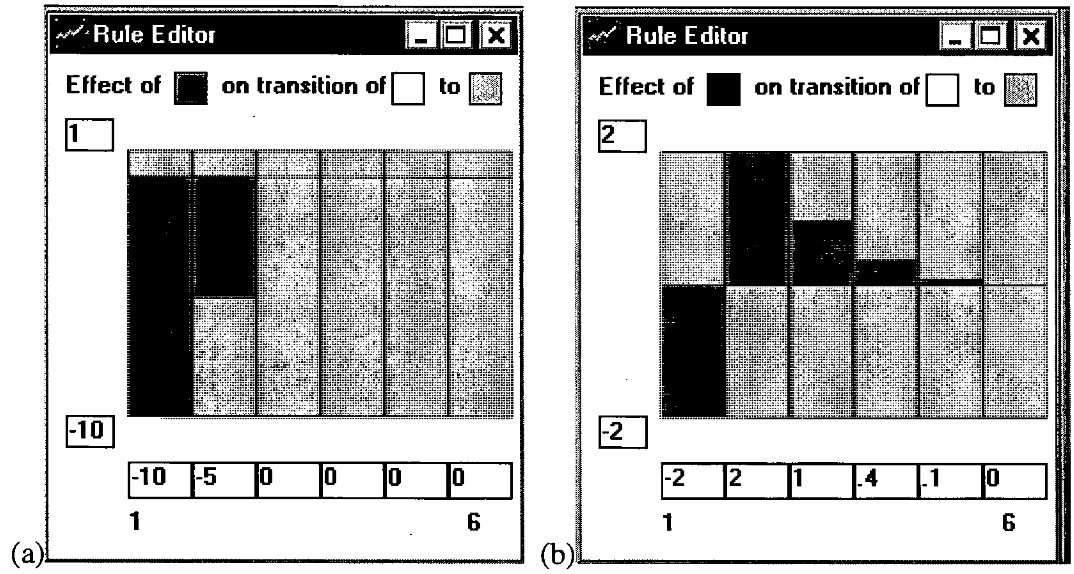


Figure 6.9: Attractiveness functions for transitions from vacant to housing category. (a) effect of nearby industrial sites (b) effect of nearby commercial sites.

Consider the case of the effect of nearby industry and commerce on the prospects for building housing on vacant land. The rule-sets from the simple four-category model are shown below in figure 6.9.

The effect of nearby industrial sites (figure 6.9a) is a simple 'push' factor - industrial sites are noisy, smelly, potentially toxic and unsightly. Here, spatial distance obviously is the guiding factor, as noise, smells, toxins, etc. propagate through physical space.

The effect of commercial sites (figure 6.9b) is more of a mixture, though. Again, at very close proximity, there is a 'push' factor, again reflecting too much noise, traffic, etc. (and possibly also interpretable as the effect of pushing up land prices near busy commercial streets). The 'pull' factor that follows on over the 200-1000m radius, though, is primarily a reflection of the desirability of having access to amenities. In other words, space is being used as a surrogate for journey time. This ignores local differences in the journey speed due to transport infrastructure, congestion, public transport routes, the 'safety level' of certain streets, etc.

A full 'correction' for these factors would require a large amount of additional modelling. In the case of journey time, a full map would be required for each point on the grid in order to represent all distances between any two combinations of points. A more parsimonious structure, in terms of data at least, would be to calculate a separate neighbourhood template transform for each cell, relating spatial and temporal distance. This would still entail a large number of minimum-distance or 'friction map' calculations, slowing down the simulation speed a great deal.

Table 6.1: Changes made to attractiveness functions under 'fast' and 'slow' transport models. Transition notation used here is as follows: 'A - B: C' denotes the effect of land-use class C on the attractiveness of cell currently of type A for transition to type B. H=housing, V=vacant, I=industry, C=commerce

	Distance Band (no. cell-widths equivalent)									
Transition	1	2	3	4	5	6	7	8	9	10
Fast Transport Speed RuleSet										
V - H: C	-2	-0.5	0.5	2	1.6	1	0.6	0.4	0.2	0.1
V - I: I	3	2.4	2	1	0.2	0.2	0.2	0.2	0.2	0.2
V - C: H	4	4	3	3	2	2	1.5	1.5	1	1
V - C: C	25	25	25	12	-1	-1	-1	-1	-1	-1
H - I: I	2	2	2	2	0	0	0	0	0	0
H - I: C	1	1	1	1	0	0	0	0	0	0
H - C: H	4	4	3	3	2	2	1.5	1.5	1	1
H - C: I	1	1	1	1	0	0	0	0	0	0
H - C: C	25	25	25	12	-2	-2	-2	-2	-2	-2
I - C: I	-2	-2	-2	-2	0	0	0	0	0	0
I - C: C	25	25	25	12	-2	-2	-2	-2	-2	-2
Slow Transport Speed Ruleset										
V - H: C	-2	2	1	0	0	0	0	0	0	0
V - I: I	3	0.2	0.2	0	0	0	0	0	0	0
V - C: H	4	2	1	0	0	0	0	0	0	0
V - C: C	25	-1	-1	0	0	0	0	0	0	0
H - I: I	2	0	0	0	0	0	0	0	0	0
H - I: C	1	0	0	0	0	0	0	0	0	0
H - C: H	4	2	1	0	0	0	0	0	0	0
H - C: I	1	0	0	0	0	0	0	0	0	0
H - C: C	25	-2	-2	0	0	0	0	0	0	0
I - C: I	-2	0	0	0	0	0	0	0	0	0
I - C: C	25	-2	-2	0	0	0	0	0	0	0

A much simpler solution has been adopted here, which retains the Euclidean representation of space, but allows for adjustments based on predominant transport modes. Although this structure cannot address factors such as local congestion of traffic, it does allow an examination of the overall effect of prevailing transport speeds upon urban form.

The only change made here is to categorise each attractiveness function as being primarily 'spatial' or primarily 'temporal' in nature, along the lines discussed already (see Table 6.1 for details). The dominant transport speed can then be altered, and the radius of the 'temporal' functions only extended or shortened by the ratio between default and revised transport speed. The effects of this parameter upon model behaviour are significant, as illustrated in Figures 6.10 and 6.11 below.

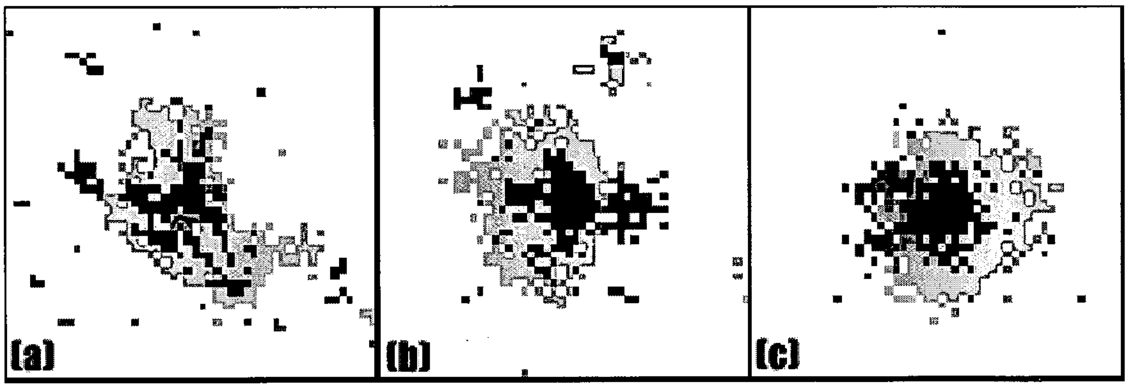


Figure 6.10: Typical examples of patterns generated under (a) reduced transport speed ruleset (b) standard ruleset (c) fast transport ruleset. Fast transport tends to result in a more regular concentric pattern, as most cells have access to the single commercial centre. Under a slow transport regime, either linear centres develop, as here, or multiple nuclei form.

Figure 6.9 shows typical results from the 'fast' and 'slow' transport models, generated using identical seeds. The structures developed are considerably different, with a clear relationship between transport speed and diversity being established. Fast transport allows for much greater centralisation of the commercial sector into a single Central Business District, within a ring of outlying suburbs. Outlying dormitory villages do not appear in the model here, but these simulation runs are simplistic in that the entire urban area has developed under a rapid transport regime. In reality, transport requirements will have altered over time, and dormitory villages can arguably be seen as historical artefacts from slower transport regimes being adapted to more mobile circumstances.

In contrast, development under the slow transport model produces disaggregated patterns with multiple local nuclei, as the sphere of influence of each individual commercial zone is much more strictly curtailed.

Figure 6.11 below illustrates that the transport speed not only affects the actual urban form, but also its degree of regularity. Overlay maps for all three transport models (slow, regular and fast) show that there is much less variation within the faster transport regime.

In extremis, the eventual land-use allocation under a slow transport model hardly seems to be predictable at all.

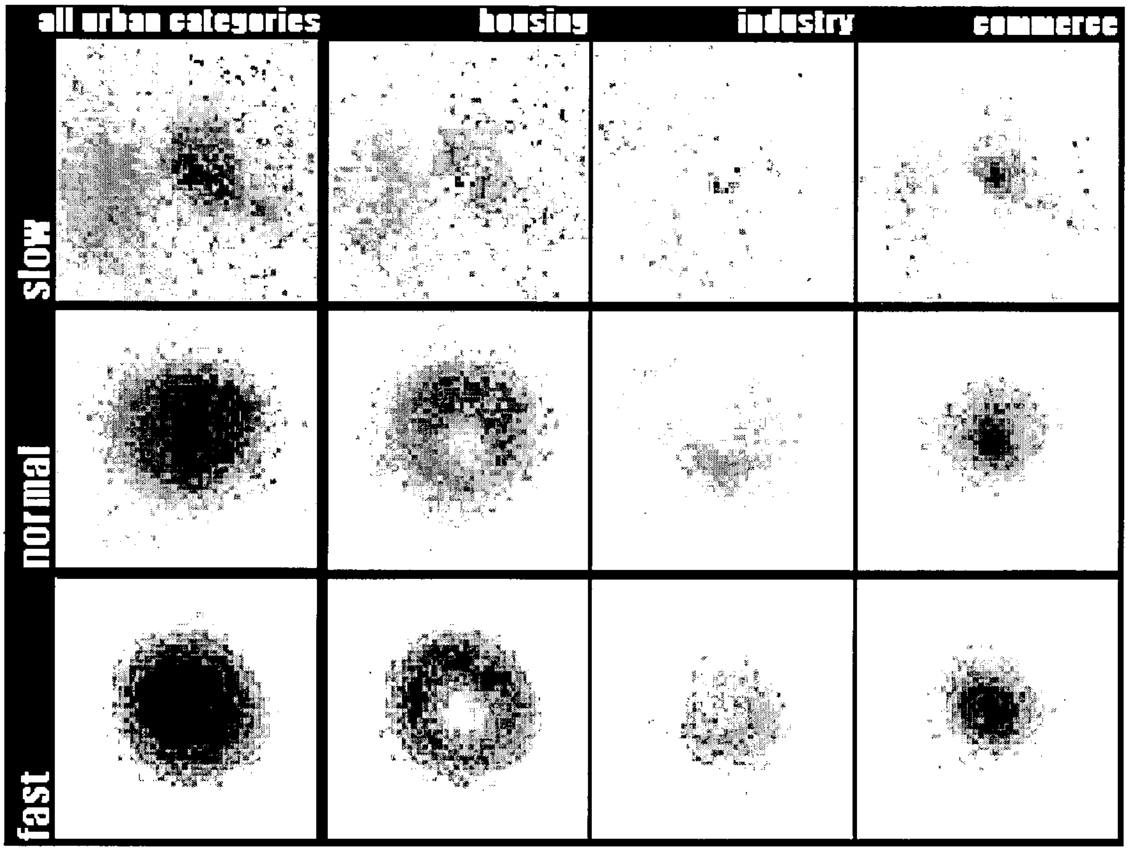


Figure 6.11: Effects of transport speed on regularity and predictability of urban form. Not only is the actual morphology of the city altered, but, under a slow transport system, the predictability of the eventual land-use pattern is much lower. This is true not only for the urban morphology as a whole, but for the internal structure. Overlay patterns for each of the three land-use classes have been generated here; notably, the slow transport system lacks the focussed central business district and 'southerly' industrial zone evident in the 'normal' and fast transport models.

6.4 Conclusions

Having presented the CarteSim model of urban land-use patterns, two criticisms have been raised regarding its 'naive' representation of space, and both have proved to reveal interesting facets both of this model, and of the modelling process in general. In addition, the results demonstrated here provide a practical illustration of the complex systems dynamics discussed in chapter 2, and returned to in the remains of this thesis.

The first issue, of the number of dimensions used by the model, raises the issue of seeking realism in models. Where a one-dimensional model captures the same dynamic range as a two-dimensional one, there is a clear question as to the advantage of using the two-dimensional model at all. The answer provided here can be extended to the general case as suggesting that the desirability of realism is provisional. In some cases, the added realism is worth it, in others not, depending upon the purpose of the model. Where possible, as with CarteSim, the development of a flexible structure that can increase or decrease the model's level of realism with minimal reprogramming seems like a promising solution to the issue.

The second issue of space and time is similar in many ways to the issues surrounding choice of numeraire, discussed regarding the 'volume-corrected' numeraire in the ECCO model (Chapter 4). The original representation, here of space, is not overturned by the insights developed, but is seen to have limited scope of application. The solution adopted here of implementing a transport-based conversion factor is entirely provisional, and, although it fails to address a number of the objections raised by the issue, does produce an interesting and plausible new set of dynamics for the model. Any model of a complex human policy issue is necessarily a set of simplified and provisional rules anyway - the important thing to note when modifying the structure is not to achieve a watertight solution, but to be aware of the effect on the model's scope and limitations of adding a new provisional structure.

Chapter 7 Interdisciplinarity & Physical Capital

The purpose of this chapter is simply to summarise the case studies presented in part 2, and to bring together the threads of the argument regarding the use of policy-relevant models discussed in Chapter 1. By discussing the two models of physical capital formation together, it is intended to bring out the contradictions between them at the formal level, and so encourage a broader understanding through reference back to the limits of each model's representation of reality.

7.1 Physical Capital and other forms of Capital

The concept of capital in its broadest sense is worth exploring briefly at this point, because the concept is so central to the debate about economic growth. A number of different arguments rely on the notion of capital; the 'biophysical' explanation that ECCO offers on a narrowly-defined 'natural capital', technology-driven arguments on a notion of accumulation of knowledge and expertise sometimes referred to as 'human capital'.

The various ideas of capital presented in different theories do not overlap closely, and can be distinguished in more than one way. Subject matter can be used, usually made explicit by a qualifying adjective; for example:

- physical capital limits itself only to physical structures
- natural capital refers only to that which comes from nature
- human-made capital refers only to humanly-produced capital
- human capital refers to 'invisible' resources embodied in human knowledge, culture or education

These classifications alone do not fully explain the way in which capital is represented. Taking the example of natural capital, the definition offered by the ECCO model is extremely narrow compared with that discussed by, for example, Vadjnal & O'Connor (1994) and Funtowicz & Ravetz (1996). The ECCO model takes only depleteable energy resources as it's area of interest, for the very specific purpose of calculating the effort involved in maintaining another type of capital. Vadjnal & O'Connor, on the other hand, are concerned with the much broader qualitative issues of the overall benefits that humanity derives from nature, and both they and Funtowicz & Ravetz are at least partly concerned with the futility of attempting a comprehensive quantification. Within a middle range, authors such as Pearce (1984) are concerned with a quantification using money terms in which a range of physical, preference and other factors are compounded.

This range of approaches to capital indicates a second difference in treatment. At the one extreme, the ECCO model is adopting a very narrow approach in order to deliver a reliable numerical method of accounting, and does so at the expense of losing a range of broader considerations regarding the idea of capital as that which delivers returns when accumulated. (This loss is incurred by the accounting procedure, not necessarily by the model as a whole. By exercising a broad reading of the assumptions made in defining natural capital, 'lost' aspects can be brought back into the discussion where appropriate.)

At the other extreme, Vadjnal & O'Connor and Funtowicz & Ravetz are attempting a very broad reading of natural capital, exploring the limits of the concept. This can raise interesting questions which can usefully challenge other, narrower, approaches, but cannot in themselves move beyond the discursive stage.

It can be argued that both extreme positions are more tenable than the middle ground. There is an inevitable tension between seeking to measure accurately and, *at the same time*, retain the full breadth of the original concept, leading to a tendency to confuse the two aims in the implementation.

This is particularly apparent in discussions involving the commensuration between different types of capital e.g. the extent to which human capital can substitute for physical capital. In the broad sense, the idea of a substitution makes sense - although one cannot dispense with physical capital in an economy, investing in education does offer a viable alternative means of growth to investing in manufacturing, in the longer run at least - but a quantified comparison between 'stocks' of production capacity and knowledge (e.g. Foster & Rosenzweig, 1996; Tranman et al., 1995) makes the discussion too specific for the merely conceptual comparison to hold.

Both the ECCO and CarteSim models represent physical capital in quite a narrow sense, albeit quite differently. The differences will be brought out in the subsequent discussion of the models, but this basic similarity should be borne in mind when returning to the growth debate, as much of the technology-driven argument is conducted in a much broader way (partly owing to a lack of 'hard' data when measuring human capital stocks, for example, and partly due to the difference in intellectual tradition discussed in Chapter 3).

7.2 Comparison of Models

The two simulation models described in part 2, ECCO and CarteSim, are considerably different in scope, purpose and style. Nonetheless, both deal with aspects of the human-made physical infrastructure, and there is sufficient overlap for each to enrich itself by engaging in a dialogue with the other. This can be done on a number of levels, embracing both formal methods and content.

7.2.1 Formal Methods

Both models employ dynamic simulation techniques of some sort. ECCO is a classical System Dynamics model, (inasmuch as it is implemented in a conventional modelling package such as Professional Dynamo or PowerSim - it is probably more tightly bound by feedback loops than the majority of system dynamics models). CarteSim is a Complex Adaptive Systems model.

The relationship between System Dynamics and Complex Adaptive Systems has already been discussed in Chapter 2. To summarise again briefly, Complex Systems developed from System Dynamics and Operational Research, and offer a fundamentally different viewpoint because of their unpredictable and non-mechanistic behaviour (with activities similar to learning by trial and error being possible).

Simply at the formal level, then, the ECCO model has something to learn from the CarteSim model, through Complex Systems' critique of System Dynamics. This need not entail a re-implementation of ECCO as a Complex Systems model, as the critique extends beyond the purely formal level to address the problems inherent in an aggregated, averaged, 'engineering' or optimising approach to social science issues.

At the practical level of the rhetorical arena in which ECCO and other policy models operate, this is important, not least because many of the ideas of the 'technological optimist' argument discussed in Chapter 4 draw strength from Complex Systems and co-evolutionary approaches. This is not to say that Complex Systems theory necessarily supports technological optimism - many of the technologist arguments are arguably based on mis-readings of complex systems - but where a valid counter-argument can be constructed by listening to the critique offered (as in the 'rebound effect' case studies of Chapter 5), there are gains to be made.

7.2.2 Contents of the Models

Both CarteSim and ECCO are primarily models of physical human-made infrastructure, although both go beyond this subject to incorporate behavioural/social elements of the systems that they study. The aspects of the infrastructure that each represents are quite different, however. The CarteSim model represents only the spatial occupancy of the infrastructure; the only physical law that is evidently represented is that two physical bodies cannot occupy the same place at the same time. ECCO incorporates far more sophisticated physical concepts, such as the transience of physical structures and the thermodynamics of transition processes. In doing so, ECCO achieves a major advantage in being able to endogenously determine the system growth rate, whereas CarteSim, in its present form, is restricted to accepting growth rates as exogenous data. (Arguably, CarteSim does not simulate progress through time - it certainly simulates change, but there is no explicit measure of the length of a timestep, or restriction on the rate at which change can occur. From the formal specification of the model alone, it is unclear whether a set of changes are occurring over decades or weeks.)

Through a straightforward transfer of content, CarteSim could incorporate ideas from Natural Capital Accounting in order to address the thermodynamic consequences of urban form, in terms of city 'metabolism', transport infrastructure requirements, urban air pollution, and so on. A hybrid of the two models' content could alternatively be seen as a 'spatial ECCO model', incorporating information on the location of HMC stocks such as power plants, industrial zones, etc, although such a disaggregation would probably be of most benefit to the transport and agricultural sectors of the model.

7.2.3 Policy Implications

The CarteSim model is developed primarily as a tool for urban planners, and for other parties interested in urban issues who wish to inform themselves of the possible consequences of their assumptions or positions. Beyond addressing spatial interaction, the subject matter of the model is potentially broad, as it could be used to address communities within urban areas, entire urban systems, or even regions in which urban areas are embedded. The classification of space, although limited primarily to physical land-use patterns and structures in the examples provided here, could easily extend beyond the representation of physical capital to cover aspects such as population density, income distribution or pollution patterns via additional grids similar to the attractiveness maps.

Policy makers involved in housing issues or roads policy, say, may use the models as aids to planning for capital stock development. This would entail use of the model in a straightforward mapping of actual areas, with an effort to capture the specific characteristics of the real region.

As was argued in Chapter 6, this is certainly not the only use to which the model can be put, and perhaps not the best one. Much more general information can be distilled from the model, regarding the unpredictable nature of changes resulting from policies, even those which might be thought to be quite narrow in scope.

Similarly, ECCO's focus on Human-Made Capital should be seen as a means to address a number of important policy areas in a range of sectors, and, more importantly, to link them together. And, if the content is partly a means, the form, here system dynamics, can also be seen to be relevant to the policy maker. ECCO is not useful simply because it determines the effect of policies on growth, but because this allows it to represent a wide range of inter-sectoral actions, and so treat the system as a genuine whole. This type of holism, in which the gaps between the conventional areas of inquiry (e.g. the individual sectors) are given primacy, is considerably 'more holistic' than a purely discursive approach in which each sector is given an equal hearing of its own story. A discursive element is, of course, an essential part of interpreting any model, as discussed in Chapter 1, but can only benefit from a rigorous approach when combined with a critically-applied formal technique.

7.2.4 Summary

There are a number of ways forward, then, in adopting the broad interdisciplinary approach of Chapter 1 and generating 'hybrid' models from ECCO and CarteSim. The range of options identified above is:

1. applying Energy Analysis to CarteSim to give a model of Urban physical 'metabolism'
2. applying cellular automaton techniques to introduce a spatial element into ECCO
3. applying Natural Capital Accounting to CarteSim to give an urban growth model
4. introducing Complex Adaptive Systems theory into the ECCO model, e.g. disaggregating many of the monolithic sectoral variables into populations of interdependent actors.

Options one and two are more or less straightforward merging of content, without either model being required to reassess its own assumptions. As such, they could be characterised as closer to the 'narrow interdisciplinary' approach, although in their own rights both models are rather 'broad'.

Option three requires more thought in an implementation, as the Natural Capital Accounting theory cannot be directly applied to a system as open as a single urban area. (In national ECCO models, international trade already requires much additional modelling; for a city system this would be much greater.)

Option four is perhaps the most interesting combination, and this is the one explored and implemented in the final section of this thesis, as the IPSO model. As will be demonstrated, a combination of Complex Adaptive Systems theory and Natural Capital Accounting requires far more than a straightforward disaggregation of the ECCO model, and opens up a number of new avenues of inquiry, and inroads into the debate regarding economic growth.

Chapter 8 A Model of Industrial Ecology

So far, two simulation models, ECCO & CarteSim have been presented, and case studies using each have been taken to illustrate several points relating to the rhetorical or 'broad' interdisciplinary use of computer models as discussed in Part 1. The key ingredient to broad interdisciplinarity was, however, the establishment of dialogue between contradictory modelling approaches in an effort to enrich the insights available from the pool of available techniques. This dialogue was established in Chapter 7, and a number of possibilities for combining parts of ECCO and CarteSim in order to develop new methods were advanced. In this Chapter, the IPSO model, which is an implementation of one of those possibilities, shall be discussed, and the practical benefits of the broad interdisciplinary method demonstrated.

In terms of the range of issues that it encompasses, and the dynamics that it offers, IPSO is more complicated than either ECCO or CarteSim. A case study of an IPSO model based on the OzEcco dataset shows how the model can be used both as a static and a dynamic tool. As a static tool, it can be used to assess the degree of interdependence between economic activities. As a dynamic tool, it can give insights into how these interdependencies evolve over time, and how relieving a 'bottleneck' in one area can affect the development of bottlenecks elsewhere. IPSO was designed as a dynamic tool - the insights coming out of the ECCO case studies in Chapters 4 & 5 strongly suggest that a dynamic simulation is necessary in order to get a realistic representation of the effects of technlogical change. Some static analyses are presented first simply as an introduction to the model's structure and capabilities.

ECCO could incorporate technological change processes only as exogenous data. IPSO has been designed to allow much greater internalisation of the technological dynamics of the system, by parameterising the technologies both at a lower level, and in a way that is more transparent (see the discussion of modelling water supply systems in Section 2.3.5). Some factors, such as the rate of technological change, cannot be internalised (nor would it be appropriate to do so here), but a greater degree of insight is obtainable as a result. Complete closure of the process within the formal model is not the aim here.

Opening up the structure of the technological innovation model presents many additional degrees of freedom, and the model is sensitive to some of these. The case studies presented here examine a number of ways of dealing with these degrees of freedom (mainly relating to ways of allocating reinvestment in new processes so as to minimise dynamic bottlenecks), and examine the way in which different sets of algorithms affect the model behaviour.

8.1 Industrial Ecology & Process-Chain Analysis

The term 'Industrial Ecology' refers to an attempt to understand economic processes by comparing them to wildlife ecology systems, and adapting formal techniques such as food web analysis to the interactions between industrial processes. The Industrial Ecology literature covers a broad range taking in material balances (Ayres, 1994), Process Chain analysis (e.g. Simon, 1995), Energy Input-Output Analysis (Bullard & Herendeen, 1973; Peet, 1993; Wilting, 1996), Complex Adaptive Systems theory (Allen, 1994a, 1994b), and ranges from the study of individual processes (Winiwarter, 1995) and buildings (Somervell & Talbot, 1991) to national economies (Wilting, ibid.).

At the policy level, the phrase has connotations of 'greening industry' through a reduction in waste flows. This is achieved primarily not by making processes more efficient (c.f. the 'Factor Four' approach of von Weizsacker et. al, (1997) for example), but by linking up processes so that they consume one another's by-products rather than raw materials. The comparisons with natural systems are apt here, as most natural systems show a high degree of closure regarding key material products.

ECCO can be considered to be an Industrial Ecological model, in that it represents interactions between a range of processes following an input-output style characterisation. In ECCO, the industrial/manufacturing sector itself is highly aggregated, being divided into at most two or three sectors (Essling et al., 1997), and usually represented as a single sector. The treatment of each sector as an aggregate capital stock parallels a style of population dynamics modelling that has recently been superseded by higher resolution techniques in which individuals within a population are modelled, in an attempt to understand the effect of diversity on the system as a whole (e.g. Holling, 1994; Nowak et al., 1994a, 1994b).

At a formal level, the problem inherent in an aggregation process can be seen to be a part of the critique of 'mechanistic' analysis offered by complex systems theory. The arguments relating to this point have been adequately treated in Chapter 2.

At the content level, the limitations of the ECCO approach are two-fold. At one level, it has a limited ability to deal with the effects of innovation, and the introduction of new technologies.

For sure, the case studies in Chapter 5 showed that it can inform the technology debate to a great extent, but this was only in the case of presenting scenarios where technology changes were exogenously imposed, and, further, these changes did not affect the overall structure of the inter-sectoral relationships, only the strengths of individual interactions. As has been stated elsewhere, there is nothing wrong with applying a provisional solution - all solutions are provisional to some extent - but one must be aware of the limitations that that provisionality imposes. Within the scope of the technology debate, it can be seen to be worthwhile to try to look beyond the system dynamics structure in order to understand the processes of reorganisation that innovation gives rise to.

A second objection is that ECCO's aggregation masks diversity, and creates a rather faceless representation within which sight of reality can too easily be lost. Nicholson-Lord's (1997) description of mainstream economics can also serve to illuminate the shortcomings of ECCO here:

> *"In the real world, the 'economy' does not exist. There are houses, roads, offices, factories, cities and countryside. There are people who do work, both paid and unpaid. There are sets of relationships - family, community, society. There are also relationships that are to do with earning a living." (p.24)*

Practitioners of ECCO would not deny this description of the real economy - the aggregation process is made as a simplifying assumption, on the understanding that the microscopic diversity being masked does not affect long-term trajectories. Some insights stemming from Complex Adaptive Systems theory suggest that this is not always the case, and that an exploration of re-modelling ECCO with some of the diversity re-introduced is worth the effort.

Process chain analysis (e.g. Simon, 1995) offers an alternative way of modelling Industrial Ecologies that can allow for a greater breakdown of the aggregated sectors into individual units. The basic precepts are similar enough to input-output analysis to provide a ready frame of reference when translating the ideas of Natural Capital Accounting into a complex systems model.

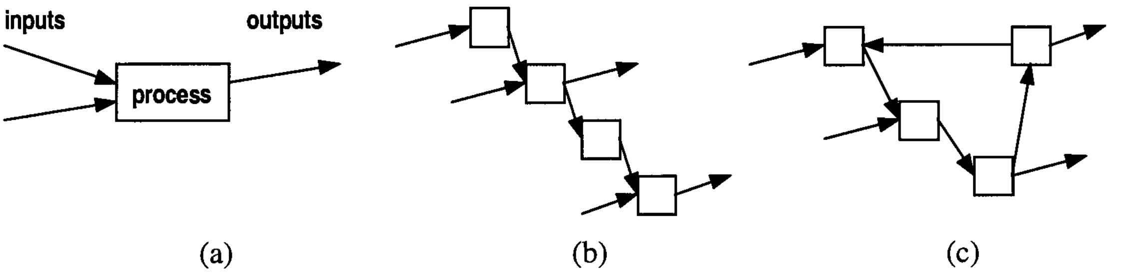


Figure 8.1: Schematic representation of main elements in process chain analysis. (a) a process is defined as a collection of inputs and outputs transformed (consumed or produced) by passage through the process. (b) Process chains and (c) loops form the higher-level units of analysis. Where a series of processes are connected by shared inputs/outputs, changes 'upstream' in a chain will affect all 'downstream' processes. Within a process loop, each process is both up- and downstream of every other one. Within a complicated network, each process may be involved in more than one chain or loop.

The basic unit of analysis is the process, which is, at its simplest, defined as a collection of inputs and a collection of outputs. For a dynamic analysis, a rate of transformation must also be assigned, either as an exogenous term, or by reference to a 'size' of the process. The analysis of the process then rests upon the construction of a 'web' of connections, within which process chains and loops can be identified (Figure 8.1). These higher-level constructs serve as a means of understanding the network of inter-dependencies within the system.

The chain and loop approach works best where each process only produces one type of output, and no two types of process produce the same output (i.e. there is no possibility of technological substitution). In these cases, chains and loops can be defined quite unambiguously, whereas in other cases, characterisation of dependencies in these terms may be ambiguous. (A process p_1 that requires supply of input i, where p_2 and p_3 both produce i, cannot be said to be definitely downstream of p_2 or p_3, but only of one of the two. If either were removed, it could rely on the other, and so the dependency is not absolute.

The restrictions for clear process chain analysis are those followed in input-output analysis. Through examination of a make matrix, one can identify the extent to which the restrictions are justified in a particular case; the sectorisation of the tables is usually chosen so that over 90% of each sector's characteristic product is produced by that sector (HMSO, 1988).

As with many formal restrictions, these are adopted in input-output analysis primarily for tractability's sake; a system of producers with heterogeneous output could not be represented in matrix form. Some authors have noted the importance of going beyond this representation in order to capture the behaviour of a system that generates potentially useable waste products (e.g. Faber, Manstetten & Proops, 1996). Certainly, the dynamics of freely interacting networks of processes can demonstrate unusual dynamics, as illustrated by Kauffmann's 'bootstrapping' models of auto-catalytic systems, which simulate the spontaneous emergence of structured chemicals from a random 'primordial soup' (Kauffman, 1990).

8.2 The Static & Dynamic IPSO Model

In order to assess the limitations of the single-output approach, a generic process-networking model has been developed, in which the analysis of network properties can be made without explicitly pre-programming the chains and loops in the system. The system is characterised by a set of products ***Pd***, each of which has the following properties:

- it is either a natural resource or a manufactured product
- if a resource, it is either renewable or non-renewable
- if a renewable resource, it has a renewal coefficient ***rc***, from which the rate of renewal is calculated
- if a product, it is either stockable or non-stockable (an example of a non-stockable product is electricity, which cannot be stored from one time-period to another)
- a stock value at time t=t. This value is set to zero if it is a non-stockable product, otherwise it is a positive number.

In addition, there are a set of available technologies ***T***. Each technology is characterised by:

- a typical size of an individual process unit
- a typical lifetime of the process unit
- an array of input products or resources
- a matching array of input coefficients, expressed in units input per unit size of process
- an array of output products
- a matching array of output coefficients, expressed in units output per unit size of process

Finally, there is a set of active process units ***Pc***, each characterised by:

- the parent technology upon which it is designed
- a size, lifetime and set of input/output coefficients similar to those of its parent, but with the possibility of minor variation
- a 'load factor' at time t=t, indicating the fraction of its full production capacity being utilised, due to lack of available inputs, lack of a market for outputs, etc.

IPSO was designed for dynamic analysis. However, the static network upon which the dynamic analysis is founded is sufficiently complicated to warrant some cursory analysis of its own. As a static tool for analysing network cohesion, IPSO measures the number of 'clusters' within a system. Two processes p_1 and p_2 are said to belong to the same cluster if:

- p_1 produces something that p_2 uses, or vice versa
- p_1 and p_2 both produce something that p_3 uses
- p_1 and p_2 both use the same product or resource

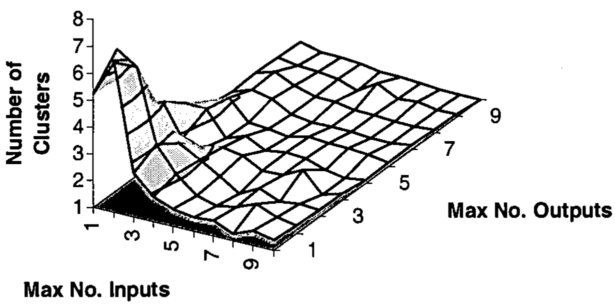
Note that this definition excludes processes that only produce the same unused product (i.e. same waste). Within the cluster, there may be chains and loops, but these are not formally identified here.

When used as a dynamic simulation tool, the stocks of products are increased by rates of production by processes, and stocks of products and resources depleted by use. The rate of usage and production by an individual process depends upon its current load factor;

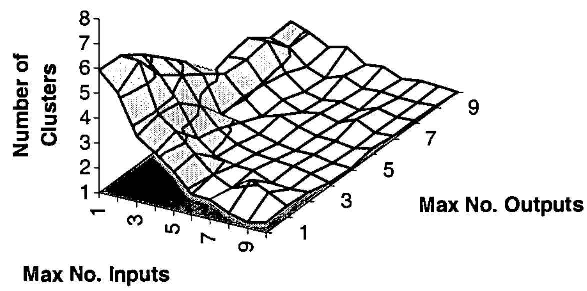
these are collectively determined by an iterative process at the start f each timestep to ensure that no stock falls below zero. The dynamics of the model are discussed in more detail later on.

8.2.1 Static Analyses

In addition to conducting dynamic analyses, static analyses of the state of the network at a given point in time can be undertaken. This may be useful, for example, in assessing the viability of automatically generated initial conditions. Using the static analysis tools, a number of random process networks were generated, with a variety in the range of inputs and outputs. The clustering patterns of these were examined (figure 8.2). It can be seen that the networks very rapidly tend towards being a single connected unit when the upper limit for either number of inputs or number of outputs is set above a value of three or four.

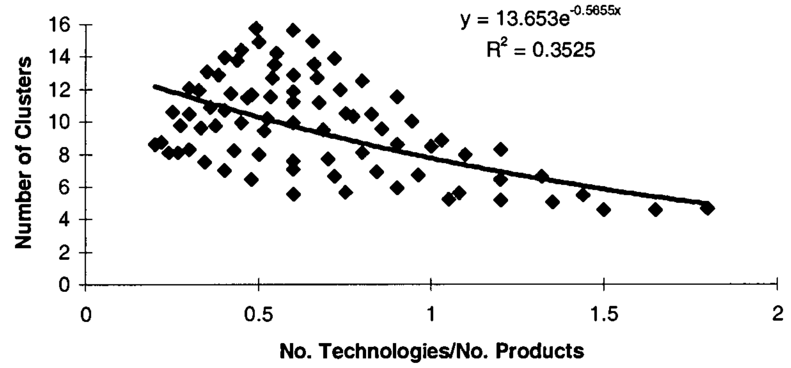


(a)

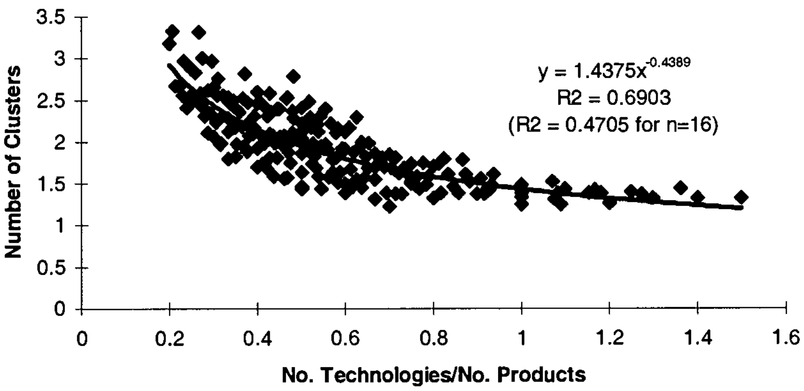


(b)

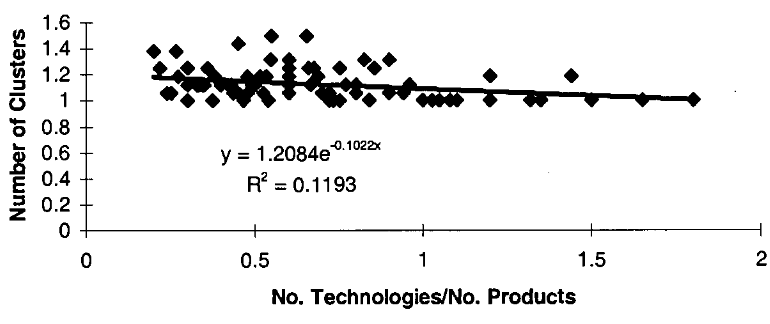
Figure 8.2: Average number of clusters in a network of (a) 48 technologies, 80 processes and 24 products (average 10% resources) (b) 12 technologies, 20 processes and 24 products (average 10% resources). For all randomly generated technology types, the number of inputs and number of outputs were set to a value between one and an upper limit. The upper limit terms for both inputs and outputs were varied independently over the range 1 to 10. Average clustering sizes are calculated from samples of 16 randomly generated systems for each combination of input and output size. As the connectivity of the individual processes increases, the system as a whole merges into a single cluster.



(a)



(b)



(c)

Figure 8.3: Relationship between Technology:Product ratio and clustering properties of process networks with range of inputs and outputs from (a) 1-10 (b) 1-5 (c) 1-2. The data was fitted to linear, logarithmic, polynomial, power and exponential functions. In each case, the exponential function gave marginally the best fit; R^2 values are recorded on the charts.

The transition towards a single cluster is similar, in many ways, to that observed in the CarteSim model as the average transport speed parameter was varied. This has implications, then, for the ability of the system to maintain diversity, suggesting that an increase in connectivity may be associated with a reduction in diversity and a qualitative change in the dynamic regime.

The transition is noticeably sharper in figure 8.2a. It was posited that this was due to the higher ratio between the number of technologies and the number of products; a system operating upon a less diverse resource base would be more likely to form a single connected unit. This hypothesis was tested by performing a second search of the network parameter space, ranging the number of technologies and products across the ranges 12-36 and 24-60 respectively, with 100 processes being generated, and 16 networks generated for each set of parameters.

Three combinations of input and output numbers were taken, with both upper limits being set at values of 2, 5 and 10. Because these first results were somewhat inconclusive, a second run was conducted for the case of 1-5 inputs and outputs, with 64 samples being taken for each permutation. The results of these experiments are presented above in figure 8.3.

The R^2 values are small in all cases. The relationship cannot be characterised rigorously, then, but it does appear that a limited range of products encourages clustering. Interestingly, this is most pronounced for the middle range of connectivity (with 1-5 inputs and outputs), even when the R^2 term from the smaller sample (n=16) is used for comparison.

8.2.2 Dynamic Analyses

The case studies using ECCO in Chapters 4 & 5 demonstrated the advantages of conducting a dynamic analysis when looking at complicated technology-economy-environment interactions. This is the main purpose for which IPSO was designed.

In order to develop a dynamic analysis from the network, a number of additional specifications must be made. It is necessary to develop algorithms for determining the way in which the pool of processes will change over time, in terms of technology mix. At its simplest, this involves specifying which existing technologies will be utilised. Even here, there are several ways of allocating reinvestment, leading to different model behaviour. Additional degrees of freedom can be introduced by allowing for new technology types to be introduced during the simulation, providing the possibility of even greater variation in model output.

In the case studies that follow, these additional factors are introduced one at a time, and their effects upon the model behaviour assessed. New factors introduced are (in order):

- variable load factors of processes over time (fixed process pool, fixed technology pool)
- finite lifetime of processes (variable process pool, fixed technology pool)
- changes in technology over time (variable process pool, variable technology pool)

8.2.2.1 Introducing Variable Load Factors of Processes

In preparing IPSO for dynamic analysis, the rate at which processes operate must be known. This is done in IPSO by defining a coefficient associated with each input and output which defines the maximum rate of production achievable per unit of capital stock in the process. Each process is also assigned a 'load factor' indicating how close to this maximum throughput it is operating at. Input and output rates are then determined as:

$$R_{io} = C_{io} \times size \times lf$$

where R_{io} is the input or output rate, C_{io} is the coefficient, ***size*** is the size of the process as measured in HMC units, and lf is the load factor (a value in the range 0-1).

The value of stocks of products and resources are updated each timestep by the sum of output rates minus input rates of that product or resource by all processes in the pool. Resources are classified as either renewable or depleteable. In the case of renewable resources, input rates are determined by a simple 'birth rate' value:

$$R_i = S \times C_i$$

where R_i is renewal rate, S is the stock and C_i is a coefficient. A sigmoid growth curve might be more realistic, but this suffices for very simple cases.

Manufactured products are classified as either stockable or non-stockable. In the latter case, stock values are not carried over from one time period to another, and the rate of production in the current timestep serves as the sole supply.

The key problem in implementing the dynamics at this level is to assign a set of load factor values to all processes that is commensurate with the existing resource base (i.e. that will not deplete any available supply below zero). The load factor of processes are calculated by an iterative process, in which two factors are taken into account:

- undersupply: a process will reduce its load factor if there is insufficient supply of any feedstock
- underdemand: a process will lower its load factor so as not to produce more of its most-demanded product than is required

These cannot be computed separately for the entire process pool, as a decrease in load factor by any process results in a change in its own demand and supply, and therefore potentially affects all other processes. Further, no optimum solution to the problem can be easily defined.

The approach adopted by IPSO is a trade-off between simplicity and effectiveness. Initially, all load factors are set to unity, and the projected rates of use and production are determined.

Each process is checked for oversupply - if it is producing products that are not being completely consumed elsewhere, its load factor is reduced so as to minimise waste production. Where several products are produced, the load factor is reduced by the smallest amount, i.e. some wastes are still produced. Once all load factors are readjusted, product and resource use and supply rates are revised.

From these rates, the scarcity of each product and resource is assessed, based on the balance between supply (production and stocks where appropriate) and demand (use rates). Processes are then assigned into four groups:

- users of scarce products/resources
- users and producers of scarce products/resources
- neither user nor consumer of scarce products/resources
- producers of scarce products/resources

The load factor of every process in the first group is reduced by the fraction required to prevent scarcity of the resource. That is, the scarcity is shared out equally between all users. This is a simplifying assumption, which introduces approximations at both a technical and content level. Technically, there is no distinction between a user of one or several scarce resources. Where a process uses both a slightly and a very scarce resource, its load factor is reduced to prevent scarcity in the very scarce one, and so it has foregone more than its equal share of the slightly scarce resource. As all processes are updated simultaneously, there is no facility for other users of the slightly scarce resource to benefit from this (within this iteration).

If alteration of the first group does not eliminate all scarcities, the second group is treated similarly.

The readjustment continues, adjusting for oversupply then scarcity, until all demands can be met.

The above algorithm is simple - a more complicated method might develop a surrogate pricing mechanism in which each process trades products with one another, prices being linked either directly or indirectly to scarcity. Another approach that may be useful is to introduce a random element into the determination of load factors, allowing the solution to 'anneal' from the combination of noise and information. These options have not been implemented yet, but may be developed in the future.

8.2.2.2 Adapting the OzEcco Dataset

Initially, the algorithm was tested on a dynamic simulation of a static network - that is, all processes in the network were immortal, and no new processes were introduced. Using the OzEcco data set, fourteen stylised processes (table 8.1) and fifteen stylised products/resources (table 8.2) were identified, and a set of some 450 processes developed.

Table 8.1: Representation of Technologies in 'OzIpso' model

Technology	Lifetime of HMC (y)	Size (VPJ)	No. inputs	No. outputs	Inputs	Coefficient	Outputs	Coefficient	Number processes
agriculture	18	36.43	4	2	HMC fuel oil electricity water	0.1375 0.121 4 28.5	animal protein veg protein	1.98 2.1	10
oil supply	10	2.46	1	1	crude oil	29.7	fuel oil	28.4	16
gas supply	10	1.9	1	1	crude gas	30.1	raw gas	28.3	8
coal mining	10	4	1	1	crude coal	28.7	coal	28.4	10
mining	10	14.7	5	1	fuel oil fuel gas coal electricity transport	0.0033 0.087 0.0053 30.3 2687	minerals	0.138	10
Technology	**Lifetime of HMC (y)**	**Size (VPJ)**	**No. inputs**	**No. outputs**	**Inputs**	**Coefficient**	**Outputs**	**Coefficient**	**Number processes**
industry	24	29.83	10	1	fuel oil fuel gas coal minerals electricity water services transport animal protein veg protein	0.211 0.216 0.194 0.0226 35.76 0.726 0.031 4050 0.218 0.23	HMC	1.5	30
fossil electricity	25	9.966	2	1	coal fuel gas	3.18 0.35	electricity	259	30
hydro electricity	70	15.4	0	1			electricity	81	10
wind electricity	20	1	0	1			electricity	36.5	0
gas treatment & pipelines	24	3.5	1	1	raw gas	12.69	fuel gas	12.64	9
water supply	60	7.838	2	1	fuel oil electricity	0.002 3.544	water	32.85	50
final demand	140	30.044	10	0	water fuel oil fuel gas coal electricity HMC services transport animal protein	0.552 0.00867 0.0231 0.00058 11.83 0.272 0.0217 963.5 0.195			90

Technology	Lifetime of HMC (y)	Size (VPJ)	No. inputs	No. outputs	Inputs	Coefficient	Outputs	Coefficient	Number processes
					Veg protein	0.206			
services	35	33.515	7	1	water fuel oil fuel gas coal electricity services transport	0.104 0.00495 0.0067 0.00179 5.228 0.0405 378	services	0.0663	100
transport *	10	0.01	2	1	fuel oil electricity	1049 1287	transport	9897500	80

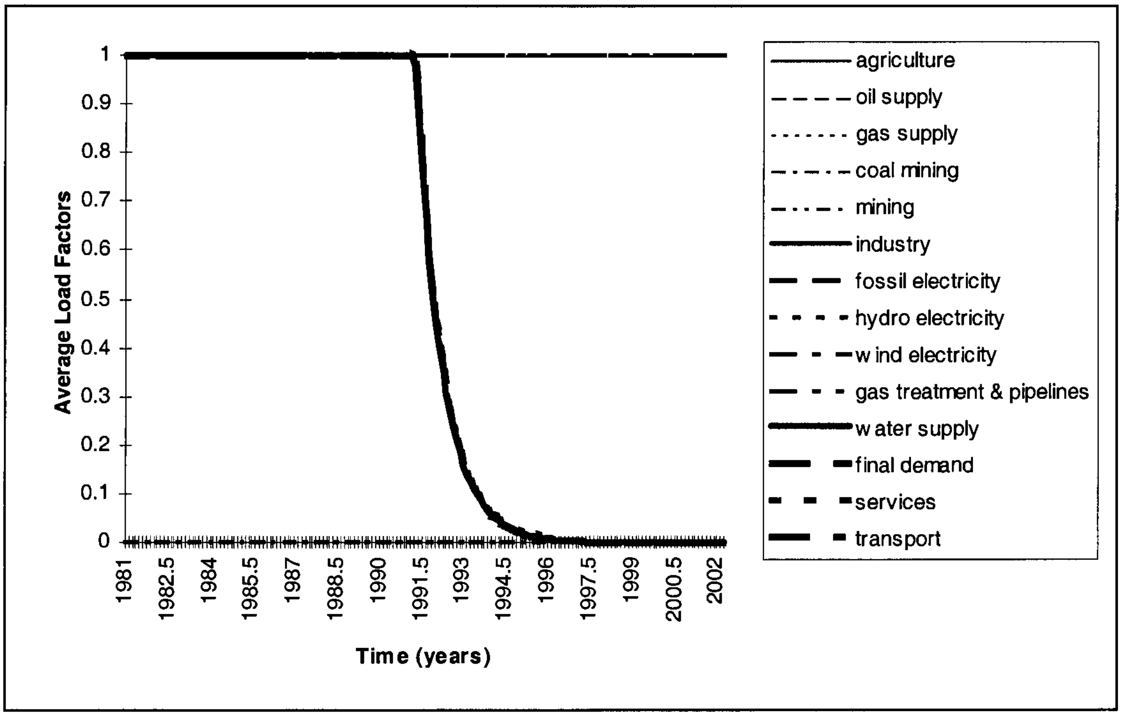
* by the conventions of the ABS National Accounts, there is no capital stock associated with transport, as this definition cross-cuts that of other sectors. A small value has been assigned here simply to fit the IPSO structure.

Table 8.2: Representation of Products and Resources in 'OzIpso' Model

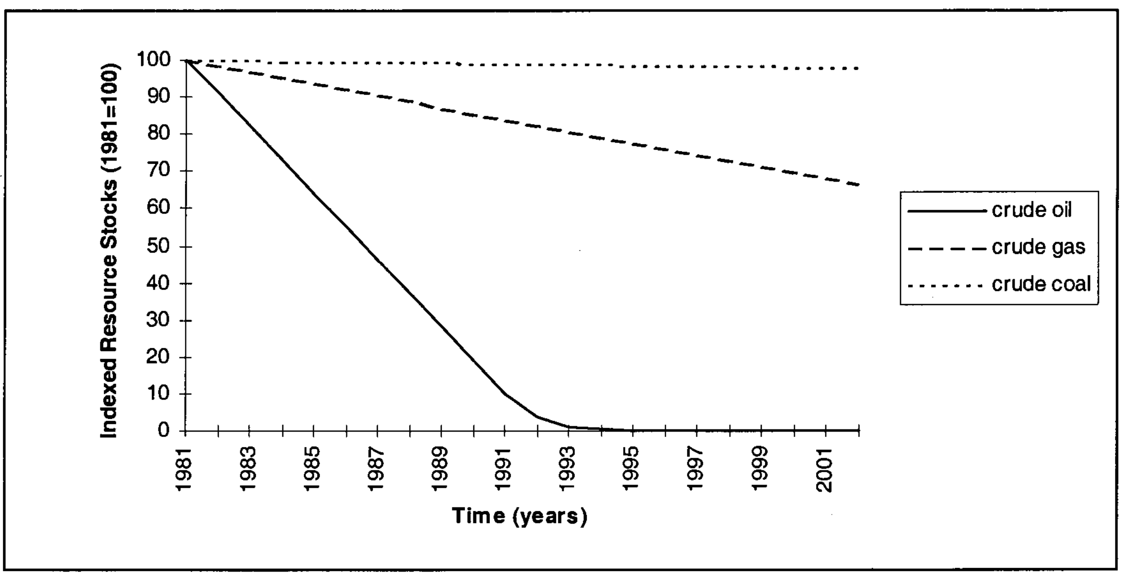
Name	Resource	Stockable	Renewable	Initial Stock
HMC	NO	YES		0
fuel oil	NO	YES		0
fuel gas	NO	YES		0
coal	NO	YES		0
crude oil	YES		NO	1.30E+04
crude gas	YES		NO	2.85E+04
crude coal	YES		NO	1.17E+06
electricity	NO	NO		0
water	NO	NO		0
animal protein	NO	NO		0
veg protein	NO	NO		0
transport	NO	NO		0
services	NO	NO		0
minerals	NO	YES		0
raw gas	NO	YES		0

The representation is obviously a simplification on the Ecco model of Chapter 5 in many ways. There is no modelling of the increased costs of extraction associated with fossil fuel depletion, and no trade is present in the model either. However, as the model is not intended to be a realistic representation of the Australian economy, but simply a viable dataset on which to test the model structure, the representation offered here is sufficient. Most of the refinements required to make it more realistic would simply be additional specific structures built onto the edge of the generic framework provided here.

The network was simulated from 1981 to 2000, with a fixed timestep of 0.0625years. (The same applies to all subsequent simulations presented in this chapter.) With all processes operating as 'immortal', the system can be seen to simulate well, with all processes operating at or near full load factor (figure 8.4a) through to around 1990, when fossil fuel reserves become depleted (figure 8.4b). This behaviour is satisfactorily close to that of the OzEcco model (if not to reality) *when OzEcco parameters are adjusted to account for the limits of the pilot IPSO model.* Specifically, fossil fuel reserves last until about 2020 in the default OzEcco scenario, due to an exogenous rate of additional discoveries of oil and gas programmed in as defaults. Where these are reset to zero in the OzEcco model, oil reserves become depleted in 1991, close to the date given by IPSO, which has no facility for representing discovery of new reserves in its current form.



(a)



(b)

Figure 8.4: Results of simulation of a static network using IPSO model (a) average load factors for each technology type are steady until around 1992, when (b) oil reserves are depleted.

8.2.2.3 Introducing a Concept of Process Lifetime

The above simulation of the model does not realise the full potential of the IPSO structure, as it essentially treats each sector as a single capital stock. (Although each sector is broken into a number of processes, these are not dynamic.)

Using the average capital lifetimes assigned to each technology in table 8.1, the model was re-initialised with a finite lifetime assigned to each process. (Processes were initialised at a random stage in their full lifetime to ensure an even initial distribution, and therefore a smooth ageing profile.) Further, surplus HMC produced by the industry processes was made available to create new processes. This leads to the next issue in model implementation, as an allocation mechanism is required to determine what types of processes should be built.

A general scheme was developed, in which each technology was assigned an 'investment allocation weight' determined as:

$$i = n - \Sigma(S_{in}) + \Sigma(S_{out})$$

where i is the investment weight, n an arbitrary constant whose value determines the sensitivity to the scarcity parameters, S_{in} the scarcity of inputs and S_{out} the scarcity of outputs. Scarcity terms were measured on a scale from -1 to 1, with negative numbers indicating a surplus and positive values a scarcity. At one extreme, a value of 1 indicates finite demand and zero supply, and at the other a value of -1 indicates finite supply but no demand. Negative values are determined as negative supply over demand, and positive values as demand over supply.

Hence, if an input is scarce, there is a disincentive to invest in technologies using it, and an incentive to invest in those that use abundant products (users of abundant natural resources are not given the same incentive as this leads to rapid overinvestment in fossil fuel supplies). Similarly, producers of scarce resources are favoured, and producers of abundant resources disfavoured.

The constant n is used to moderate the investment allocation mechanism. Where n is small, the weighting scheme will depend heavily on resource scarcity. Where it is large, the scarcity terms will be effectively swamped, and all investment weights will approximate n.

The weights are used in the model to determine investment in new processes as follows. The weights for all technologies are summed, and a random value from within the range of the sum calculated. A new process is built using that technology as a template, and the process continued until available HMC is exhausted. Figure 8.5 shows the evolution of investment weight terms for typical simulation run using a range of values for ***n***. At low values, the distribution is highly uneven and changeable, and at high values it does give equal weight to each technology.

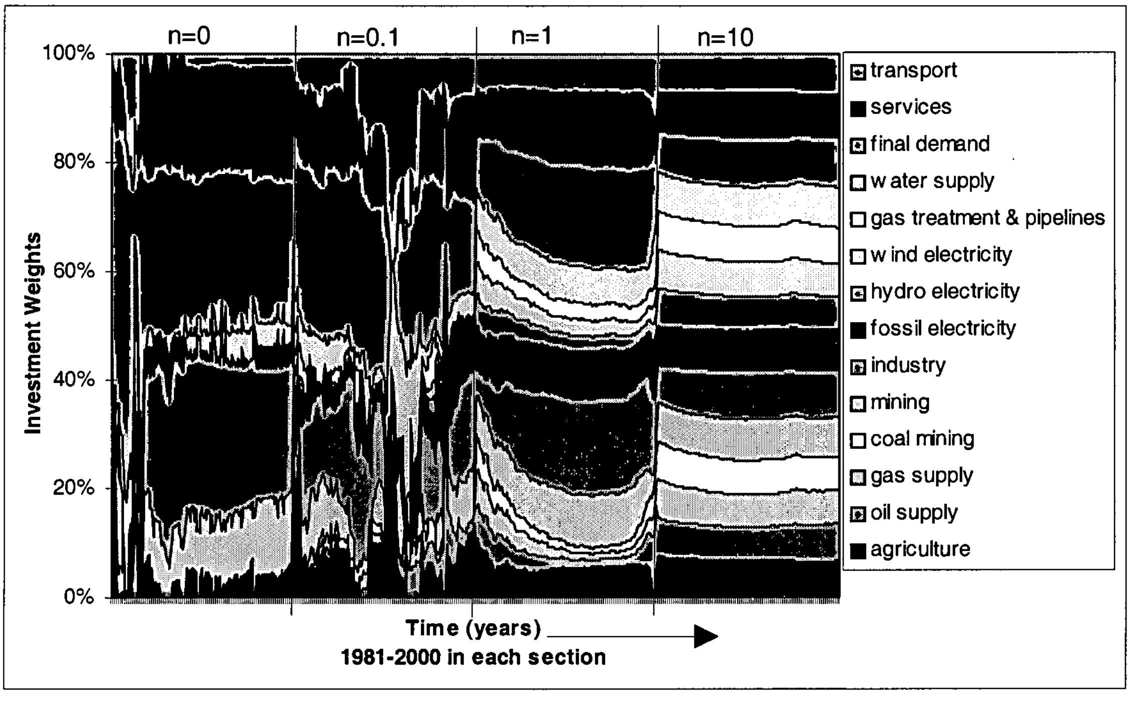
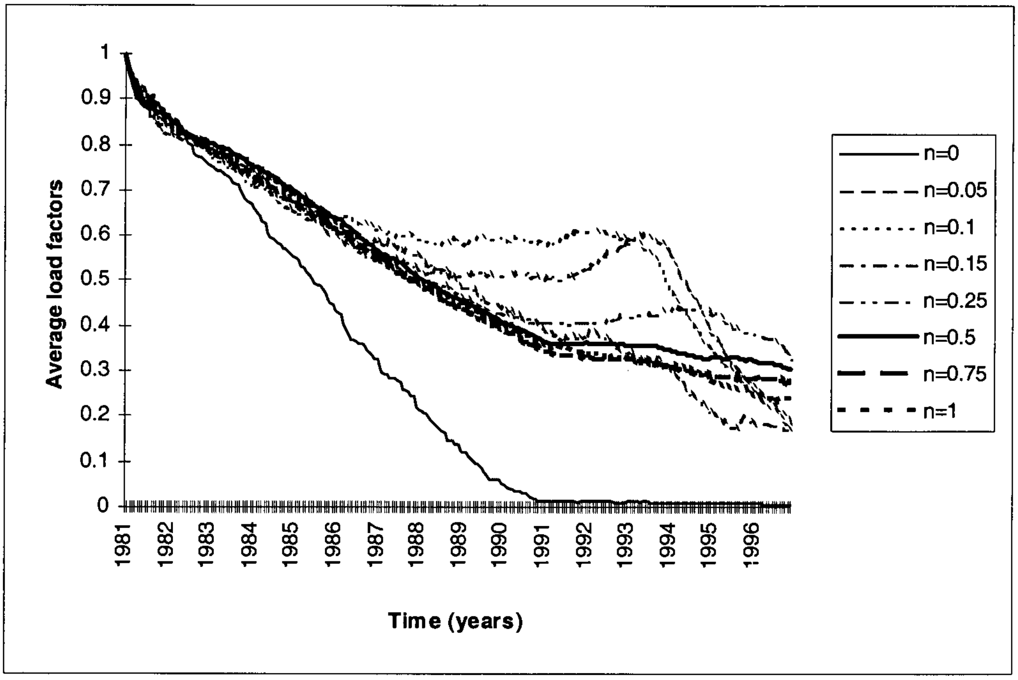
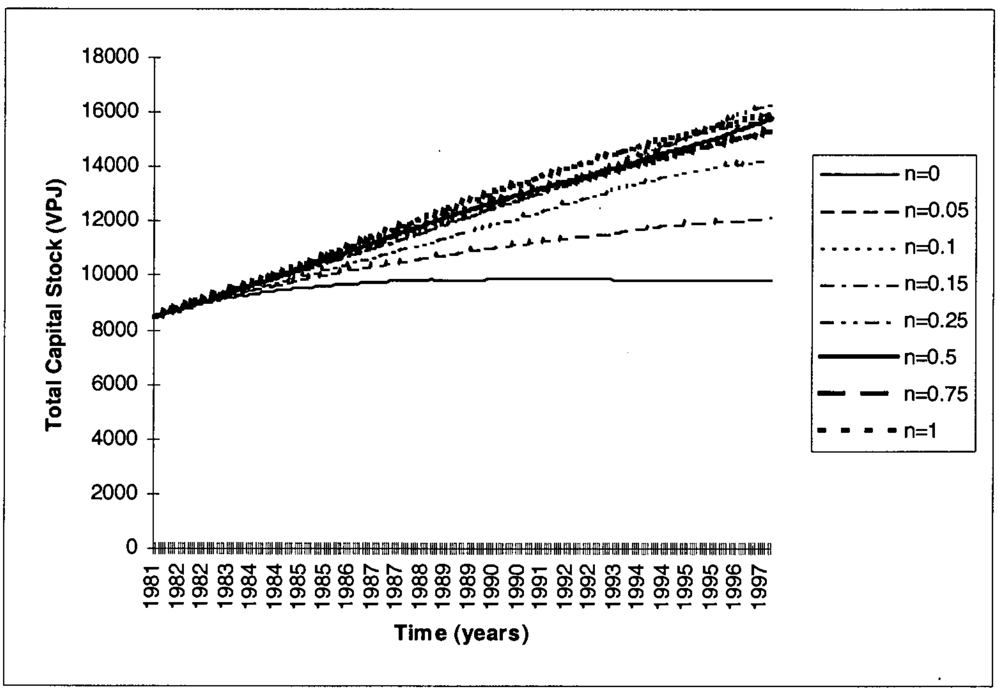


Figure 8.5: Distribution of investment weights between sectors for a range of degrees of smoothing.



(a)



(b)

Figure 8.6 Results from IPSO simulation with dynamic process network but fixed technology. Each trace is a composite average from 24 simulation runs. The degree to which randomness is introduced in the investment allocation mechanism was varied over a range of values. These affected both (a) average load factor of processes (b) accumulation of capital stock. For a purely

deterministic mechanism, growth was minimal and load factors dropped rapidly over time. With small amounts of randomness (i.e. n<=0.15), much higher load factors were achieved, although growth increased less than with a greater degree of randomness.

Figure 8.6 illustrates the effects of the n-parameter on average load factor of all processes and on the rate of capital accumulation. The first thing to notice is that the load factors quickly decline under a dynamic network regime, presumably as the initial fine balance of inputs and outputs becomes skewed by the 'death' of existing processes and the 'birth' of new ones. Where ***n***=0, i.e. the investment allocation is most structured, the decline is strongest, with an average load factor of zero being achieved by 1991. (Note that this does not occur due to fossil fuel scarcity - no more than 20% of the oil reserves have been depleted by this point. The economic process simply grinds to a halt due to mis-coordination of activities.)

Interestingly, the highest average load factor is maintained at relatively low values of ***n***, where the investment allocation is still uneven (see figure 8.5). In these cases, the overall growth of HMC is less, but that which is accumulated is being used more efficiently.

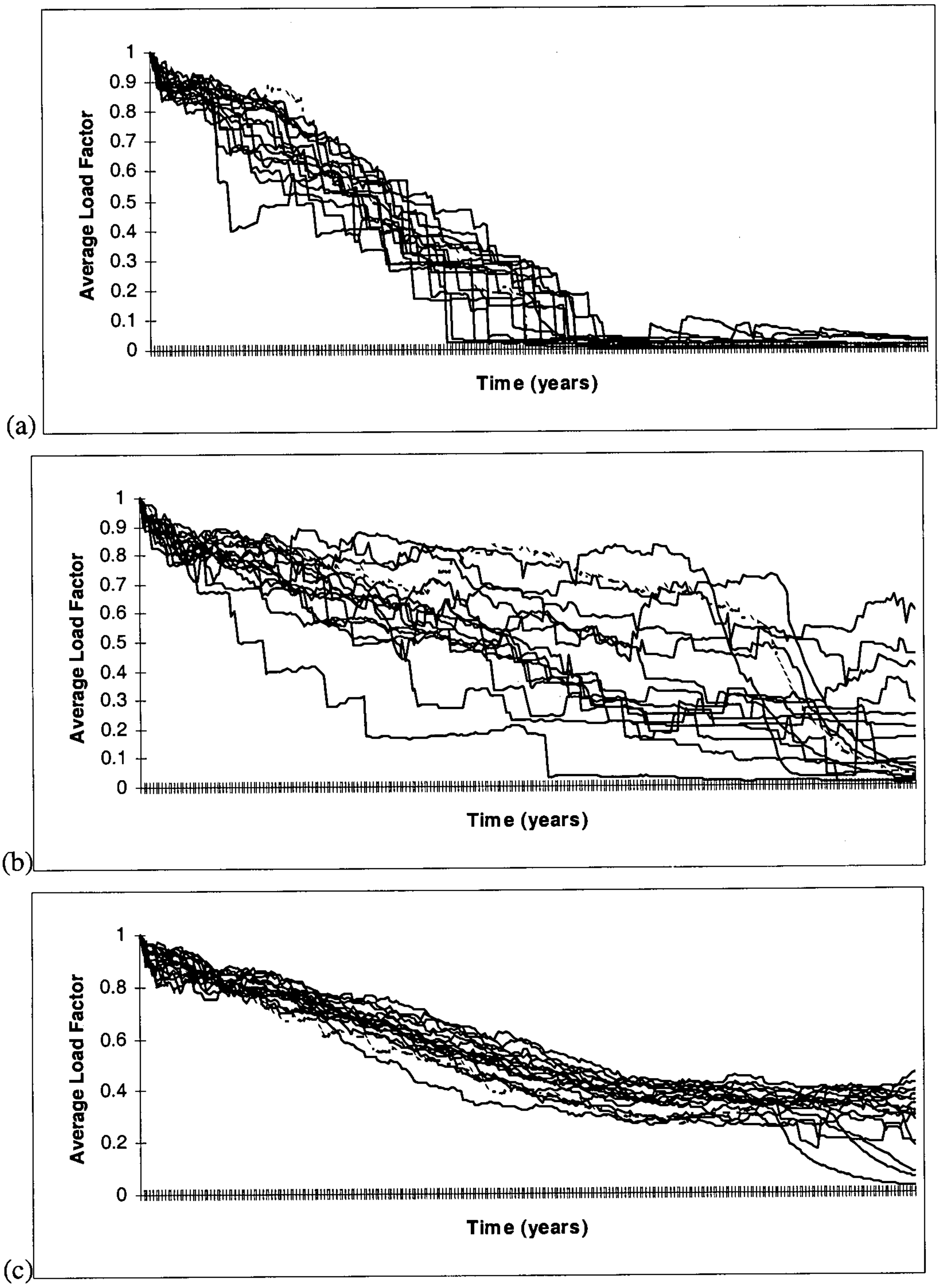


Figure 8.7: Effect of the n parameter upon diversity of model behaviour. (a) n=0 (b) n=0.05 (c) n=0.5. In each case, sixteen example runs from the set of twenty-four used in figure 8.6 have been used, to prevent excessive cluttering of the figures.

Both low and high values produce relatively regular and monotonic behaviour, whereas the middle value generates a variety of outcomes, many of which undergo rapid changes and switches in value throughout the simulation.

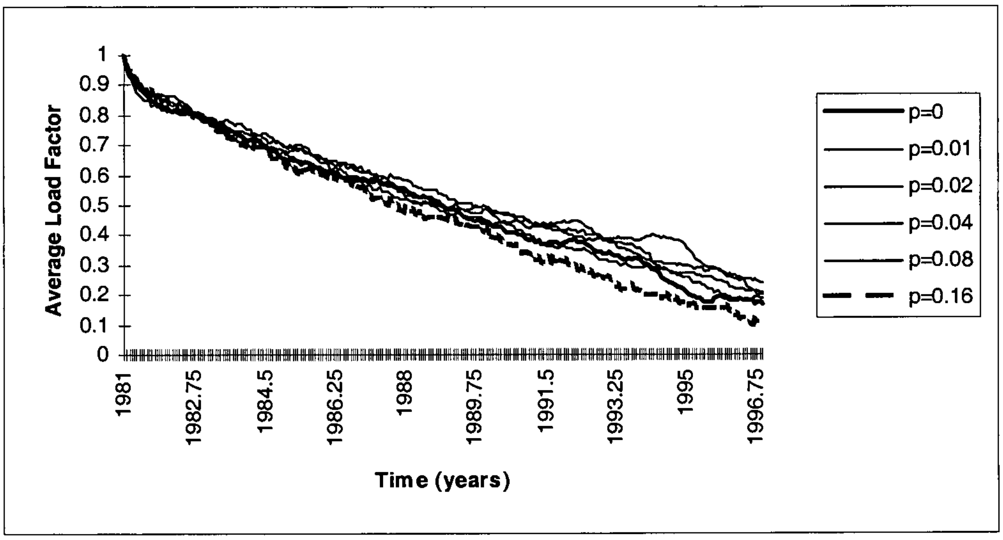
Finally, it is worth noting that the middle range of values of n, around 0.05, result in a far greater diversity of outcomes than either higher or lower values, including cases in which the system grinds to a halt as with the n=0 simulations, some where it depletes resources resulting in the rapid exponential drop seen in figure 8.4, and some where it operates at a range of sub-optimal values over the full simulation time. Figure 8.7 illustrates this with three examples.

8.2.2.4 Introducing Change to the Technology Base

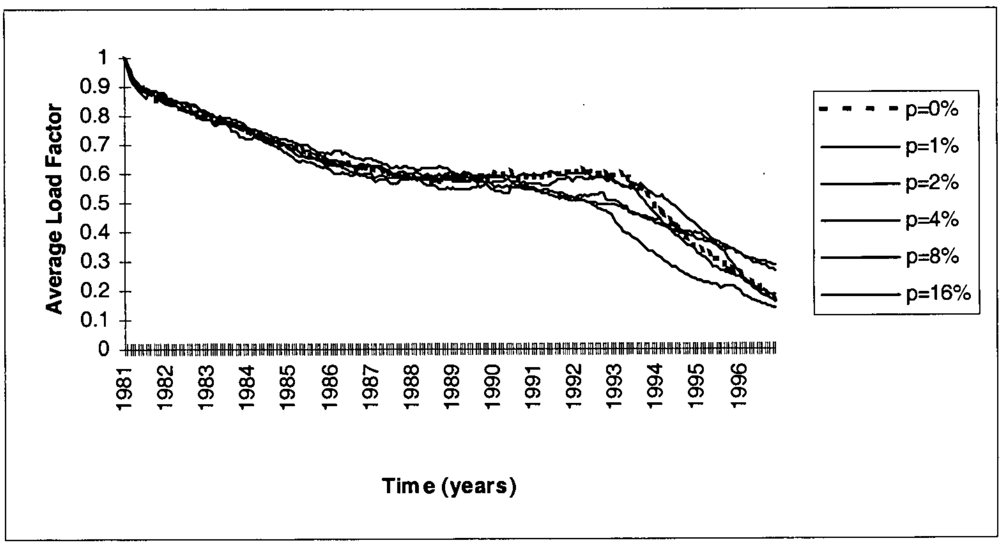
The final stage in dynamising the model involved allowing the set of available technologies to change over time. This was effected in the model by setting an additional parameter as the probability of a new technology entering the system at each timestep. As with introduction of finite process lifetime, this introduces new degrees of freedom, and more than one algorithm has been explored below.

Initially, new technologies were determined randomly, with a range of 1-9 inputs drawn at random from the set of products and resources, and 1-2 outputs from the set of products. (Resources, by definition, can only act as inputs.) A random size between 1 and 2 units of HMC and a lifetime of 20-40 years were assigned to each new technology, these values reflecting the characteristics of existing technologies in the model.

Sets of simulations were repeated for values of the n-parameter of 0.05 and 0.1 (i.e. just below and at the optimum values for average load factor noted for the fixed technology set, figure 8.6a), ranging the probability of adding new technologies from 1 to 16%. The results are shown in figures 8.8 & 8.9.

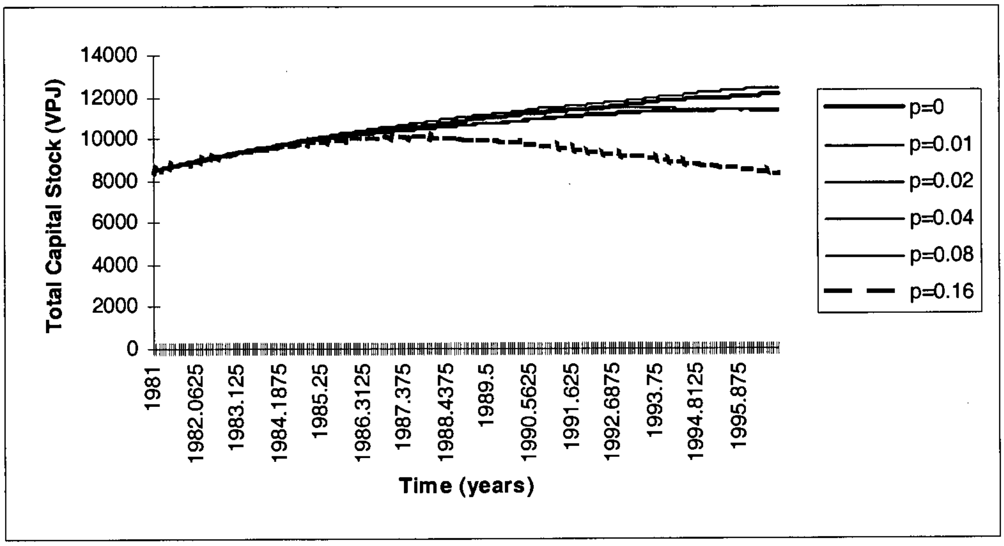


(a)



(b)

Figure 8.8: Effects of increasing pool of technologies on load factor for (a) n=0.05 (b) n=0.1.A range of probabilities from 1% to 16% per timestep were explored, giving an average range from 17 to 55 technologies in the pool by the end of the simulation. In neither case does the invention probability p have a significant impact upon the load factor, nor upon the diversity of outcomes developed within each set of simulations. Each average profile shown here is based on twelve individual simulations.

(a)


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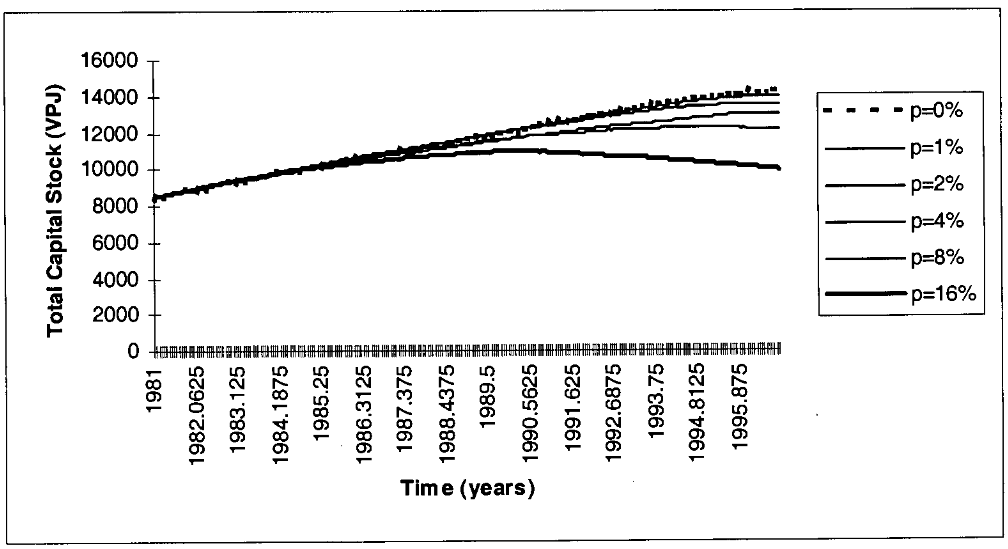


Figure 8.9: Effects of increasing pool of technologies on capital accumulation for (a) n=0.05 (b) n=0.1. Increasing innovation rates appear to decrease the rate of capital accumulation in both cases, and by similar amounts.

Given that these results were rather unremarkable, a second set of experiments was attempted, in which a degree of 'intelligence' was programmed into the invention of new technologies. Specifically, new technologies' choice of inputs was weighted towards those that were abundant, and choice of outputs towards those that were scarce. The reasoning behind this was simply that these reflected the presence of 'gaps in the market' which R&D activity (under whatever institution) might be targeted towards.

The weighting scheme used was based on the 'scarcity' parameter assigned to each product and resource, as described above (range -1 to 0 for abundant products, 0 to 1 for scarce products). Potential inputs are assigned a weight defined by:

$$W_i = 1 - S_i$$

where W_i is the weight assigned to product or resource i, and S_i is the scarcity. In the case of abundant resources (i.e. $S_i<0$), the weight is set to unity, so as not to encourage rapid depletion of resources (the same exception was applied to investment weighting, above). This results in a minimum value of zero for absolutely scarce resources (i.e. there is a demand, but no supply exists), and 2 for unused resources.

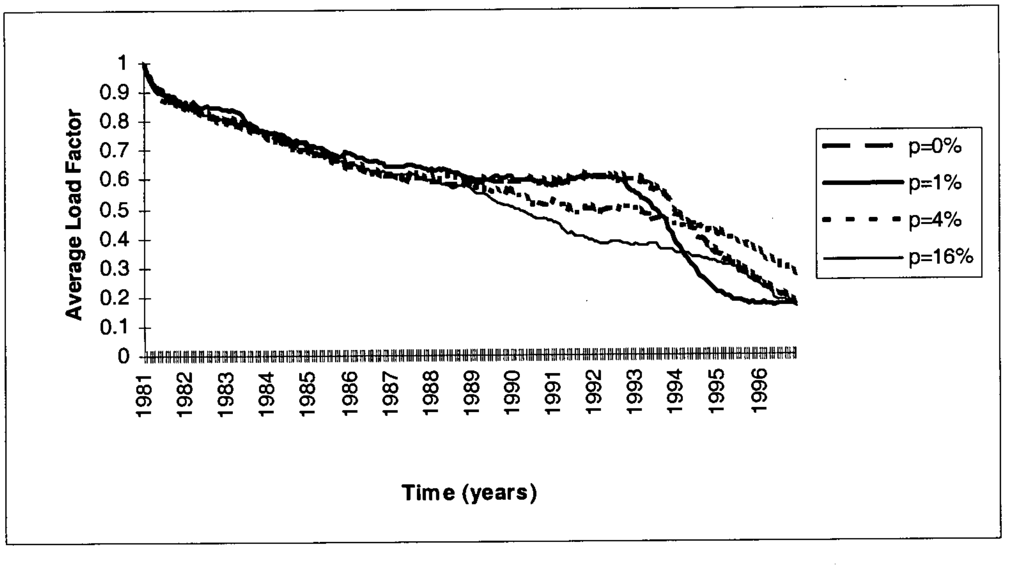
The formula is applied in reverse to potential outputs, i.e.

$$W_o = S_o - 1$$

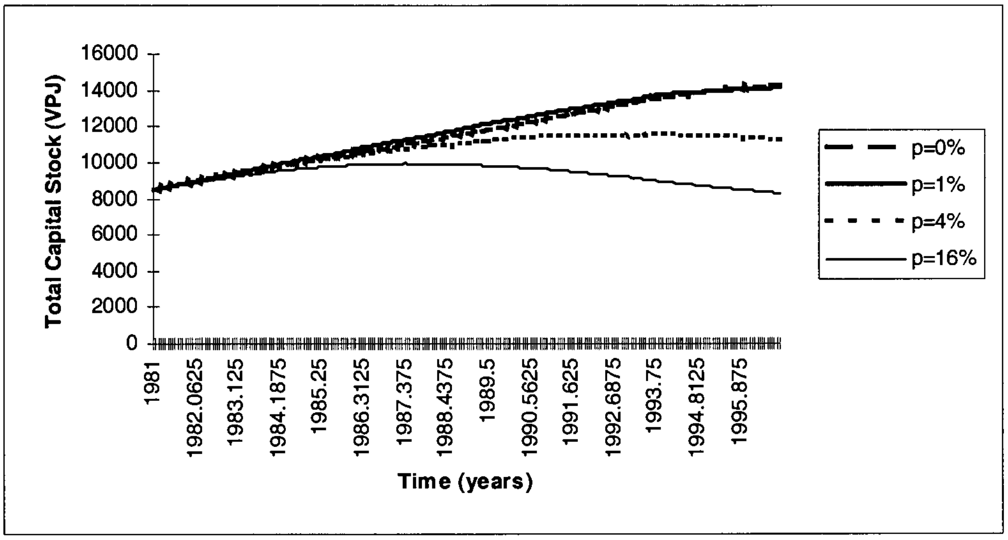
so as to give a minimum value of 0 for unused resources, and 2 for absolutely scarce resources. As resources cannot be outputs of processes, no exceptions are applied.

In both input and output determination, weights are summed, and a random value within the range of the sum used to pick eligible products and/or resources.

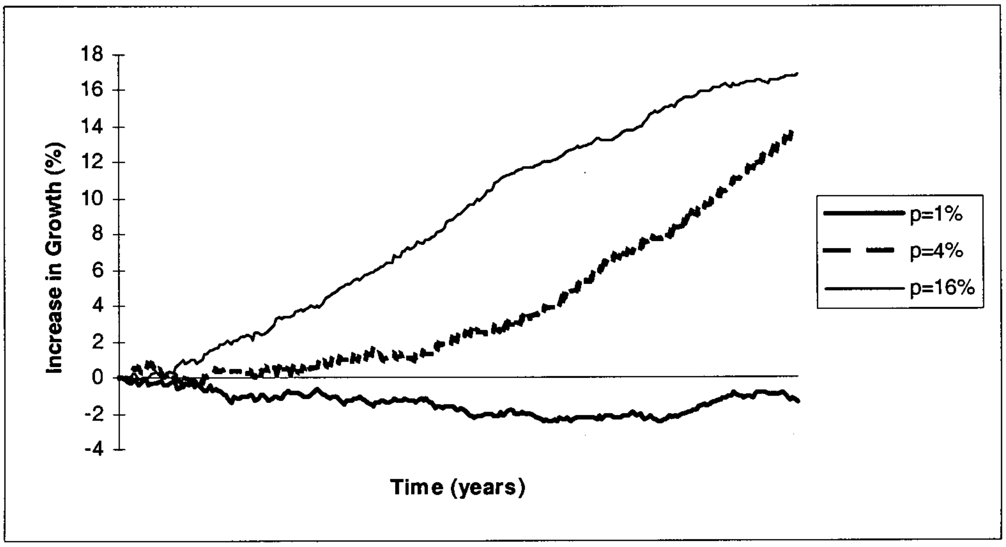
The results of applying this algorithm are shown in figures 8.10 and 8.11 below.



(a)



(b)



(c)

Figure 8.10: Effects of 'targeted' invention of new technologies, for n=0.1. Each trace is composed from twelve sets of simulation results. (a) higher rates of invention do appear to have a stabilising influence on load factor, if not actually altering the trajectory significantly. (b) Overall growth rates are comparable to the non-targeted invention simulations shown in figure 8.9, although (c) at higher rates of invention, the increase in the growth profile becomes significant later in the simulation.

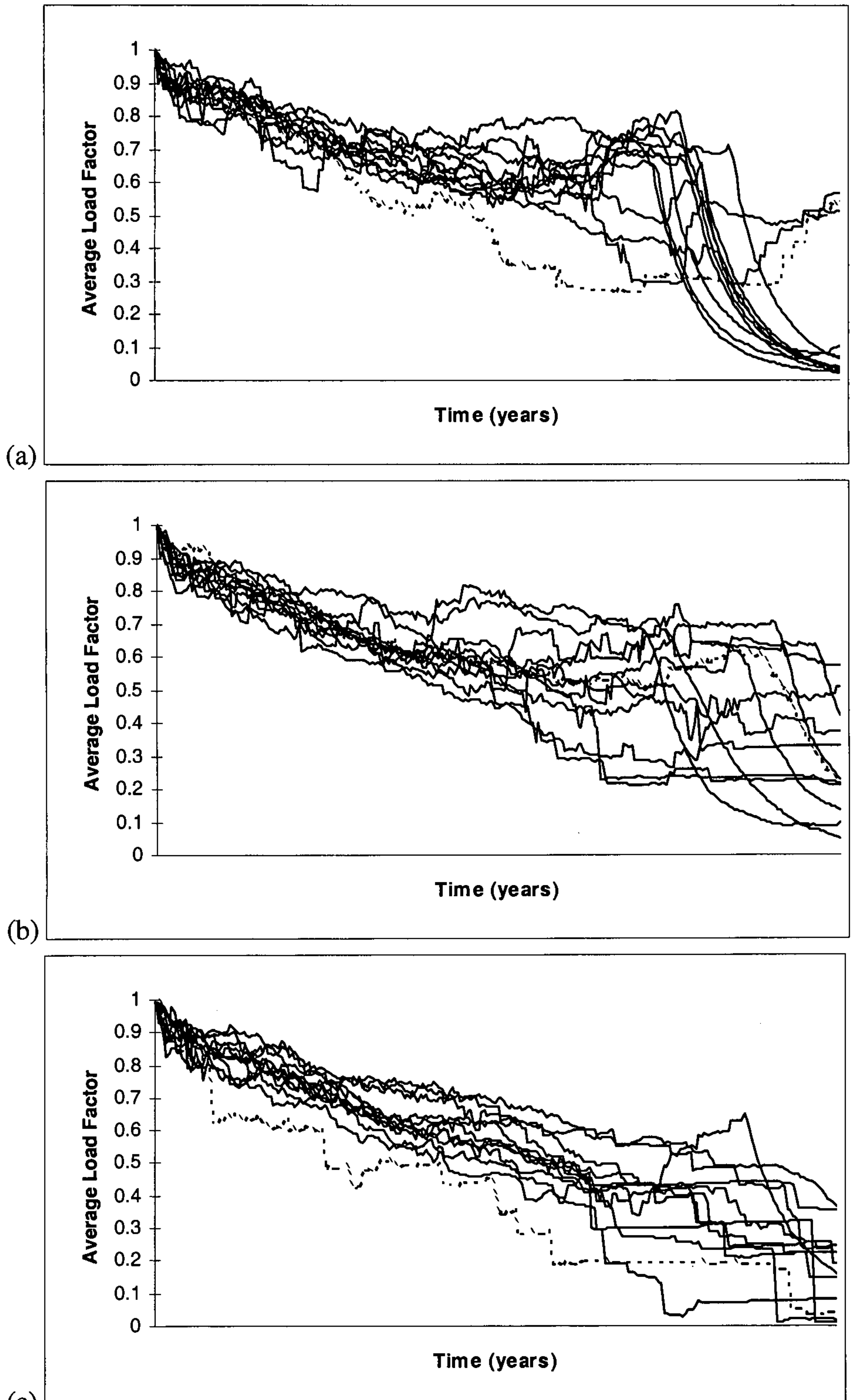

(a)
Average Load Factor
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (years)
(b)
Average Load Factor
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (years)
(c)
Average Load Factor
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (years)

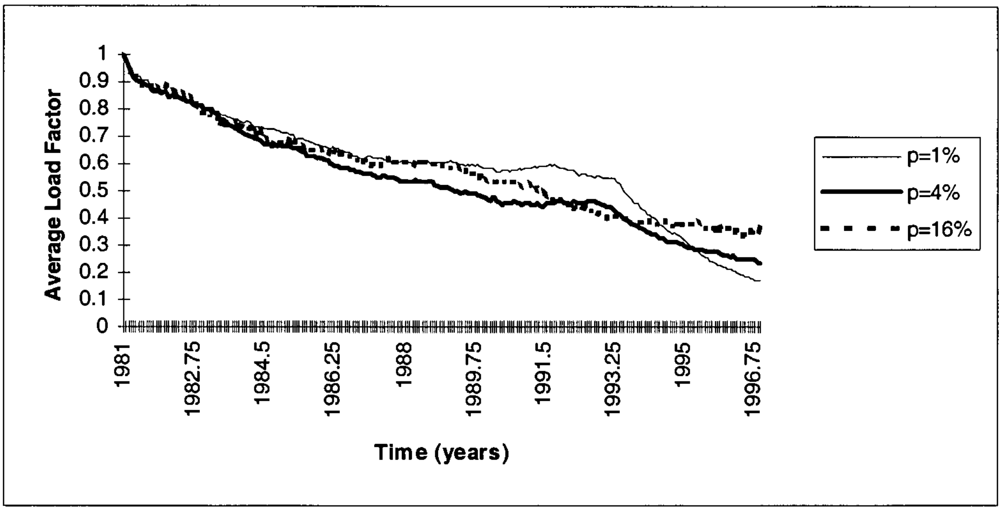
Figure 8.11 (previous page): Effects of 'targeted' invention rate on load factor profiles (a) p=1% (b) p=4% (c) p=16%. As the 'invention rate' increases, there is a marked decrease in the number of profiles terminating in the exponential decay associated with resource depletion, as the responsiveness of the system is increased.

In this case, the effects of the new technology can be discerned, although they are still not remarkable. The most extreme of the three scenarios does show some degree of avoidance of resource scarcity, and a slightly increased growth rate, but the overall pattern is still one of slow eventual decline, and, although the targeted p=16 runs perform better than their untargeted equivalent, they still exhibit less growth than the p=0 (i.e. no technological change) simulations.

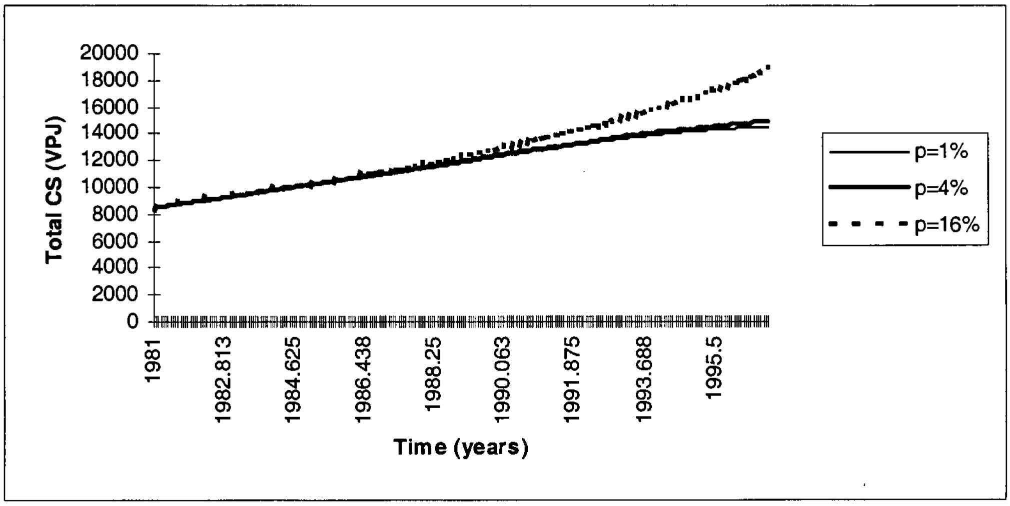
A second approach to technological change resulted in more striking results. Here, new technologies were added to the 'pool' as before, but were generated by 'mutating' existing technologies rather than randomly creating new ones. As the current investment allocation algorithm ignores input & output coefficients, the mutations were made by either removing an input or adding a new output (50% chance of either, unless there is only one input, in which case a new output is added). The effects of these algorithms are shown in figure 8.12 below.

The important difference here is seen in figure 8.12b. By selecting new technologies using existing ones as templates, an increase in growth is seen to be effected by an increase in the rate of introduction of new technologies.

Note that this algorithm, and the previous 'random' invention one contravene the Natural Capital Accounting principles in that they do not distinguish between energy carriers and other inputs, and can therefore generate processes that operate with no (direct) energy inputs. Whether a tightening of these rules would result in a change to the results remains an issue for future research.



(a)



(b)

Figure 8.12: Effects of 'mutation' algorithm on simulations (a) As before, the effect on average load factor is mostly a simple smoothing out. Unlike the random invention algorithm, though (b) the effects on growth are positive in this case.

8.3 Conclusions

These preliminary explorations of the interactions between technology, resource scarcity and capital accumulation using the IPSO model have provided mixed results. The system can be seen to be sensitive to technological change in a number of cases, although the presence of technological change does not appear to steer the system in any particular direction. While it confers extra flexibility on the system, it seems to affect growth in unpredictable ways. Importantly, the more detailed representation of technologies here allows us to distinguish between types of technological change. Specifically, the deepening of a given technology (i.e. steady improvements on a basic template, as modelled using ECCO) is different to the broadening of the pool modelled here. The latter is prone to be far less predictable, on the strength of the results obtained here.

Given the provisional nature of the load factor calculations and the investment allocation and technology-generating algorithms, as discussed above, these remarks cannot be generalised to a wide range of real economic systems, and there is considerable scope for refining the model. Alternative types of load factor allocation drawing on simulated annealing techniques have already been proposed as one way forward, and it is suggested that similar recent developments in complex computation could be applied elsewhere. The technology-generating algorithm, for example, currently takes no account of other current 'occupants' in the 'technology possibility space', and models such as Allen's (see Chapter 2) could be usefully combined here. Where Allen's model takes a more complex representation of the interactions between technologies, the characterisation of these is far more stylised than in IPSO, where technologies are represented in terms of real physical processes. Allen's model is effectively a generic model of speciation in an adaptive population, interpreted as a system of technologies undergoing change.

As a provider of insight into the growth debate, then, IPSO has encountered mixed success. Certainly, it has not produced findings that greatly strengthen either side of the debate, and perhaps the best that can be said of the results presented here is that they illustrate, again, the complexity of the relationships between technology, resources and growth. Changes in minor factors, such as the 'invention algorithm' change the relationship between overall invention and growth in unexpected ways. This can be viewed as a warning against sweeping generalisations (which both sides of the debate have advanced); the effects of technological change are, as its exponents claim, unpredictable, but respond to the specific nature of the system in which they work. The results obtained here have been broadly neutral, but are based solely upon the single dataset abstracted from the OzEcco model, and it would not be surprising if other datasets responded differently. A full test of this requires an extensive parameter search of the model and testing of a number of revised algorithms, extending beyond the scope of this thesis.

8.4 Towards Further Dialogue

In addition to assessing the effect of the model on the growth debate, it is necessary here to review IPSO as a creation of the broad interdisciplinary methodology of Chapter 1. In this, it has been largely successful, generating a structure by which the principles of Natural Capital Accounting can be taken in new directions that would not be possible with the ECCO model alone.

IPSO is not designed as a replacement for ECCO; indeed, at its current state of development it cannot be. The model requires some further refinements before it can be deployed as a specific policy tool, rather than as a general synthetic analysis tool, as here. This progress is also unlikely to be rapid due to the large requirements of data if it were used to model a regional or national economy. In the short term, perhaps its most useful immediate role is as a model of local industrial ecologies; something quite removed from its original purpose, but for which it is admirably suited (and where some of the problematic growth issues would not be relevant).

In addition, it can serve as a useful counterpart to the ECCO model, as a secondary monitor on the ECCO modelling process. When more generic results have been obtained from it, it may serve as a check on the realism of the aggregating assumptions, and a means of assessing criticism of some of ECCO's inbuilt assumptions. For example, the ECCO model has been successful in assigning full load factors to all economic sectors during simulation. Under 'healthy' growth conditions in IPSO (e.g. figure 8.7b), load factors are seen to vary considerably over the short term, and, although this may be partly due to roughness in the model's algorithms, it is in accord with certain economic schools of thought. Whether this noise has consequences on the long-term trajectory remains to be seen (see discussion on this point regarding Urban models in Chapter 6).

IPSO and CarteSim also have scope for further dialogue. Both operate from a similar theoretical stance, and could easily be coupled in order to assess spatial and economic dynamics. The potential for joining CarteSim and ECCO in this way was discussed at the end of Chapter 7, and much of those comments apply to IPSO too.

Chapter 9 Conclusions

This chapter draws together the two main arguments running through the thesis, and addresses the hypothesis presented in the introduction, and re-presented below.

> *Intellectual theories about human activity cannot adequately be treated as purely objective or rational. These theories can only be understood by taking account of the broader context in which they are developed.*
>
> *Discussion about economic growth can be divided into two polarised positions, with one side emphasising the limits imposed by natural resources and the other emphasising the freedom from such limits offered by technological change. The debate cannot be resolved by determining which position is 'correct'. It is possible to encompass both positions by looking at the context in which the debate occurs, even within an exercise as apparently mechanical as computer modelling.*

The first statement has been tested in part 1 of the thesis, both in the abstract case (Chapters 1 & 2) and in the historical account of the mainstream and ecological schools of economics (Chapter 3). Beginning with the Philosophy of Science literature, an even broader approach was developed, in which much of the non-intellectual context of the debate - personal, political, social - has to be considered.

As stated at the outset, the existence of the polarity in the growth debate is to be taken as a given. However, in the process of developing the idea of broad interdisciplinarity in Chapters 1 to 3 of the thesis, a history of economic and ecological economic thinking has been developed which offers support to this statement.

It was noted that the polarity within economic theory cannot easily be discerned from the intellectual content of the theories alone, but requires that a number of secondary factors such as intellectual values, social values, professional bodies and vested interests be taken into account. The discussion in Chapter 2 about the history of system dynamics and complex systems also offers an explanation of the polarity in some of the more recent forms taken by the debate, in which complexity has become equated with technological optimism. From this, the final statement can be seen to be well-founded.

9.1 Simulation Case Studies

The main work of the thesis has been in developing a series of case studies to address the third part of the hypothesis. The contention that the debate has polarised for non-intellectual reasons can only be usefully applied to the debate if it provides an insight into how to move the debate forward or to see beyond the current deadlock. Part 1 of the thesis laid the groundwork for this, by abstracting a generic model of broad interdisciplinarity which could be applied to this debate, and to the simulation models presented here.

The model of broad interdisciplinarity was then applied to the ECCO (Chapters 4 & 5) and CarteSim (Chapter 6) models in order to develop the IPSO Model (Chapter 8).

These modelling exercises were pertinent to the broader growth debate for the following reasons:

1. The ECCO model has an unusual and informative approach to economic growth, or, at least, to the growth of physical structures in economic systems. Although it is a system dynamics model with an emphasis on resource limitations, it is unlike other system dynamics models of resource-limited economies, such as the 'Limits to Growth' Models (Meadows et al., 1971, Meadows et al., 1991). In the latter, growth rates are essentially imposed externally. In ECCO, potential growth rates are automatically determined out of a combination of resource constraints and allocation policies.
2. From the ECCO case studies here, some insights into the complexity of the interplay between resource limitations, allocation and demand, and other system properties such as technological change and underlying growth rates could be identified. ECCO reached its limits in developing an understanding of these issues. A qualitatively similar 'rebound effect' for energy efficiency in the UK (Chapter 4) and water efficiency in Australia (Chapter 5) was observed, although the magnitude of the rebound differed considerably, being much larger for the Australian water case. From longer-term historical patterns, a similarly large rebound for energy use has been observed, indicating that the difference is not due simply to the resource bases. In Chapter 5, a broad qualitative conclusion was arrived at, suggesting which types of

economic regime might give rise to large rebounds, but the hypothesis presented there could not be fully tested by the ECCO model.

3. Recent trends in the debate have levelled criticism at the simplifying assumptions of system dynamics models, specifically those based on the Forrester/Meadows school (e.g. Ausabel, 1996; Isaacson, 1998; Simon, 1998). Technological change has been posited as a key factor in eliminating resource constraints, and a key oversight of system dynamics models in general. Complex systems theory's critique of system dynamics as a limited subset has been drawn upon here as well.
4. With the climate of the debate in this state, it is quite likely that ECCO's unique insights be overlooked, if it is dismissed as another system dynamics model of resource limits. It is, and, as noted above, it can only proceed so far in analysing the rebound dynamics encountered when using it. However, the understanding of these dynamics that it has achieved is at least as advanced as that of any complex systems model with access to a more flexible set of rules.
5. In order to advance the analysis of the rebound effect on growth, some synthesis between ECCO and complex systems was seen to be required. The IPSO model offers such a synthesis, and, although it has raised more questions than it has answered, it has served to clarify a number of points. Specifically, by allowing a richer representation of technological change, it has provided a better taxonomy with which to attempt classification of regimes under which rebound effects will occur.
6. The broad interdisciplinarity concept has been important here in providing a framework within which to construct the IPSO model. Specifically, it allowed a clear separation of ECCO and the underlying Natural Capital Accounting theory, so that the latter could be transferred into the IPSO structure without the specific implementation-based limits of ECCO.
7. More importantly, broad interdisciplinarity assisted in the subsequent analysis of the results. By offering the option of qualitative dialogue between partially incompatible models, it prevented the ECCO model from being discarded. IPSO was not developed as a replacement for ECCO, but as a complement. Both models are capable of assessing certain aspects in greater detail than the other, and both bring insights to interpretation of the other's results. They should not even be considered as

intermediate stages in the process of developing a single unified model of rebound, as further progress would be more likely to be in the form of creating additional hybrids combining key features of ECCO, IPSO and other models.

Between them, IPSO and ECCO do not provide a full understanding of the complex interactions behind the growth debate. Nonetheless, they do offer a greater degree of insight into these interactions than either could achieve alone, and have been able to do so only by first examining the ways in which scientific, economic and interdisciplinary theories are developed and applied to policy-oriented discussions in general. To this extent, the third part of the hypothesis has been demonstrated to be true.

9.2 Towards a Thick Reading

This general examination also offers further insights into the debate, aside from its application to the simulation case studies.

The examination of the growth debate so far mirrors the discussion of economics in general, conducted in Chapter 3. An appraisal of two competing schools has been undertaken from the content level, with the main conclusion being that there is something worth listening to in both sides of the argument. This reading of the debate has failed to account for the strong polarisation of the debate.

In order to understand the debate in this way, it is necessary to go beyond the content to a 'thick' reading, and consider some of the contextual factors operating upon it. Some broad starting points for such a thick reading are outlined below.

In terms of social trends, the resource scarcity side of the argument precedes the pro-technology side by some ten to twenty years, having its immediate roots in the ecology movement of the 1960's and the broader development of the 'counter-culture' in that decade. A key specific factor in the development of this was the OPEC price hike of 1974, although a number of influential works (e.g. Carson, 1961; Meadows et al., 1971) preceded this event. Certainly, the general mood of despondency that characterised the 1970's was conducive to acceptance of these ideas.

There is also, of course, a strong appeal to predicting disaster. Precedents can be found as far back as written records extend (certainly to ancient Rome) of a bemoaning of the ruination of nature, and the lack of moral fibre in the younger generation. Detractors of the resource scarcity argument often apply the derogatory label of 'ecological

Cassandras' (leaving aside the fact that the Cassandra of myth was correct in her predictions).

The pro-technology debate has its immediate roots in the events of the late 1980's and early 1990's, with the increasing liberalisation of world markets and decline of communism. At the same time, the rise in the use of computers can be seen to play a role, in that much of the emphasis on technology's beneficial aspects lies in describing a substitution of materials by information, and a perception of opening up new ways of doing things.

This technological optimism can also be linked to the development of information technology and 'cyber-culture', and the renewed interest in the substitution of the human body by information systems. Discussions of these possibilities, until recently relegated to the backwaters of science fiction and other fringe areas (e.g. Moravec' (1989) discussion of a re-configurable robot replacement for the human body consisting of millions of molecule-width 'fingers' - presented as a factual account) has recently re-entered 'respectable' discussion, with Nobel-prize winner Murray Gell-Mann giving it a favourable mention in an otherwise serious popular science text (Gell-Mann, 1994), and Time Magazine devoting a recent editorial to the subject (Isaacson, 1998). Ausabel (1996) hints at similar possibilities in discussing a 'liberation *from* the environment' that technology also offers, whereby nature and humanity go their separate ways.

These discussions share a heady optimism, a fascination with what can be done that brushes over the issue of whether it is desirable. Technology is characterised as the driving force in opening up new actualities rather than new possibilities from which choices can be made.

In contrast to the ecological school's romantic roots (notably Thoreau, and the Arts & Crafts movement's association with John Stuart Mills), these ideas also come strongly from the intellect. There is very little interest in emotional response, or in the sensations of the body (often referred to as 'the meat' in cyber-culture). Arguably, the increasing emphasis on mathematisation of economics has created a mind-set receptive to this outlook of the individual. In terms of the language of Chapter 1, the two sides of the argument fail; to agree not because of an incompatibility of the economic models per se, but because of an underlying incompatibility in the models of human beings, and how they relate to their context.

This can offer no more than a starting point to a thick reading of the 'growth debate', and, for the purposes of this thesis must remain highly speculative. Nonetheless, it is suggested that such a broader analysis is necessary both to understand the debate, and to participate in it effectively. This suggests that the third statement presented in the hypothesis is true beyond the application of the simulation models presented here.

Appendix 1 Demonstration ECCO Models Source Code

The demonstration ECCO models used in the discussion on energy numeraires in chapter 4 were implemented in Professional Dynamo for DOS version 3.6. Source code listings are given below.

Uncorrected Demonstration Model Program Listing

The basic structure of the demonstration model is extremely simple, consisting of only four main sectors; industry, energy supply, other sectors and consumption.

```
* CAPDEEP.DYN - simple testing model for examining methods to cope with
capital deepening-related decoupling of embodied energy and
functionality of CS.

  Model to perform satisfactorily under four types of change:
  1] change in GER of energy supply system                       MCRT
  2] change in GER of factor-of-production supplier to industry   TCOT
& CSPOST
  3] change in input use ratio by industry                        TCIT
& FOSTIN
  4] change in capital use ratio by industry
CAPINT

  VERSION 1

 - 1 -   Industrial Sector
L CSIND.K=CSIND.J+DT*(RCFIND.JK-RDCIND.JK)
                                           man-made capital stock,
GJ
N CSIND=100
R RCFIND.KL=LEFT.K*FIND                 GJ/y
R RDCIND.KL=CSIND.K/LTIND                GJ/y
I LTIND=20                                 lifetime CSIND, y
I FIND=0.2                                        Consumption policy
option

A TEDIND.K=CSIND.K*PICRIND*TCI.K                 based on OCR=0.278,
LT=31
I PICRIND=0.25
A TCI.K=TABHL(TCIT,TIME.K,0,40,10)                user-defined tech.
change
T TCIT=1/1/1/1/1
A PEDIND.K=TEDIND.K*SYSGER.K

A CAPINDF.K=TABHL(CAPINT,TIME.K,0,40,10)
T CAPINT=1/1/1/1/1
```

```
A CSIND1.K=CSIND.K/CAPINDF.K

 * Growth Loop variables, expressed in embodied energy terms
A  INDOUT.K=RDCIND.KL+PEDIND.K+OSINP.K          total embodied energy of
INDOUT,
A LEFT.K=INDOUT.K-RCFOS.KL-RCFEN.KL


 - 2 -  Energy Supply System
L  CSEN.K=CSEN.J+DT*(RCFEN.JK-RDCEN.JK)          CS resource extraction,
GJ
N CSEN=DCSEN
R RCFEN.KL=DCSEN.K-CSEN.K+RDCEN.KL             GJ/y
R RDCEN.KL=CSEN.K/LTEN                         GJ/y
I LTEN=15                                          lifetime of capital,
years
A  MCR.K=0.272*TABHL(MCRT,TIME.K,0,40,10)          marginal cap. req.,
GJ/GJ
T MCRT=1/1/1/1/1
A DCSEN.K=MCR.K*TTED.K                            desired CS, GJ
A TTED.K=TEDIND.K+TEDOS.K
A SYSGER.K=1+(RDCEN.KL/TTED.K)

 - 3 -  Other Sector Providing Inputs
L CSOS.K=CSOS.J+DT*(RCFOS.JK-RDCOS.JK)         CS other sectors, GJ
N CSOS=100
R RCFOS.KL=DCSOS.K-CSOS.K+RDCOS.KL             GJ/y
R RDCOS.KL=CSOS.K/LTOS                         GJ/y
I LTOS=30
A DCSOS.K=DOSOUT.K*CSPOS.K
A DOSOUT.K=OSINP.K+OSCONS.K
A CSPOS.K=CSPOSN*TABHL(CSPOST,TIME.K,0,40,10)
T CSPOST=1/1/1/1/1
K CSPOSN=CSOS/(PEDOS+RDCOS)

A TEDOS.K=CSOS.K*PICROS*TCO.K                 based on OCR=0.278, LT=31
I PICROS=0.15
A  TCO.K=TABHL(TCOT,TIME.K,0,40,10)                    user-defined tech.
change
T TCOT=1/1/1/1/1
A PEDOS.K=TEDOS.K*SYSGER.K

A OSOUT.K=PEDOS.K+RDCOS.KL
A OSINP.K=CSIND.K*INPPCS.K
A INPPCS.K=INPPCSN*TABHL(FOSTIN,TIME.K,0,40,10)
I INPPCSN=0.1
T FOSTIN=1/1/1/1/1
A OSCONS.K=OSCONSN*MSOLF.K
K OSCONSN=OSOUT-OSINP

 - 4 -  Consumption and Material Affluence
A CONS.K=LEFT.K*(1-FIND)                       $/y

L MSOLF.K=MSOLF.J+DT*(RFMSOL.JK-RDMSOL.JK)
N MSOLF=1
R RFMSOL.KL=CONS.K/CONSN
R RDMSOL.KL=MSOLF.K
```

```
K CONSN=CONS

 - 5 -  Simulation Specifications, etc.
C INITIME=0
N TIME=0
SPEC DT=0.125,LENGTH=40,SAVPER=1
```

Corrected Demonstration Model Program Listing (Solution 1)

Under solution 1, capital stocks and the main growth loop are run using actual embodied energy units. Two solutions are presented, labelled solution 1 and solution 1a. The changes in CAPD1.DYN incorporated into CAPD1A.DYN are listed below the main program listing. Actual embodied energy is noted 'GJ', and service-corrected embodied energy as 'VGJ' in the program comments.

```
* CAPDEEP.DYN - simple testing model for examining methods to cope with
capital
  deepening-related decoupling of embodied energy and functionality of
CS.

  Model to perform satisfactorily under four types of change:
  1] change in GER of energy supply system                        MCRT
  2] change in GER of factor-of-production supplier to industry    TCOT
& CSPOST
  3] change in input use ratio by industry                         TCIT
& FOSTIN
  4]     change     in     capital     use     ratio     by     industry
CAPINT

  VERSION 1 of the model tries to run all capital stocks using the
embodied
  energy numeraire as the primary measure, correcting as it goes along.

  - INDOUTB expresses INDOUT in constant volume terms
  1]  PEDIND  is  direct  fuel  measure,  not  embodied,  so  no  direct
correction
  2] dealt with by OSINPB = OSINP*OSOUTF
  3] dealt with by PEDINDB = PEDIND/TCI  &  OSINPB = OSINP/INPPCSF
  4] dealt with by inserting CSIND1 not CSIND in PEDIND & OSINP equns.


 - 1 -   Industrial Sector
L CSIND.K=CSIND.J+DT*(RCFIND.JK-RDCIND.JK)
                                          man-made   capital   stock,
GJ
N CSIND=100
R RCFIND.KL=LEFT.K*FIND                 GJ/y
R RDCIND.KL=CSIND.K/LTIND                GJ/y
I LTIND=20                                lifetime CSIND, y
I FIND=0.2                                      Consumption policy
option

A TEDIND.K=CSIND1.K*PICRIND*TCI.K
I PICRIND=0.25
A  TCI.K=TABHL(TCIT,TIME.K,0,40,40)             user-defined  tech.
change
T TCIT=1/1
A PEDIND.K=TEDIND.K*SYSGER.K
```

```
A CAPINDF.K=TABHL(CAPINT,TIME.K,0,40,40)
T CAPINT=1/1
A CSIND1.K=CSIND.K/CAPINDF.K                    corrected CSIND for
calculating
                                                volume-based  vars  eg.
PEDIND
```

- 1.1 - Central Model Growth Loop

```
A INDOUT.K=RDCIND.KL+PEDIND.K+OSINP.K           total embodied energy of
INDOUT, GJ
A LEFT.K=INDOUT.K-RCFOS.KL-RCFEN.KL

A INDOUTB.K=RDCINDB.K+PEDINDB.K+OSINPB.K        total embodied energy of
INDOUT, VGJ
A RDCINDB.K=CSIND1.K/LTIND
A PEDINDB.K=TEDIND.K*SYSGERN/(TCI.K)
A OSINPB.K=OSINP.K/(OSOUTF.K*INPPCSF.K)
A OSOUTF.K=OSOUT.K/OSOUTB.K
A OSOUTB.K=(TEDOS.K*SYSGERN/TCO.K)+(RDCOS.KL/REDEII.K)

 set as a level variable only to avoid simultaneous equations
L REDEII.K=REDEII.J+dt*(RFEII.JK-RDEII.JK)
N REDEII=1
R RFEII.KL=INDOUT.K/INDOUTB.K
R RDEII.KL=REDEII.K
```

- 2 - Energy Supply System

```
L CSEN.K=CSEN.J+DT*(RCFEN.JK-RDCEN.JK)          CS resource extraction,
GJ
N CSEN=DCSEN
R RCFEN.KL=DCSEN.K-CSEN.K+RDCEN.KL              GJ/y
R RDCEN.KL=CSEN.K/LTEN                          GJ/y
I LTEN=15                                           lifetime of capital,
years
A MCR.K=0.272*MCRF.K
A MCRF.K=TABHL(MCRT,TIME.K,0,40,40)           marginal cap. req., GJ/GJ
T MCRT=1/1
A DCSEN.K=MCR.K*TTED.K                            desired CS, GJ
A TTED.K=TEDIND.K+TEDOS.K
A SYSGER.K=1+(RDCEN.KL/TTED.K)
K SYSGERN=SYSGER
```

- 3 - Other Sector Providing Inputs

```
L CSOS.K=CSOS.J+DT*(RCFOS.JK-RDCOS.JK)          CS other sectors, GJ
N CSOS=100
R RCFOS.KL=DCSOS.K-CSOS.K+RDCOS.KL              GJ/y
R RDCOS.KL=CSOS.K/LTOS                          GJ/y
I LTOS=30
A DCSOS.K=DOSOUT.K*CSPOS.K
A DOSOUT.K=OSINP.K+OSCONS.K
A CSPOS.K=CSPOSN*CSPOSF.K
A CSPOSF.K=TABHL(CSPOST,TIME.K,0,40,40)
T CSPOST=1/1
K CSPOSN=CSOS/(PEDOS+RDCOS)
```

```
A TEDOS.K=CSOS.K*PICROS*TCO.K                    based on OCR=0.278, LT=31
I PICROS=0.15
A  TCO.K=TABHL(TCOT,TIME.K,0,40,40)                        user-defined tech.
change
T TCOT=1/1
A PEDOS.K=TEDOS.K*SYSGER.K

A OSOUT.K=PEDOS.K+RDCOS.KL
A OSINP.K=CSIND1.K*INPPCS.K
A INPPCS.K=INPPCSN*INPPCSF.K
A INPPCSF.K=TABHL(FOSTIN,TIME.K,0,40,40)
I INPPCSN=0.1
T FOSTIN=1/1
A OSCONS.K=OSCONSN*MSOLF.K
K OSCONSN=OSOUT-OSINP

 - 4 -  Consumption and Material Affluence
A CONS.K=LEFT.K*(1-FIND)                        $/y

L MSOLF.K=MSOLF.J+DT*(RFMSOL.JK-RDMSOL.JK)
N MSOLF=1
R RFMSOL.KL=CONS.K/CONSN
R RDMSOL.KL=MSOLF.K
K CONSN=CONS

 - 5 -  Simulation Specifications, etc.
C INITIME=0
N TIME=0
SPEC DT=0.125,LENGTH=40,SAVPER=1
```

Version 1a of the model (CAPD1A.DYN) differs in the following lines of code:

VERSION 1A of the model tries to run all capital stocks using the embodied
  energy numeraire as the primary measure, correcting as it goes along.
  Input terms such as TEDIND, which are CS driven, are altered by factor
  REDEII, as if entire CS were reduced immediately with tech changes.

  - INDOUTB expresses INDOUT in constant volume terms
  1] PEDIND is direct fuel measure, not embodied, so no direct correction
  2] dealt with by OSINPB = OSINP*OSOUTF
  3] dealt with by PEDINDB = PEDIND/TCI & OSINPB = OSINP/INPPCSF
  4] dealt with by inserting CSIND1 not CSIND in PEDIND & OSINP equns.

```
A TEDIND.K=(CSIND1.K/REDEII.K)*PICRIND*TCI.K
I PICRIND=0.25
A TCI.K=TABHL(TCIT,TIME.K,0,40,40)                         user-defined tech.
change
T TCIT=1/1
A PEDIND.K=TEDIND.K*SYSGER.K

A  TEDOS.K=(CSOS.K/REDEII.K)*PICROS*TCO.K                            based on
OCR=0.278, LT=31
```

```
I PICROS=0.15
A  TCO.K=TABHL(TCOT,TIME.K,0,40,40)                    user-defined tech.
change
T TCOT=1/1
A PEDOS.K=TEDOS.K*SYSGER.K
```

Corrected Demonstration Model Program Listing (Solution 2)

Under solution 2, capital stocks and the main growth loop are run using volume-corrected embodied energy units.

```
* CAPDEEP.DYN - simple testing model for examining mehods to cope with
capital
  deepening-related decoupling of embodied energy and fnctionality of
CS.

  Model to perform satisfactorily under four types of change:
  1] change in GER of energy supply system                          MCRT
  2] change in GER of factor-of-production supplier to industry    TCOT
& CSPOST
  3] change in input use ratio by industry                          TCIT
& FOSTIN
  4]    change    in    capital    use    ratio    by    industry
CAPINT

  VERSION 2 of the model tries to run all capital stocks using the
constant
  embodied energy numeraire as the primary measure. Actual metabolic
flows are
  secondary here.

  - INDOUTB expresses INDOUT in constant volume terms
  1]  PEDIND  is  direct  fuel,  not  embodied  energy,  so  no  primary
correction
  2] dealt with by OSINPB = OSINP*OSOUTF
  3] dealt with by PEDINDB = PEDIND/TCI  &  OSINPB = OSINP/INPPCSF
  4] dealt with by inserting CSIND1 not CSIND in PEDIND & OSINP equns.
  - RCF terms corrected by REDEII for non-industry sectors
  - LEFTB used to determine CONS and therefore MSOLF, and to run growth
loop

 - 1 -   Industrial Sector
L CSIND.K=CSIND.J+DT*(RCFIND.JK-RDCIND.JK)
                                             man-made  capital  stock,
VGJ
N CSIND=100
R RCFIND.KL=LEFTB.K*FIND                    VGJ/y
R RDCIND.KL=CSIND.K/LTIND                   VGJ/y
I LTIND=20                                    lifetime CSIND, y
I FIND=0.2                                          Consumption policy
option

A TEDIND.K=CSIND1.K*PICRIND*TCI.K
I PICRIND=0.25
A  TCI.K=TABHL(TCIT,TIME.K,0,40,40)                user-defined tech.
change
T TCIT=1/1
A PEDIND.K=TEDIND.K*SYSGER.K
```

```
A CAPINDF.K=TABHL(CAPINT,TIME.K,0,40,40)
T CAPINT=1/1
A CSIND1.K=CSIND.K/CAPINDF.K                      corrected CSIND for
calculating
                                              volume-based  vars  eg.
PEDIND


 - 1.1 -  Central Model Growth Loop
A INDOUT.K=RDCIND.KL+PEDIND.K+OSINP.K         total embodied energy of
INDOUT, GJ/y
A LEFT.K=INDOUT.K-RCFOS.KL-RCFEN.KL
A LEFTB.K=INDOUTB.K-RCFOS.KL-RCFEN.KL

A INDOUTB.K=RDCINDB.K+PEDINDB.K+OSINPB.K
       total embodied energy of INDOUT, VGJ/y
A RDCINDB.K=CSIND1.K/LTIND
A PEDINDB.K=TEDIND.K*SYSGERN/TCI.K
A OSINPB.K=OSINP.K/(OSOUTF.K*INPPCSF.K)
A OSOUTF.K=OSOUT.K/OSOUTB.K
A OSOUTB.K=(TEDOS.K*SYSGERN/TCO.K)+(RDCOS.KL/REDEII.K)

 set as a level variable only to avoid simultaneous equations
L REDEII.K=REDEII.J+dt*(RFEII.JK-RDEII.JK)
N REDEII=1
R RFEII.KL=INDOUT.K/INDOUTB.K
R RDEII.KL=REDEII.K


 - 2 -  Energy Supply System
L CSEN.K=CSEN.J+DT*(RCFEN.JK-RDCEN.JK)          CS resource extraction,
VGJ
N CSEN=DCSEN
R RCFEN.KL=DCSEN.K-CSEN.K+RDCEN.KL            VGJ/y
R RDCEN.KL=CSEN.K/LTEN                        VGJ/y
I LTEN=15                                         lifetime of capital,
years
A MCR.K=0.272*MCRF.K
A MCRF.K=TABHL(MCRT,TIME.K,0,40,40)         marginal cap. req., VGJ/GJ
T MCRT=1/1
A DCSEN.K=MCR.K*TTED.K                          desired CS, VGJ
A TTED.K=TEDIND.K+TEDOS.K
A SYSGER.K=1+(RDCEN.KL/TTED.K)
K SYSGERN=SYSGER


 - 3 -  Other Sector Providing Inputs
L CSOS.K=CSOS.J+DT*(RCFOS.JK-RDCOS.JK)        CS other sectors, VGJ
N CSOS=100
R RCFOS.KL=DCSOS.K-CSOS.K+RDCOS.KL            VGJ/y
R RDCOS.KL=CSOS.K/LTOS                        VGJ/y
I LTOS=30
A DCSOS.K=DOSOUT.K*CSPOS.K
A DOSOUT.K=OSINP.K+OSCONS.K
A CSPOS.K=CSPOSN*CSPOSF.K
A CSPOSF.K=TABHL(CSPOST,TIME.K,0,40,40)
```

```
T CSPOST=1/1
K CSPOSN=CSOS/(PEDOS+RDCOS)

A TEDOS.K=CSOS.K*PICROS*TCO.K                 based on OCR=0.278, LT=31
I PICROS=0.15
A  TCO.K=TABHL(TCOT,TIME.K,0,40,40)                     user-defined tech.
change
T TCOT=1/1
A PEDOS.K=TEDOS.K*SYSGER.K

A OSOUT.K=PEDOS.K+RDCOS.KL
A OSINP.K=CSIND1.K*INPPCS.K
A INPPCS.K=INPPCSN*INPPCSF.K
A INPPCSF.K=TABHL(FOSTIN,TIME.K,0,40,40)
I INPPCSN=0.1
T FOSTIN=1/1
A OSCONS.K=OSCONSN*MSOLF.K
K OSCONSN=OSOUT-OSINP

 - 4 -  Consumption and Material Affluence
A CONS.K=LEFT.K*(1-FIND)                       VGJ/y
A CONSB.K=LEFTB.K*(1-FIND)

L MSOLF.K=MSOLF.J+DT*(RFMSOL.JK-RDMSOL.JK)
N MSOLF=1
R RFMSOL.KL=CONSB.K/CONSN
R RDMSOL.KL=MSOLF.K
K CONSN=CONS

 - 5 -  Simulation Specifications, etc.
C INITIME=0
N TIME=0
```

Appendix 2 Source Code Listings for OzEcco Model

The OzEcco model was implemented using the MS-DOS version of the Professional Dynamo software (version 3.6) developed by Pugh-Roberts Associates. The annotated source code for the program is given below. Other than the default runtime extensions and function libraries provided with Dynamo, all code and data is contained in a single text file.

```
* OZ.DYN: Australian ECCO Model Draft 3.4

== TIME NOTATION
 Australian National Accounts and other data sources give time series
data by
 financial year. For simplicity, these are referred to by first
calendar year,
 e.g. model is initialised in 1981/82, denoted as 1981 in model.

 This year of initialisation chosen because several IO tables for
following
 years are available, and because it is earliest year reported on in
1992-3
 National Accounts. This gives an 11-year period for validation, as
1992-3 is
 latest year for which full data is available.

 == SECTORISATION
 Following the breakdown of fixed
 capital given in the National Accounts and Energy Statistics, the
following
 sectors are identified:

   Agriculture - inc. Agriculture, forestry, fishing & hunting
   Mining
   Industry - inc. Manufacturing, Construction
   Electricity    \
   Gas            |- need disaggrgating from El, Gas & Wat category
   Water          /
   Domestic - inc. ownership of dwellings
   Services - inc. Wholesale/retail, Transport etc., Finance, etc.,
Community,
               Recreation etc.

 Additional sectors not requiring a capital stock are:

   Population
   Resource Bases
   Consumption
   Pollution

   Transport DOES entail a stock of fixed capital, but this is subsumed
within
 the CS's of other sectors, in keeping with ABS conventions. Hence, the
```

transport sector of the model makes no explicit reference to the capital
stock requirements of that activity, and it is not included within section 2
of the model.

== REFERENCES

AusPopT&P'92 Australia's Population Trends & Prospects 1992, Jing Shu & Siew Ean Khoo, Australian Govt. Publishing Service, Canberra

AusNI'92 Australian National Accounts 1992-3: National Income Expenditure and Product, ABS Cat no. 5204.0

YB'95 Year Book Australia 1995, ABS

ABARE'92 Energy Demand & Supply Projections, Australia 1992-3 to 2004-5 ABARE Research Project

AusIO'?? Australian National Accounts Input-Output Table for year 19??/?+1, ABS

BF_FAX_ddMONyy refers to faxed or emailed info sent by Barney Foran on date given

BP'92 British Petroleum Statistical Review of World Energy June 1992

NOTE: Conventions adopted in this model:
refined energy vectors that are immediately usable are called FUELS
Energy as it is extracted is referred to as primary energy and called ENERGY, and requires treatment before it can become a FUEL

Capital stock is called HMC stock- Human made capital - and is quantified as the ENERGY that was irretrievably dissipated in its production and delivery to the point of use/assembly/activity.
Rates of capital formation are expressed HMC per year.

==== Initial Conditions: must be reset if model altered ================

See manual for description of iterative procedure for resetting these terms

= Energy Intensity of Industry: see section 2.1

C EII=7.27E-9 energy intensity calculations, PJ/$ PEDIND=1126PJ; total PED input ~1320PJ when AFF,TRA,SER counted RDC terms for IND, AGR(27%), SER(6.5%) amount to ~$7E9 INDOUT$=$141E9= HCONS$+HTRCF$-HBALPAY$=$(93+78-30)E9 Intermediate Goods are 20% of output in IO tables So initial EII calculation =

```
                        (1320*0.8)/(141-(6*0.8)E9)=7.8E-9PJ/$          After
iteration,
                        this settles on ~7.3E-9, quoted above DC'96b

A NEWEII.K=INDOUT.K/INDOUT$
                       model-calculated  initial  value,  for  checking  EII
value. As
                        INDOUT$ is static, this term is meaningless beyond
first
                        year
I    INDOUT$=141E9   money value of INDOUT in year of initialisation -
from IO
                        table 31.8E9@81 prices, rough deflator 0.6

 historical  INDOUT  time  series  based  on  sum  of  intermediate  inputs  to
the
 industrial sector in 81/2, 89/90 & 92/3 input-output tables DC'97B
A
HINDOT$.K=FIFGE(HINDT3$.K,FIFGE(HINDT1$.K,HINDT2$.K,TIME.K,1986),TIME.K
,1989)
A HINDT1$.K=TABHL(HINDT1T,TIME.K,1986,1989,3)*1E9
T HINDT1T=126.0/156.5
A HINDT2$.K=TABHL(HINDT2T,TIME.K,1981,1986,5)*1E9
T HINDT2T=141.0/126.0
A HINDT3$.K=TABHL(HINDT3T,TIME.K,1989,1992,3)*1E9
T HINDT3T=156.5/202.9

A HINDOUT.K=HINDOT$.K*EII/REDEII.K

 = System Energy Transformation Coefficients: see section 0
I   FERELN=11.70E-3 initial value for FEREL DC'96b
I   SYSGERN=1.081 initial value for SYSGER DC'96b

 = Material Standard of Living Initialised in 1983: section 3.1
I    MSOL83=31.9 56.297     GJ personal average per cap affluence, GJ/y
DC'96a

 =  INDEX  of  industrial  output  for  1992,  used  to  set  up  driver  for
BALPAY
 when historical data series terminates: see Section 2.1
I   INDEX92=1.532  value of INDEX in 1992  DC'96a

 == 0  SYSTEM ENERGY TRANSFORMATION COEFFICIENTS
 WARNING!
    kWh & GWh denote only electricity.
    MJ, GJ, and PJ denote calorific yield of fuels on combustion. All
    fuels must be expressed in terms of a standard thermodynamic
    quality (Availability). In ECCO models the convention is to adopt
    the  quality  associated  with  hard  coal,  natural  gas  and  oil
products,
    all  of  which  have  thermodynamic  Availabilities  within  2%  of  each
other.

    In this program the unit of embodied energy used is the peta-joule
(PJ)
```

An important variable in an ECCO model is the system-wide measure of the
amount of primary energy dissipated to deliver one unit of fuel to the market.
This is known as SYSGER (see ECCO training manual) and will change as the
resource base and the technologies of transformation evolve. SYSGER cannot
be computed accurately at present, as capital costs of the energy supply line
are not fully incorporated (e.g. oil refineries, gas supply lines). However,
the current derived value is a valid approximation.

```
L SYSGER.K=SYSGER.J+dt*(RCSYS.JK-RDSYS.JK)
                    system gross energy requirement
N   SYSGER=SYSGERN
R RCSYS.KL=1+((RPOIL.KL*(EREOIL.K-1)+OILDEM.K*(OILREF.K-1)+RPGAS.KL* ^
    (EREGAS.K-1)+RPCOL.KL*(ERECOL.K-1)+BIODEM.K*(EREBIO.K-
1))/PRIMED.K)
                    instantaneous value of SYSGER
R RDSYS.KL=SYSGER.K
                    old value of SYSGER: for internal calculations
```

As ECCO is modelled in terms of primary energy dissipated per unit output, it
is necessary to compute the primary energy required to deliver one unit of
electricity. This coefficient will vary with technology of electricity
generation, the first law efficiency of that generation, distribution
losses and the mix of tecnologies used. In ECCO it is first computed as
FEREL (fuel energy requirement for electricity) and its primary energy
analogue - GEREL = FEREL * SYSGER. As with SYSGER, FEREL cannot be accurately
computed till the energy supply sector is fully modelled. In the pilot model
a dummy value of 12 MJ/kWh (electric) is used, which about the West European
value. Ccovering direct fuel, capital inputs and some allowance for
distribution networks etc. not directly represented in pilot model

```
L FEREL.K=FEREL.J+dt*(RCFEREL.JK-RDFEREL.JK)
                    fuel input per unit electricity at final demand,
PJ/GWh
N   FEREL=FERELN
R RCFEREL.KL=(FUELEL.K+BIOEL.K+((RDCCOEL.K+RDCHYD.K+RDCREN.K+RDCBIO.K)^
                    /REDEII.K))/EEDFD.K
                    instantaneous value of FEREL, PJ/GWh  DC'96b
R RDFEREL.KL=FEREL.K
                    old value of FEREL: for internal calculations
A GEREL.K=FEREL.K*SYSGER.K
                    primary energy input per unit electricity at final
demand,
                     PJ/GWh
```

== 1 BIOSPHERE COMPONENTS

= 1.1 HUMAN POPULATION

It is reccomended that an age-disaggregated population module be inserted, if
a detailed understanding of population dynamics (relating to employment, say)
is required.

```
I POPSCEN=1     population scenario switch
                1 (default) gives declining NBR representing demographic
                 shifts, leading to 26million in 2050
                2 (POP35) gives 35 million in 2050
                3 (POP50) gives 50 million in 2050
                4 (POP20) gives 20 million in 2050
                The switch operates on both NBR & NMIG terms
 * Initial values & population sector structure
L TPOP.K=TPOP.J+dt*(NBR.JK+NMIG.JK)
                    total population, persons
N   TPOP=14.923e6  AusPopT&P'92 T1.1
A HPOP.K=TABHL(HPOPT,TIME.K,1981,1995,1)*1E6
                    historical demographic profile, capita

 historical data on population
T
HPOPT=14.923/15.184/15.393/15.579/15.788/16.018/16.263/16.532/16.814/ ^
     17.065/17.284/17.489/17.656/17.838/18.054  data  from  AusPopT&P'92
Table 1.1

 * Natural change through births and deaths - cap/y
R NBR.KL=TPOP.K*NBRF.K
                    net birth rate, cap/y
A NBRF.K=(FIFGE(TABHL(NBRFT4,TIME.K,1980,2050,10),^
          FIFGE(TABHL(NBRFT3,TIME.K,1980,2050,10),^
          FIFGE(TABHL(NBRFT2,TIME.K,1980,2050,10),^
          TABHL(NBRFT1,TIME.K,1980,2050,10),^
          POPSCEN,2),POPSCEN,3),POPSCEN,4))/1000
                    net birth rate factor, cap/1000.y
T   NBRFT1=8.50/8.50/4.50/4.20/3.75/2.51/0.67/-0.18
                    net birth rate factor - cap/y per 1000 DATA
                     this particular set gives 26 million people in 2050
                     P'92, T1.1: average 1981-91 (nat. increase)
T   NBRFT2=8.50/8.50/7.29/6.50/5.00/3.89/2.45/1.50
                     this particular set gives 35 million people in 2050
                     P'92, T1.1: average 1981-91 (nat. increase)
T   NBRFT3=8.50/8.50/7.50/6.81/6.06/5.50/4.50/3.50
                     this particular set gives 50 million people in 2050
                     P'92, T1.1: average 1981-91 (nat. increase)
                     figures supplied by BDF 5-2-97
T   NBRFT4=8.50/8.50/2.50/2.50/1.52/-0.75/-1.65/-1.31
                     this particular set gives 20 million people in 2050
                     P'92, T1.1: average 1981-91 (nat. increase)
                     figures supplied by BDF 5-2-97


 * In- and Out-Migration flows - cap/year
R NMIG.KL=(FIFGE(TABHL(NMIGT4,TIME.K,1980,2050,10),^
           FIFGE(TABHL(NMIGT3,TIME.K,1980,2050,10),^
           FIFGE(TABHL(NMIGT2,TIME.K,1980,2050,10),^
           TABHL(NMIGT1,TIME.K,1980,2050,10),^
```

```
          POPSCEN,2),POPSCEN,3),POPSCEN,4))*1000
                    net migration, cap/y
T   NMIGT1=86/86/86/86/86/86/86/86
                    net migration - cap/y DATA FROM AusPopT&P'92, T1.1:
average
                     1981-92 Migration Australia 94-95 ABS cat 3412.0
T   NMIGT2=86/86/150/202/202/202/202/202
                    net migration - cap/y DATA FROM AusPopT&P'92, T1.1:
average
                     1981-91
T   NMIGT3=86/86/395/395/395/395/395/395
                    net migration - cap/y DATA FROM AusPopT&P'92, T1.1:
average
                     1981-91
                    figures for three scenarios supplied by BDF 5-2-97
T   NMIGT4=86/86/86/10/10/10/10/10
                    net migration - cap/y DATA FROM AusPopT&P'92, T1.1:
average
                     1981-91
                    figures for three scenarios supplied by BDF 5-2-97
```

== 1.2 NATURAL RESOURCE BASES

Resource bases are described in terms of the relationship between cumulative extraction and inaccessibility, the latter measured by ERE (energy requirement for energy), which determines the amount of process energy input (direct and indirect) required to bring the resource to the surface. ERE is a function of both geology and technology.

Only energy resources are modelled at present. Reserves and extraction rate are determined in energy units (PJ), here referring to calorific rather than embodied energy content.

New structure following NRA Energy Accounts for Australia 1995, with stocks adjusted by (endogenous) extraction rates, and (exogenous) discovery rates, the latter set at zero default value. Allows exploration of scenarios in which fossil fuel depletion not seen as a serious limit. DC'96a

The OPTxxx variables are set up for validation model only: if OPT=0 then RCF is set equal to HRCF, effectively switching off most of that sector. OPT=1 sets RCF to model determined value. This allows sectors (and errors assoc'd with them) to be flipped easily with historical data, isolating certain sectors for testing purposes.

```
I   OPTOIL=1        switches oil extraction to historical rate
I   OPTGAS=1        switches gas extraction to historical rate
I   OPTCOL=1        switches coal extraction to historical rate
```

```
 = Mineral Oils
 size of stocks (PJ) affected by extraction and new discoveries (PJ/y)
 covers both economic & subeconomic stocks, as defined by McKelvey
classific'n
 extraction cost dealt with via ERE function
L OILSTK.K=OILSTK.J+dt*(DISCOIL.JK-RPOIL.JK)
N OILSTK=13E3       NRA_EA 270Gl oil + 83Gl condensate
R RPOIL.KL=FIFGE(FIFZE(HRPOIL.K,CSOIL.K/CSPOIL,OPTOIL),0,OILSTK.K,0)
                    extra switch to cease production when stocks hit
zero DC'97c
                    rate of extraction of oil, PJ/y
K   CSPOIL=CSOIL/HRPOIL
                    capital stoc req. per unit oil extracted
R DISCOIL.KL=TABHL(DISTOIL,TIME.K,1980,2050,10)
                    discovery of new oil reserves, PJ/y
T DISTOIL=500/2000/500/1500/0/0/0/0
                    default=0, as discovery unpredictable DC'96a
                     bdf 20/2/97 set at above to equal BRS probable
finds
                     bdf new stocks 16/10/97:STRAIGHT LINE FINDS
A HOILSTK.K=(TABHL(HCRUSTT,TIME.K,1981,1994,1)^
           +TABHL(HCNDSTT,TIME.K,1981,1994,1))*37
T HCRUSTT=270/261/249/231/231/224/231/240/252/278/258/251/247/273
T HCNDSTT=83/78/71/82/81/80/118/118/121/107/124/129/135/147
 1981 data from ABARE'93 spreadsheets DC'96a
 1982-94 data from abs Energy Accounts 1993-4 (EDR only) DC'96b

 ERE for oil reserves, set as function of cumulative extraction
 with lower limit introduced for abundance scenarios
A EREOIL.K=MAX(1.02,TABXT(EREOILT,OILSTK.K,1E3,17E3,2E3))
                    or ERE for energy resources
T   EREOILT=1.16,1.12,1.10,1.08,1.07,1.06,1.05,1.04,1.03
                    ERE data based on NRA_EA DATA TABLE 3.2: 10E3PJ
economic
                     plus 7E3PJ subeconomic reserves at end 1992 for
crude plus
                     condensates   (@37PJ/Gl:   NRA_EA   table   2.3)
Discoveries
                     between 1981 & 92 factored in DC'96a

 ERE of Middle Eastern oil, for purposes of calculating competitiveness
 based on world oil ERE determined by GLOBECCO model under business as
usual
 or hydrogen transition scenarios (choose using GLOBH2 switch)
I GLOBH2=0    0=BAU, 1=H2 economy world ERE data
A  EREME.K=1+SWITCH(EREWOT1.K,EREWOT2.K,GLOBH2)
A    EREWOT1.K=TABHL(EREWT1,TIME.K,1992,2097,5)*0.01      EREOIL  crude
GJ/GJ
A    EREWOT2.K=TABHL(EREWT2,TIME.K,1992,2097,5)*0.01      EREOIL  crude
GJ/GJ
T
EREWT1=6.23/7.33/8.56/9.56/10.97/12.48/14.15/15.45/17.88/20.05/21.80/23
.06^
         /32.54/46.34/56.05/64.04/70.91/77.02/82.51/87.48/92.01/96.16
```

```
T
EREWT2=6.23/7.33/8.51/9.24/10.14/11.18/12.21/12.79/13.29/13.74/14.16/14
.52^
         /14.84/15.11/15.33/15.49/15.59/15.68/15.77/15.86/15.93/16.01

A PWOILPR.K=TABHL(PWOITPR,TIME.K,1993,2009,1)
T PWOITPR=14.90/16.00/16.40/18.70/18.00/17.60/19.00/19.00/21.00^
          /22.00/20.50/19.30/19.00/18.80/22.00/24.00/24.00
  projected world oil prices, US$/BBL ABARE'95 T13 DC'97c
A PWOILX.K=PWOILPR.K/14.90
  index of above projection
A WOILX.K=FIFGE((EREME.K-1)/0.0645,1,TIME.K,1993)
  index of model's own assumptions from GlobEcco DC'97c

 = Natural Gas
 size of stocks (PJ) affected by extraction and new discoveries (PJ/y)
 covers both economic & subeconomic stocks, as defined by McKelvey
classific'n
 extraction cost dealt with via ERE function
L GASSTK.K=GASSTK.J+dt*(DISCGAS.JK-RPGAS.JK)
N GASSTK=28.5E3      NRA_EA 640Gm3 gas + 130Gl LPG
R    RPGAS.KL=FIFGE(FIFZE(HRPGAS.K,CSGAS.K/CSPGAS,OPTGAS),0,GASSTK.K,0)
DC'97c

 ERE for gas reserves, set as function of cumulative extraction
 with lower limit introduced for abundance scenarios
A EREGAS.K=MAX(1.02,TABXT(EREGAST,GASSTK.K,5E3,85E3,10E3))
                   or ERE for energy resources
T     EREGAST=1.18,1.12,1.07,1.06,1.055,1.05,1.045,1.04,1.035    REVISED
DC'96b
            1.18,1.14,1.10,1.07,1.06,1.05,1.04,1.033,1.03
                   ERE data based on NRA_EA DATA TABLE 3.2: 40E3PJ
economic
                    plus 45E3PJ subeconomic reserves at end 1992 for
gas plus
                    LPG (@39PJ/Gm3 & 26.5PJ/Gl resp.: NRA_EA table 2.3)
                    Discoveries between 1981 & 92 factored in DC'96a

 = Coal (black & brown)
 size of stocks (PJ) affected by extraction and new discoveries (PJ/y)
 covers both economic & subeconomic stocks, as defined by McKelvey
classific'n
 extraction cost dealt with via ERE function
L COLSTK.K=COLSTK.J+dt*(DISCCOL.JK-RPCOL.JK)
N COLSTK=1170E3      NRA_EA 30Gt black + 36Gt brown
R
RPCOL.KL=FIFGE(FIFZE(HRPCOL.K,CSCOL.K*CSCEFF.K/CSPCOL,OPTCOL),0,COLSTK.
K,0)
                   rate of extraction of coal, PJ/y    DC'97c
K   CSPCOL=CSCOL/HRPCOL
                   capital stoc req. per unit coal extracted
A CSCEFF.K=TABHL(CSCEFT,TIME.K,1981,2051,10)
T CSCEFT=1/1.2/1.2/1.2/1.2/1.2/1.2/1.2
                   capital efficiency coal, exog. tech. change  DC'96b

R DISCCOL.KL=TABHL(DISTCOL,TIME.K,1980,2050,10)
                   discovery of new coal reserves, PJ/y
```

```
T DISTCOL=66E3/66E3/1000/1000/1000/1000/1000/1000
                    default=0, as discovery unpredictable DC'96a
                    bdf 20/2/97 new data
A HCOLSTK.K=TABHL(HBLCSTT,TIME.K,1981,1993,1)*27E3^
           +TABHL(HBRCSTT,TIME.K,1981,1993,1)*10E3
T
HBLCSTT=30/30.4/31.0/35.0/34.0/34.0/49.5/49.7/50.8/51.1/51.4/52.0/52.0
T
HBRCSTT=36/36.2/37.0/41.9/41.9/41.9/41.9/41.8/41.8/41.7/41.7/41.0/41.0
 1981 data from ABARE'93 spreadsheets DC'96a: orig data in Gt, conv. to
PJ
 1982-94 data from abs Energy Accounts 1993-4 (EDR recoverable only)
DC'96b

 ERE for coal reserves, set as function of cumulative extraction
 with lower limit introduced for abundance scenarios
A ERECOL.K=MAX(1.01,TABXT(ERECOLT,COLSTK.K,200E3,2000E3,1800E3))
                    or ERE for energy resources
T   ERECOLT=1.018,1.014
                    ERE data based on NRA_EA DATA TABLE 3.2: 1.8E6PJ
economic
                     plus .2E6PJ subeconomic reserves at end 1992 for
Brown &
                     black coal (@27E3PJ/Gt & 10E3PJ/Gt resp.: NRA_EA
table 2.3)
                     Discoveries between 1981 & 92 factored in DC'96a
                     ERECOL has very low values based on comparison of
money
                     value and energy content of exports, giving an
average
                     of 1.015 for '89-'94. This sorts out previous
overestimate
                     of visibles balance of payments   DC'96b

 NB: ERE data calculated very crudely at present, as a linear increase
over
 range from a current 1.03 to 1.08, at quoted "uneconomic" point,
followed by
 steeper rise to around 1.16 through sub-economic reserves.
 Investment will cease when ERE of reserve reaches ERECUT, the economic
 cut-off point. Production will not cease automatically, but dwindle
over time.
A ERECUT.K=TABHL(ERECUTT,TIME.K,1981,2051,10)
T ERECUTT=1.1/1.1/1.1/1.12/1.14/1.16/1.18/1.2
                     threshold ERE at which resource base uneconomic:
user
                     defined

 == Total Demand for Energy
A
PRIMED.K=(TEDAFF.K+TEDTMIN.K+TEDIND.K+FUELEL.K+BIOEL.K+TEDDOM.K+TEDSER.
K+ ^
     TEDTRA.K)*SYSGER.K
                    primary energy demand, PJ/y  AGR -> AFF. BIOEL added
also;
                    adding together on calorific value basis, despite
lower
```

availability of fuelwood cf. fossil hydrocarbons.
This
approximation is OK so long as BIOFUEL contrib
small, and
mainly allocated to space heating (as current use),
where
availability not an issue, or with bio-electricity
plants,
where availability reflected in low thermal
efficiency, and
in FEREL. DC'96b

== 1.2.1 == Water Resources ===

Water Resources are characterised in the ABS data sets as ground- and fresh-, and, cross-cutting these, as fresh, marginal, brackish & saline. The ground & fresh are here divided into fresh, nonfresh & non-available, the latter covering desalination of seawater, not included in ABS, but represented here as a capital-intensive last resort. Estimates of capital costs for each type of extraction are included, but are open to user re-evaluation.

The analysis of demand and resources is based on a state-by-state linear extrapolation of current resources and use rates, and assumes that demand grows proportionally for each state. Hence, although country as a whole has plenty water, the geography of water & people means that certain areas are short of water, and will need to adopt more costly technologies sooner rather than later. DC'96b

Acronyms are GW=ground water SW=surface water
FSH=fresh MGN=marginal-saline SEA=sea water

The fractions computed here are used to assess average capital costs etc. of meeting water supply as the demand profiles increase. Choice between surface and ground water is made by urban and agricultural supplies separately, in water supply sector.

DSW & DGW terms compute resource quality profile if no cutback in irrigation, for purpose of computing irrigation cutback required to avoid desalination option under DESAL=0 DC'96b

== Surface Water
fractional usage if no irrigation cutbacks

```
A DSWFSH.K=TABHL(FSWFSHT,SWDEMF1.K,1,3,0.2)/100
T FSWFSHT=100/100/100/98.4/95.4/93.0/90.5/85.7/81.8/78.3/75.4
```

```
A DSWMGN.K=TABHL(FSWMGNT,SWDEMF1.K,1,3,0.2)/100
T FSWMGNT=0/0/0/1.6/2.0/1.9/0.9/0.9/0.9/0.9/0.8
A DSWSEA.K=1-DSWFSH.K-DSWMGN.K

A FSWCUT.K=SWDEM.K/SWDEM1.K     fractional cut in surf water demand due
to
                                DESAL=0 policy option

 actual usage, accounting for any irrigation cutbacks
A FSWFSH.K=DSWFSH.K/FSWCUT.K
A FSWMGN.K=DSWMGN.K/FSWCUT.K
A FSWSEA.K=1-FSWFSH.K-FSWMGN.K

 == Ground Water
 fractional usage if no irrigation cutbacks
A DGWFSH.K=TABHL(FGWFSHT,GWDEMF1.K,1,3,0.2)/100
T FGWFSHT=83.7/78.1/74.2/71.2/67.8/62.1/56.9/52.7/49.1/46.0/43.3
A DGWMGN.K=TABHL(FGWMGNT,GWDEMF1.K,1,3,0.2)/100
T FGWMGNT=16.3/21.9/25.8/28.8/32.2/37.9/43.1/45.5/45.4/45.4/44.8
A DGWSEA.K=1-DGWFSH.K-DGWMGN.K

A FGWCUT.K=GWDEM.K/GWDEM1.K     fractional cut in ground water demand
due to
                                DESAL=0 policy option

 actual usage, accounting for any irrigation cutbacks
A FGWFSH.K=DGWFSH.K/FGWCUT.K
A FGWMGN.K=DGWMGN.K/FGWCUT.K
A FGWSEA.K=1-FGWFSH.K-FGWMGN.K

 == 2  HUMAN-MADE CAPITAL INFRASTRUCTURES

 == 2.1  SUPPLY OF INFRASTRUCTURE: INDUSTRIAL OUTPUT
  We measure two aspects on industrial output; the embodied energy
required to
  generate the flow, and the 'service-corrected' index of output. The
latter is
  developed in recognition of the fact that differences in technology
and
  practice may result in the same service being provided at more or
less EE. As
  time progresses and the structure of production changes, the two
measures of
  output may be expected to diverge.
    Rather than trying to measure the service provided directly (which
we don't
  believe to be possible; 'service' is too nebulous a concept to
measure using
  a scalar numeraire) we measure the 'service-corrected' output; that
is,
  output in notional EE terms based on a reference technology/practice.
Changes
  in technology/practice during the model run are automatically
corrected for
  in this term to the reference system, so that increases or decreases
in the
```

```
  'service corrected' term will reflect changes in the flow of service
provided
  more accurately than the actual EE value based on current technology
and
  practice. service corrected values are denoted in units of 'VPJ', for
  'virtual' PetaJoule. DC'96b

  formulation for INDOUT is a simplified version of Leontief-type
calculation:
  only those inputs deemed sufficiently large are explicitly
incorporated here
A
INDOUT.K=PEDIND.K+(RDCIND.KL/REDEII.K)+RESIND.K+SEROUT.K*FSERIND.K+AGRO
UT.K*^
     FAGRIND.K+PEDTRA.K*FTRAIND.K-(DDINTGD.K/REDEII.K)  DC'95a DC'96b
                    embodied energy of output, PJ/y

A
INDOUTB.K=PEDINDB.K+RDCINDB.K+RESINDB.K+SEROUTB.K*FOTSERX.K*FSERIND.K^
     +AGROUTB.K*FAGRIND.K+PEDTRAB.K*FTRAIND.K-DDINTGD.K
                    INDOUT at "service corrected" embodied energy, VPJ/y

 terms from INDOUTB - "B" suffix denotes "base" or constant
functionality
A          PEDINDB.K=(CSIND1.K*(5200E-12+(2.6E-7*FERELN)))*SYSGERN/EII
DC'95a
                    PEDIND at "constant functionality", VPJ/y
A RDCINDB.K=CSIND1.K/LTIND
                    RDCIND at "constant functionality", VPJ/y
A RESINDB.K=MININDB.K+(WATINDB.K*GERUWTB.K)
                    RESIND at "constant functionality", VPJ/y
                    updated to folow new RESIND structure DC'96b
A MININDB.K=CSIND1.K*1.65E-10/EII
                             initial value of MICRIND used here
DC'96b
A WATINDB.K=CSIND1.K*WATPIND     EFFUWT term omitted here DC'96b
A GERUWTB.K=(PEDUWTB.K+RDCUWT.KL)/WATURBN
A PEDUWTB.K=(TEDUWTB.K+(EEDUWTB.K*FERELN))*SYSGERN
A TEDUWTB.K=CSWAT.K*TICRWAT      ACCUWT term omitted here DC'96b
A EEDUWTB.K=CSWAT.K*EICRWAT      ACCUWT term omitted here DC'96b

A  SEROUTB.K=(((CSSER.K*(100E-12+(3.7E-8*FERELN)))*SYSGERN/EII)+CSSER.K/
^
     LTSER)
     SEROUT at "constant functionality", VPJ/y  DC'95a

A  FOUTSER.K=(((CSSER.K*(100E-12+(3.7E-8*FERELN)))*SYSGERN/EII)+CSSER.K/
^
     LTSER)*FSERIND.K/INDOUTB.K  DC'95a
K FOTSERN=FOUTSER                DC'95a
  index of change in fractional input by services:level to avoid sim eq
DC'95a
L FOTSERX.K=FOTSERX.J+dt*(RFSERX.JK-RDSERX.JK)
N FOTSERX=1
R RFSERX.KL=FOUTSER.K/FOTSERN
R RDSERX.KL=FOTSERX.K
```

```
A AGROUTB.K=(DVEGOUT.K*PERPTVN+DANOUT.K*PERPTAN)*FOTAGRX.K    DC'95a
K PERPTVN=PERVEG/DVEGOUT     PER per tonne protein in initial year
K PERPTAN=PERAN/DANOUT       PER per tonne protein in initial year
A     FOUTAGR.K=(DVEGOUT.K*PERPTVN+DANOUT.K*PERPTAN)*FAGRIND.K/INDOUTB.K
DC'95a
K FOTAGRN=FOUTAGR                DC'95a
  index of change in fractional input by agric:level to avoid sim eq
DC'95a
L FOTAGRX.K=FOTAGRX.J+dt*(RFAGRX.JK-RDAGRX.JK)
N FOTAGRX=1
R RFAGRX.KL=FOUTAGR.K/FOTAGRN
R RDAGRX.KL=FOTAGRX.K

A PEDTRAB.K=((TEDTRA.K+(EEDTRA.K*FERELN))*SYSGERN)*FOTTRAX.K DC'95a
A   FOUTTRA.K=((TEDTRA.K+(EEDTRA.K*FERELN))*SYSGERN)*FTRAIND.K/INDOUTB.K
DC'95a
K FOTTRAN=FOUTTRA                DC'95a
  index of change in fractional input by transport:level to avoid sim
eq DC'95a
L FOTTRAX.K=FOTTRAX.J+dt*(RFTRAX.JK-RDTRAX.JK)
N FOTTRAX=1
R RFTRAX.KL=FOUTTRA.K/FOTTRAN
R RDTRAX.KL=FOTTRAX.K

 Reduction in EII arising through technological change in production
process
 REDEII is treated as level variable to avoid simultaneous equations
L REDEII.K=REDEII.J+dt*(RFEII.JK-RDEII.JK)
                   reduction in EII arising through technological
production
                    changes
N   REDEII=1
R RFEII.KL=INDOUT.K/INDOUTB.K
                   instantaneous value of REDEII
R RDEII.KL=REDEII.K
                   old value of REDEII: for internal calculations

 = Intermediate goods - Industrial output that immediately re-enters
industry
 sector, and so doesn't count towards output to final demand
A DINTGD.K=CSIND.K*IICRIND.K   DC'95a
                   demand for intermediate goods, VPJ/y
A DDINTGD.K=DELAY3(DINTGD.K,1)
                   delayed outflow of INTGD, VPJ/y
A IICRIND.K=FIFGE(TABHL(IICR2T,TIME.K,1990,2050,10),^
           TABHL(IICRIT,TIME.K,1981,1989,8),TIME.K,1990)*(141/266)
                   the factor (141/266) converts value to final demand
                    purchasing price cf. IO table output value of
INDOUT
                    (INDOUT$=$141E9, IO output term quotes $266E9) see
manual
                    for an explanation of the valuation of Industrial
Output
T   IICRIT=0.65/0.65
T   IICR2T=0.65/0.65/0.65/0.65/0.65/0.65/0.65
                   unitless ratio INTGD per CSIND IO data shows that in
1981,
```

```
                    20% of output re-entered intermediate goods cycle,
and in
                    1989, 27%: in terms of intgd/csind ratio, this is
fairly
                    constant INTGD/CSIND in current$ '81=52.4E9/123E9:
'89=
                    94.6E9/149E9

 = INDEX of industrial production: indicator
 index is expressed as a level variable to avoid simultaneous equations
 (index drives TEDTRA, for example, which is a component of INDOUT)
L INDEX.K=INDEX.J+dt*(RFINDEX.JK-RDINDEX.JK)
                   index of industrial output, 1981=1
N   INDEX=1
R RFINDEX.KL=INDOUTB.K/INDOUTN  DC'95a
                   index of industrial output
R RDINDEX.KL=INDEX.K
                   old value of INDEX: for internal calculations
K   INDOUTN=INDOUTB initial value of industrial output  DC'95a


 = Further steps in determining available output for indigenous
infrastructure
 creation, factoring in international trade, consumption of HMC, etc.
A TICFR.K=INDOUTB.K-TRES.K-CONS.K-RQXBEN.K  DC'95a
                   indigenous supply of HMC for FIXED CS formation,
VPJ/y
A TACFR.K=TICFR.K-NETXPGD.K
                   available HMC for building domestic infrastructure/
                    consump'n, VPJ/y BALPAY multiplied by REDEII, as
raw data
                    is money units, so increase in energy intensity
reflects
                    increase in VPJ content (Embodied Energy Value)
A NETXPGD.K=-BALPAY.K  DC'95a
                   net exports of goods needed for zero balance of
payments,
                    VPJ/y


A
RCFOS.K=RCFAFF.K+RCFTMIN.K+RCFUTIL.K+RCFDOM.KL+RCFSER.KL+RCFNGV.K+RCFCO
2.K
                   Rate of Fixed Capital Formation, all non-industrial
sectors,
                    VPJ/y DC'96b (REDEII removed) DC'96a (NGV term
added)
                    AGR -> AFF DC'96b
A RCFUTIL.K=RCFEL.K+RCFGASD.KL+RCFWAT.K
                   Rate of Fixed Capital Formation, all utility
sectors, VPJ/y
A RCFEL.K=FIFZE(HRCFEL.K,RCFCOEL.K+RCFHYD.K+RCFREN.K,OPTEL)
                   Rate of Fixed Capital Formation, all electricity
generating
                    sectors, VPJ/y
A HRCFOS.K=HRCFAFF.K+HRCFTMN.K+HRCFUTL.K+HRCFDOM.K+HRCFSER.K
                   historical data for comparison  DC'96b
```

```
L RCFIND1.K=RCFIND1.J+dt*(RFIND1.JK-RDIND1.JK)
                   rate of input of re-investment in industry, VPJ/y
K   RCFIND1=HRCFIND            DC'96b
R RFIND1.KL=TACFR.K-RCFOS.K  DC'95a
                   instantaneous value of RCFIND1
R RDIND1.KL=RCFIND1.K
                   old value of RCFIND1: for internal calculations

 Rate of Capital Formation Industry: follows Historical for first two
years,
 while RCF's of other sectors adjust from "Cold Start".
 written as level variable to avoid simultaneous equations

 == Balance of Payments: outflows minus inflows of trade resulting in
change in
   potential of system to grow. Those factors not directly attributable
to
   physical processes within the country
   +ve elements are exports of goods, use of overseas services by Aus
residents
   -ve elements are imports of goods, use of Aus services abroad
   Note that this differs from traditional formulation, in that, for
   calculating availability of HMC:
   [1] exports of goods reduce local HMC availability
   [2] exports of services increase local HMC availability

A BALPAY.K=VISBP.K+INVBP.K
                   total balance of payments, VPJ embodied/y

 = visibles balance: exports of goods are +ve, decreasing TACFR.
FULEIMP is
 effectively a service (i.e. not part of INDOUT), therefore import is
+ve
A VISBP.K=EXPGDS.K-IMPGDS.K-(FULEIMP.K*REDEII.K)
                   visibles balance of payments: HMC & fuels, VPJ/y
                   DC'96b (REDEII added)
A FULEIMP.K=OILEIMP.K+GASEIMP.K+COLEIMP.K
                   embodied energy ("natural price") fuels, PJ/y
A OILEIMP.K=OILIMP.K*(FIFGE(EREME.K,EREOIL.K,OILIMP.K,0)-1)
                   embodied energy of oil imports, PJ/y
A GASEIMP.K=GASIMP.K*(EREGAS.K-1)
                   embodied energy of gas imports, PJ/y
A COLEIMP.K=COLIMP.K*(ERECOL.K-1)
                   embodied energy of coal imports, PJ/y

A EXPGDS.K=AGREXP.K+MINEEXP.K+OTHEXP.K
                   total exported goods excluding fuels, VPJ/y
A AGREXP.K=ANEEXP.K+WOLEEXP.K+VEGEEXP.K
                   agricultural exports; animal & veg protein + wool,
VPJ/y
                   note proteins based on embodied energy values, not T
prot.
                   for 1989, model calculates $3E9 animal, $3.8E9 veg
values,
                   cf. AusBoP T7, $2.9E9 meat, $4.4E9 veg. A very good
fit to
```

```
                   'natural price', in other words.   DC'96b
A ANEEXP.K=(ANEXP.K/DANOUT.K)*PERAN.K*ANPRF.K       VPJ/y
A ANPRF.K=TABHL(ANPTF,TIME.K,1981,2051,10)
T  ANPTF=1.2/1.2/1.2/1.2/1.2/1.2/1.2/1.2
    mineral price factor: profit margin factor by which exported
A WOLEEXP.K=WOLEXP.K*WOLPRIC.K*EII          VPJ/y
    note that WOLEEXP < HWOLEEX, because the selling of stocks of wool
in
    early 1990's not reflected in model, which only sells what's
sheared in
    same year DC'96b
A VEGEEXP.K=(VEGEXP.K/DVEGOUT.K)*PERVEG.K*VEGPRF.K  VPJ/y
A VEGPRF.K=TABHL(VEGPTF,TIME.K,1981,2051,10)
T  VEGPTF=1.6/1.6/1.6/1.6/1.6/1.6/1.6/1.6
    mineral price factor: profit margin factor by which exported
A MINEEXP.K=DMINEXP.K*MINPRF.K
A MINPRF.K=TABHL(MINPTF,TIME.K,1981,2051,10)
T  MINPTF=1.5/1.5/1.5/1.5/1.5/1.5/1.5/1.5
    mineral price factor: profit margin factor by which exported
minerals
    (mainly gold & other precious minerals) exceed their 'natural
price'
    determined empirically to fit HMINEEX   DC'96b

A OTHEXP.K=FIFGE(TABHL(EXTGDS2,TIME.K,1990,2050,10),^

TABHL(EXTGDS,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K
                   other goods exported by Australia to rest of World,
PJ/y
T   EXTGDS=13.5/27.9
T   EXTGDS2=27.9/27.9/27.9/27.9/27.9/27.9/27.9
                   all merchandise: AusBoP'94 T8, sum other categories
DC'96b

 == Historical merchandise export series for 1989-94, VPJ/y ==
A HEXPGDS.K=TABHL(HEXTGDS,TIME.K,1989,1994,1)*1E9*EII
T HEXTGDS=48.6/54.5/59.8/63.0/68.7/70.1
  AusBoP'94 all merchandise exports  DC'96b
A HAGREEX.K=HWOLEEX.K+HVEGEEX.K+HANEEX.K
A HWOLEEX.K=TABHL(HWOLEXT,TIME.K,1989,1994,1)*1E9*EII
T HWOLEXT=3.7/4.0/5.8/5.2/5.4/5.0
  AusBop'94 T7  'wool & sheepskins'  DC'96b
A HVEGEEX.K=TABHL(HVEGEXT,TIME.K,1989,1994,1)*1E9*EII
T HVEGEXT=4.4/4.5/3.6/4.3/5.1/4.3
  AusBop'94 T7  'cereals etc.' plus 'sugar etc.' DC'96b
A HANEEX.K=TABHL(HANEXT,TIME.K,1989,1994,1)*1E9*EII
T HANEXT=2.9/3.3/3.5/3.8/3.8/3.7
  AusBop'94 T7  'meat & meat prep.'  DC'96b
A HMINEEX.K=TABHL(HMINXT,TIME.K,1989,1994,1)*1E9*EII
T HMINXT=16.0/18.2/19.8/19.9/21.5/21.2
  AusBop'94 T7 'metal ores & minerals' plus 'metals'  DC'96b
A HOTHEEX.K=HEXPGDS.K-HAGREEX.K-HMINEEX.K

A IMPGDS.K=FIFGE(TABHL(IMTGDS2,TIME.K,1990,2050,10),^

TABHL(IMTGDS,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K
                   goods imported by Australia from rest of world, PJ/y
```

```
T   IMTGDS=29.8/56.6
T   IMTGDS2=56.6/56.6/56.6/56.6/56.6/56.6/56.6
                   all merchandise: AusNA'93 T61, deflated to 89/90$

 = invisibles balance: exports of services are -ve, thereby increasing
TACFR
 direct investment (ROZDIA & RFDIOZ) involves direct HMC investment,
and so
 is treated as a goods export
 NOTE that feedbacks between direct investment and remittances (a part
of the
 receipts and payments account) has not been built in to the pilot
model.
 invisibles data all taken from AusNA'93 T12,61-2: deflated to 89/90$
A INVBP.K=RECEIPT.K-PAYMENT.K-ROZDIA.K+RFDIOZ.K+NBORBP.K
                   invisibles balance of payments, VPJ/y
                   net borrowing/debt term added DC'96b

A RECEIPT.K=FIFGE(TABHL(RCPTT2,TIME.K,1990,2050,10),^

TABHL(RCPTT,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K^
           +FIFGE(IMWLTH.K,0,TIME.K,1992)  DC'95b
                   receipts, VPJ/y includes immigrant's incoming wealth
post-92
T   RCPTT=2.9/6.0
T   RCPTT2=6.0/6.0/6.0/6.0/6.0/6.0/6.0
A   IMWLTH.K=NMIG.KL*WPIM*1E-6      PJ wealth flow into economy by
immigrants DC'95b
I WPIM=10                          average wealth per immigrant, VGJ/cap
DC'95b
                                   75VGJ/cap is roughly $10,000, as rough
guide

A PAYMENT.K=FIFGE(TABHL(PYMTT2,TIME.K,1990,2050,10),^

TABHL(PYMTT,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K
                   payments, VPJ/y
T   PYMTT=7.77/18.26
T   PYMTT2=18.26/18.26/18.26/18.26/18.26/18.26/18.26
    new data series has net borrowing removed and added to INVBP
separately
    DC'96b

A ROZDIA.K=FIFGE(TABHL(ROZD2AT,TIME.K,1990,2050,10),^

TABHL(ROZDIAT,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K
                   rate of Australian direct investment abroad, VPJ/y
T   ROZDIAT=3.4/0
T   ROZD2AT=0/0/0/0/0/0/0

A RFDIOZ.K=FIFGE(TABHL(RFD2OZT,TIME.K,1990,2050,10),^

TABHL(RFDIOZT,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII*DRIVE.K
                   rate of foreign direct investment in Australia,
VPJ/y
T   RFDIOZT=15.8/15.0
T   RFD2OZT=15.0/15.0/15.0/15.0/15.0/15.0/15.0
```

```
 = International Debt structure: debt accumulates from borrowing, set
in table
   BORRT. Switch variable NOBOR=1 will shut off all borrowing, forcing
economy
   to meet balpay deficit by export of HMC (as per old structure).
    No distinction between gov and private sector debt here; the
figures from
   AusNA'92 T12 are broken down fully in T62, and include both types.
    Note that borrowing data is not driven by DRIVE term, unlike other
INVBP
   data series. DC'96b
L DEBT.K=DEBT.J+DT*(BORROW.JK-REPAY.JK)     national debt
K DEBT=HDEBT                                initial value
R BORROW.KL=FIFZE(BORROW1.K,BORROW2.K,NOBOR)
                                            net borrowing rate, VPJ
equiv
I NOBOR=0                                      set =1 for zero borrowing
policy
                                            post-1993 only  DC'96b
A BORROW1.K=FIFGE(TABHL(BORR1T,TIME.K,1990,2050,10),^
          TABHL(BORR2T,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EII
                                            default time series data
A
BORROW2.K=FIFGE(0,TABHL(BORR2T,TIME.K,1981,1992,11),TIME.K,1993)*1E9*EI
I
T BORR2T=13.15/12.01                        borrowing '81-'92 trendline
T BORR1T=12.01/12.01/12.01/12.01/12.01/12.01/12.01
                                            future borrowing rate
estimates
                                            for NOBOR=0  DC'96b
R REPAY.KL=DEBT.K*RRATE.K                   repayment rate, VPJ equiv.
A RRATE.K=TABHL(RRT,TIME.K,1981,2051,10)
T RRT=0/0/0/0/0/0/0/0                          repayment rate coefficient
DC'96b
A DINT.K=DEBT.K*DINTR.K                     national debt interest
A DINTR.K=TABHL(DINTRT,TIME.K,1981,2051,10)  debt interest rate
T DINTRT=0.12/0.06/0.06/0.06/0.06/0.06/0.06/0.06
                                            trend of historical data
A NBORBP.K=BORROW.KL-REPAY.KL-DINT.K          net influence of borrowing
on INVBP

 historical data for validation purposes (SOURCE Kriesler/ABS 1995)
DC'96b
A HDEBT.K=TABHL(HDEBTT,TIME.K,1981,1994,1)*1E9*EII
T HDEBTT=29.1/37.1/44.8/72.7/99.6/101.9/103.8/114.5/140.8/148.0/164.3/^
         157.3/163.0/180.6
  undeflated
16.4/23.4/29.9/51.2/75.0/82.4/90.3/108.2/140.8/152.7/172.3/^
         166.7/163/180.6
A HDINT.K=TABHL(HDINTT,TIME.K,1981,1992,1)*1E9*EII
T HDINTT=3.2/4.7/5.6/7.7/9.4/10.3/10.6/11.6/13.6/14.5/12.8/10.8
         undeflated
1.8/2.9/3.7/5.4/7.1/8.3/9.2/11.0/13.6/15.0/13.4/11.5
A HDINTR.K=HDINT.K*100/HDEBT.K

 = endogenous driving mechanism for future INVBP estimates
```

```
A DRIVE.K=FIFGE(INDEX.K/INDEX92,1,TIME.K,1992)
                    driver for balance of payments post-validation
period.
                     Assume that factors will increase in step with
growth of
                     indigenous economy


 == 2.2-7 == DOMESTIC DEMAND FOR INFRASTRUCTURE
 The OPTxxx variables are set up for validation model only: if OPT=0
then RCF
 is set equal to HRCF, effectively switching off most of that sector.
OPT=1
 sets RCF to model determined value. This allows sectors (and errors
assoc'd
 with them) to be flipped easily with historical data, isolating
certain
 sectors for testing purposes.
I   OPTAGR=1        agricultural sector
I   OPTMIN=1        mining sector
I   OPTEL=1         electricity generation: only for RCFOS equation
I   OPTWAT=1        water supply
I   OPTGASD=1       gas distribution
I   OPTIND=1        industrial sector
I   OPTDOM=1        domestic sector
I   OPTSER=1        services sector
I   OPTMSOL=1       runs affluence index on historical data

 == 2.2  Agriculture - inc. Agriculture, forestry, fishing & hunting
Note:  output of agricultural sector is quantified in terms of protein
       not calories or tonnes of primary product.

L CSAGR.K=CSAGR.J+dt*(RCFAGR.JK-RDCAGR.JK)
                    fixed capital stock, agriculture, VPJ
K   CSAGR=EII*51.687e9-DCSWDS
                    initial money value changed to VPJ
                    forestry sector data separated out DC'96b
R                           RCFAGR.KL=FIFZE(HRCFAFF.K-RCFWDS.KL,DCSAGR.K-
CSAGR.K+RDCAGR.KL,OPTAGR)
                    rate of capital formation, agriculture, VPJ/y
                    AGR -> AFF DC'96b
R RDCAGR.KL=CSAGR.K/LTAGR
                    rate of depreciation of fixed capital, VPJ/y
I   LTAGR=18        capital lifetime: derived from AusNA'92 data

A PERAGR.K=PERAN.K+PERVEG.K
                    process energy inputs to agriculture, PJ/y
A PERAGRX.K=PERAGR.K/PERAGRN
K PERAGRN=PERAGR    index of primary energy use, agriculture  DC'96b

A TEDAGR.K=PERAGR.K*FPAGRT.K
                    thermal energy demand, PJ/y
A EEDAGR.K=(PERAGR.K*(1-FPAGRT.K))/FEREL.K
                    electrical energy demand, GWh/y
A FPAGRT.K=TABHL(FPAGRTT,TIME.K,1981,2051,10)
T FPAGRTT=0.7/0.63/0.63/0.63/0.63/0.63/0.63/0.63
   energy mix between thermal and electrical fuels  DC'96b
```

```
A RESAGR.K=50*PERAGRX.K
                          non-energy resource consumed, PJembodied energy/y
very
                          approx. figure from T15.51 average values
Superphosphate
                          2.5E6t @ 6MJ/kg (H3PO4) Nitrogenous 440E3t @
50MJ/kg (NH3)
                          Other fertiliser 1E6t @ 10MJ/kg (GUESS) PER data
from
                          Slesser & Lewis (1976) p.183


A PEDAGR.K=(TEDAGR.K+(EEDAGR.K*FEREL.K))*SYSGER.K
                         primary energy demand associated with fuel & elec.
                          consumption, PJ/y

A AGROUT.K=PERVEG.K+PERAN.K
                         Embodied Energy Output of Agriculture, PJ/y
A FAGRIND.K=FIFGE(TABHL(F2GTIND,TIME.K,1990,2050,10),^
             TABHL(FAGTIND,TIME.K,1981,1989,8),TIME.K,1990)
                         fraction AGROUT -> IND
T   FAGTIND=0.27,0.43
T   F2GTIND=0.43/0.43/0.43/0.43/0.43/0.43/0.43
                         data from IO tables

A DCSAGR.K=DCSVEG.K+DCSAN.K
                         desired agricultural CS, VPJ

A GNL.K=35E-3*(MSOLF.K**0.25)
                         Desired nutritional level, tonnes protein per cap
per year
                          (34kg/y) revised DC'96a to fit new FAOagristats
data
A HGNL.K=TABHL(HGNLT,TIME.K,1980,1990,1)*365.25*1E-7
T HGNLT=937/953/967/952/979/984/997/996/984/1005/1007
  DC'96a  FAO data orig units GRAMS PR/CAP/DAY expressed as t pr/y
  presume original data to have a factor 10 error: approx. 1kg
pr/cap.day!!
A FVEG.K=FIFGE(TABHL(FVEGT2,TIME.K,1990,2050,10),^
          TABHL(FVEGT,TIME.K,1981,1990,9),TIME.K,1991)
                         fraction protein intake as vegetable
T   FVEGT=0.29,0.33   DC'96a
T   FVEGT2=0.33/0.33/0.33/0.33/0.33/0.33/0.33
                          revised data from FAO agrostats oridg data in
protein terms
                         GNL, etc. data taken from AusYB'85 p. 255. More
recent YB's
                          don't list it in protein terms
A VGNL.K=GNL.K*FVEG.K
                         vegetable protein goal nutritional level, T/cap.y
A AGNL.K=GNL.K*(1-FVEG.K)
                         animal protein goal nutritional level, T/cap.y


 = 2.2.1 == Vegetable & Cereal Protein
 Land Area used for vegetable crops
```

```
A VAGRA.K=FIFGE(TABHL(VAGRAT,TIME.K,1990,2050,10),^
          TABHL(HVAGRAT,TIME.K,1981,1991,1),TIME.K,1991)*1E6
                   vegetable agricultural land, ha
T   HVAGRAT=43.0/46.4/44.8/47.1/47.2/46.8/46.9/46.8/48.7/48.8/46.7
                   FAO agristats data DC'96a
           19.6/19.4/22.0/21.1/20.9/19.8/18.4/17.5/17.0/17.4/16.4/17.3
                   YB'95  p.474,  T15.14:  note  -  this  erroneous,  as
(omitted)
                   data  on  'sown  pastures  and  grasses'  contributes  to
feeds
T VAGRAT=46.7/46.7/46.7/46.7/46.7/46.7/46.7
                   user defined data for extending/shrinking intensive
                   agriculture system DC'96a

A DVEGOUT.K=VEGDEM.K+VEGEXP.K       total demand, tonnes prot/y DC'96a
A  VEGDEM.K=(TPOP.K*VGNL.K)+FEEDS.K    domestic  demand,  tonnes  prot/y
DC'96a
A VEGEXP.K=VEGDEM.K*(VSSA.K-1)        exports, tonnes prot/y DC'96a
                   desired agricultural output,T/y
A
VSSA.K=FIFGE(TABHL(VSSAT,ACCAWT.K,1,10,1)*RIRRF.K**IRREXPF,2.4,TIME.K,1
995)
T VSSAT=2.4/2.4/2.2/2.0/1.5/1.0/1.0/1.0/1.0/1.0
                   desired  self-sufficiency  in  vegetables,  approx
determined
                   empirically assuming no wastage factor, as stated in
                   AusYB'95 p.493 "apparent consumption" note DC'96a
                   table  function  responds  to  higher  irrigation
requirements
                   by decreasing exports of agricultural produce, which
                   presumably becomes less competitive. Also responsive
to a
                   reduction  in  irrigation  water  use,  as  part  of
cutback from
                   DESAL policy: see IRREXPF below  DC'96b
I IRREXPF=0           factor for reduction or exports associated with
irrigation
                   cutbacks  from  desalination  avoidance  (DESAL=0).
Default=0
                   makes  VSSA  &  ASSA  unresponsive  to  RIRRF,  but
positive values
                   will  automatically  induce  cutbacks  on  production
DC'96b
A HVEGOUT.K=TABHL(HVYIELD,TIME.K,1981,1993,1)*0.03*1E6
                   historical  rate  of  veg/cereal  protein  production,
PJ/y
T
HVYIELD=26.9/17.5/34.3/32.0/28.6/27.7/23.7/25.6/26.2/26.8/22.7/29.1/28.
3
                   data  in  tonnes  weight/y,  at  average  3%  Protein
content
                   1981-92 FAO data total cereals, veg + fruit,
                   1993 YB'95 T15.16-25   DC'96a
A                  HVEGDEM.K=TABHL(VEGDEMT,TIME.K,1980,1990,1)*365.25*1E-
7*HPOP.K+FEEDS.K
T VEGDEMT=281/295/298/298/317/326/332/323/319/317/335
```

```
  DC96'a FAOagristats data all vegetables, w. factor 10 error allowed
for
   (see HGNL notes): original data given in protein terms
  FEEDS term added for consistency w. model VEGDEM DC'97c

A VPRPH.K=MAX(PZERO+1E-6,(DVEGOUT.K-PZERO*SAL.K)/VAGRA.K)  DC'96a
                    Required  intensity  of  vegetable  protein  output,
T/ha.y
                    NB:  Cannot  fall  below  PZERO,  at  which  point  no
inputs used
I   PZERO=0.01      !! no data at present Zero input subsistence farming
output,
                      T/y
A SAL.K=TABHL(SALT,TIME.K,1995,2050,5)
T SALT=0/0/0/0/0/0/0/0/0/0/0/0
                     "balance" land currently used as extensive grazing
that
                     may be brought into play. Upper limit to this is
probably
                     defined by distance from populated areas? Estimated
upper
                     limit  of  40E6  suggested  (10%  of  total  "balance
land")
                     DC'96a
A PERPHV.K=60E-5*(VPRPH.K-PZERO)**1.4
                    Process Energy Input per hectare, PJ/ha.y Based on
Slesser
                     Curve  Pv=52.5(ES)^.72,  w.  Pv  in  kg/ha.y,  ES  in
PJ/ha.y
A PERVEG.K=PERPHV.K*VAGRA.K
                    total process energy requirement of vegetable crops,
PJ/y
 IRRVEG - irrigation of crops/horticulture: see water sector

A CPPV.K=FIFGE(TABHL(CPPVT2,TIME.K,1990,2050,10),^
         TABHL(CPPVT,TIME.K,1981,1991,10),TIME.K,1992)*1E3*EII
                    average value for vegetable plus animal protein
T   CPPVT=33/26     Capital stock per tonne vegetable output, VPJ/T
T   CPPVT2=26/26/26/26/26/26/26
   data adjusted after separation of forestry DC'96b
A DCSVEG.K=DVEGOUT.K*CPPV.K
                    desired CS vegetable crops, VPJ


 = 2.2.2 == Animal Protein (terrestrial only)
 Land Area used for animal husbandry
A AAGRA.K=AAGRA1.K-NEWEUCA.K-NEWPINA.K  DC'97c
    new plantation will cut inTo grazing land - see NEWPINA & NEWEUCA

A AAGRA1.K=FIFGE(TABHL(A2GRAT,TIME.K,1990,2050,10),^
          TABHL(AAGRAT,TIME.K,1981,1991,1),TIME.K,1992)*1E6*FINT
                    intensive animal agricultural land, ha
T   AAGRAT=440/432/426/426/426/424/424/425/418/418/416
T   A2GRAT=416/416/416/416/416/416/416
                    FAO agristats all perm pasture
I FINT=0.1         fraction animal land used intensively DC'96a
                    guess based on fitting data to "Slesser curve"
```

```
A DANOUT.K=ANDEM.K+ANEXP.K    total demand, tonnes prot/y  DC'96a
A ANDEM.K=TPOP.K*AGNL.K       domestic demand, tonnes prot/y  DC'96a
A ANEXP.K=ANDEM.K*(ASSA.K-1)  exports, tonnes prot/y DC'96a
                     desired agricultural output, T/y
A ASSA.K=FIFGE(TABHL(ASSAT2,ACCAWT.K,1,10,1),^
         TABHL(ASSAT,TIME.K,1981,1992,11),TIME.K,1993)*RIRRF.K**IRREXPF
T   ASSAT=1.95/2.20
T   ASSAT2=2.2/2.2/2.0/1.8/1.5/1.0/1.0/1.0/1.0/1.0
                     table  function  2  responds  to  higher  irrigation
requirements
                     by decreasing exports of agricultural produce, which
                     presumably becomes less competitive. Also responsive
to cuts
                     in irrigation water use: see IRREXPF above  DC'96b
                     desired  self-sufficiency  animal  protein  data  based
on:
                      1981-1990 FAOagristats see HANOUT & HANDEM DC'96a
A HANOUT.K=TABHL(HAYIELD,TIME.K,1980,1992,1)*1E3
                     historical animal protein output, tonnes Protein/y
T   HAYIELD=761/741/747/763/727/746/780/819/835/818/875/907/937
                     data for HANOUT in tonnes PROTEIN/y, ave 20% protein
content
                     for  meat,  AND  4%  for  dairy  products  FAOagristat
DC'96a
A HANDEM.K=TABHL(HANDEMT,TIME.K,1980,1990,1)*365.25*1E-7*HPOP.K
T HANDEMT=656/658/669/653/661/657/665/674/666/688/672
  DC96'a FAOagristats data all animal prods, w. factor 10 error allowed
for
  (see HGNL notes): original data given in protein terms
A HASSA.K=HANOUT.K/HANDEM.K

A APRPH.K=DANOUT.K*FANINT/AAGRA.K
                     Required intensity of animal protein output, T/ha.y
I FANINT=0.10          fraction animal protein reared intensively !! data
is an
                      informed  guess  matching  TEDAGR+RESAGR+RDCAGR  w.
PERAN+
                      PERVEG  need  better  values,  as  this  guess  is  well
below
                      error limit for, e.g., RESAGR: analysis of "Slesser
curves"
                      gives  feasible  range  of  8-25%  FOR  0-100%  intensive
landuse
A PERPHA.K=18E-3*(APRPH.K)**1.6
                     Process  Energy  Input  per  hectare,  PJ/ha.y  Based  on
Slesser
                      Curve  Pa=8.75(ES)^.63,  with  Pa  in  kg/ha.y,  ES  in
PJ/ha.y
A PERAN.K=PERPHA.K*AAGRA.K
                     process energy requirement of animal crops, PJ/y
 IRRAN - irrigation of animal pastures: see water sector

A CPPA.K=FIFGE(TABHL(CPPAT2,TIME.K,1990,2050,10),^
         TABHL(CPPAT,TIME.K,1981,1991,10),TIME.K,1992)*1E3*EII
                     average value for vegetable plus animal protein
T   CPPAT=33/26      Capital stock per tonne animal output, VPJ/T
```

```
T   CPPAT2=26/26/26/26/26/26/26
   data adjusted after separation of forestry DC'96b
A DCSAN.K=DANOUT.K*CPPA.K
                    desired CS animal crops, VPJ

A FEEDS.K=DANOUT.K*FEEDPA.K
                    vegetable output fed back to animal husbandry, T/y
A FEEDPA.K=FIFGE(TABHL(FEEDT2,TIME.K,1990,2050,10),^
          TABHL(FEEDT,TIME.K,1989,1991,1),TIME.K,1992)
                    feeds input per animal output, T/T
T   FEEDT=0.23/0.19/0.15
T   FEEDT2=0.15/0.15/0.15/0.15/0.15/0.15/0.15
                    comparison of HANOUT data with YB'95 T15.31 data, T
Protein
                     output calc'd on assumption that per ha yield for
silage
                     and hay the same, and hay is 3% protein (i.e. same
as veg
                     matter average)

 = 2.2.2.1 == Sheep as subsection of animal protein
 Sheep are considered hete separately, because of wool's importance in
export
 market. Sheep meats subsumed within ANOUT equations: only wool is a
separately
 identified production here. DC'96b

A SHEEP.K=DANOUT.K*FSHEEP.K
                    production of lamb & mutton, T prot/y
A FSHEEP.K=TABHL(FSHPT,TIME.K,1981,2051,10)
T FSHPT=0.18/0.18/0.18/0.18/0.18/0.18/0.18/0.18
                    fraction DANOUT as sheep, about 18% over 87-92
                    (AusYB'95 p.489-90) DC'96b
A WOLOUT.K=SHEEP.K*WOLPSHP.K
                    wool output, tonnes greasy/y
A WOLPSHP.K=TABHL(WOTPSHP,TIME.K,1981,2051,10)
T WOTPSHP=7/6/6/6/6/6/6/6
                    wool weight sheared per tonne protein produced,
                    t greasy/t prot; highest in early years due to
1980's
                    'wool boom' (AusYB'95 P.490): rough figures
calculated
                    from official data

A WOLEXP.K=WOLOUT.K*FWOLEXP.K
                    wool exported, tonnes greasy/y
A FWOLEXP.K=TABHL(FWOTEXP,TIME.K,1981,2051,10)
T FWOTEXP=0.66/0.66/0.66/0.66/0.66/0.66/0.66/0.66
                    fraction wool exported: based on 1987 data from
AusYB'95
                    a straight calculation for 1992 would yield 130!! -
the
                    situation here is complicated by institutional
changes,
                    and removal of reserve price scheme in 1990-1
season. In
```

```
                    subsequent years, much of stockpile of wool was sold
off,
                    hence exports temporarily higher than production.
This
                    short-term 'blip' hasn't been replicated in the
model DC'96b
A WOLPRIC.K=TABHL(WOTPRIC,TIME.K,1981,2051,10)
T WOTPRIC=6E3/3E3/4.5E3/4.5E3/4.5E3/4.5E3/4.5E3/4.5E3
                    wool prices realised for exports, 1989 A$/tonne
greasy
                    The halving of prices over validation period due to
(i) an
                    artificially high price sustained by Reserve Price
Scheme
                    (ii) an artificially low price following abolition
of RPS.
                    Default future price assumes a partial recovery of
prices
                    after stockpiled wool is sold off  DC'96b


 = Historical Data on Sheep =
A HSHEEP.K=TABHL(HSHEEPT,TIME.K,1987,1992,1)*0.2
T HSHEEPT=586/544/628/668/667/643  AusYB'95 T15.40
                    production of meat (mutton & lamb), tonnes protein/y

A HWOLOUT.K=TABHL(HWOLOTT,TIME.K,1987,1992,1)*1E3
T HWOLOTT=916.4/959.0/1102.0/1066.1/875.0/869.4  AusYB'95 T15.44
                    production of wool, tonnes greasy/y



 = 2.2.3 == Forestry Sector
 Plantation woods are felled at the maximum sustainable rate,
determined
 by the number of trees reaching full maturity in a given year RPWDS1.
 The planting rate at least matches this to ensure a minimum planted
area with
 an even age distribution. The plant rate may be augmented over and
above this
 providing additional CO2 storage.

 Forestry divided into PIN (pine, european tree species) and EUC
(eucalypts,
 native tree species), but CS, TED etc. only treated at aggregate level
(WDS).

 === Capital Stock Forestry ===
L  CSWDS.K=CSWDS.J+DT*(RCFWDS.JK-RDCWDS.JK)          CS in forestry
equipment
N CSWDS=DCSWDS

R RCFWDS.KL=(DCSWDS.K-CSWDS.K)+RDCWDS.KL
A DCSWDS.K=WDSA.K*CSPHWDS.K
A CSPHWDS.K=TABLE(MCE,TIME.K,1981,2051,10)*1000*EII
T MCE=2,2,2,2,2,2,2,2
  marginal cost of plantation 1000$/hectare converted to PJ/ha
```

```
R RDCWDS.KL=CSWDS.K/FLT
C FLT=25


 === Energy & Resource Requirements of Forestry ===
A RESWDS.K=RICRWDS.K*CSWDS.K
A RICRWDS.K=RICWDSN*EII
C RICWDSN=1                              !!! no data

A TEDWDS.K=TICRWDS.K*CSWDS.K
A TICRWDS.K=TICWDSN
K  TICWDSN=HTEDAFF*.1/CSWDS                        from  'back  of  envelope@
calculations by BF
                                          &  team,  sent  18.12.96,  max  10%
TEDAFF is
                                          attributable to WDS DC'96b

A EEDWDS.K=EICRWDS.K*CSWDS.K
A EICRWDS.K=EICWDSN
C EICWDSN=0                              >99% of PEDWDS is petroleum

A PEDWDS.K=((EEDWDS.K*FEREL.K)+TEDWDS.K)*SYSGER.K
         primary energy demand, forestry, PJ
A PEDWDSB.K=((EEDWDS.K*FERELN)+TEDWDS.K)*SYSGERN
         primary energy demand, forestry, PJ
A GERWDS.K=(RDCWDS.KL+PEDWDS.K)/RCWDS.K
         GER per unit timber, PJ/m3

A FOROUTB.K=PEDWDSB.K+RDCWDS.KL
         Embodied Energy Output, DC'97B

 === Plantations of Pine & other Coniferous species ===
 (Potential) Timber Stock in plantation
L  PINSTK.K=PINSTK.J+DT*(RGPIN.JK-RCPIN.JK)         total  standing  stock
/m3
N  PINSTK=PINA*PINGRR*MGRPIN/2                       assumes initial even
age
                                                 distribution
R RGPIN.KL=PINA.K*MGRPIN*FPPIN
R RCPIN.KL=DELAY3(RPPIN.K,PINGRR)
C  PINGRR=15                    mean  felling  age  =  age  at  which  growth
saturates, y
                          based  on  Nabuurs  &  Mohren  type  9  &  10  average
values
                          (fig 2's peak used as indicator of drop-off in
growth)
A RPPIN.K=PRPIN.KL*PINPHA
N PINPHA=PINGRR*MGRPIN*FPPIN
C MGRPIN=23               forest marginal growth/year in m3/hectare/y
                          based  on  Nabuurs  &  Mohren  type  9  &  10  average
values
C FPPIN=0.85                                    fraction of land planted

 Forested Area
L PINA.K=PINA.J+DT*(PRPIN.JK-LRPIN.JK)
```

```
N PINA=741E3                                    1992 data, AusYB'83 T16.2,
Ha
R PRPIN.KL=PR1PIN.KL+LRPIN.KL                  additional planting and
                                                      replacement, Ha/y
R PR1PIN.KL=TABLE(PRPINT,TIME.K,1976,2051,5)*1000
T PRPINT=0,26,27,30,30,30,30,30,30,30,30,30,30,30,30,30
                                                total planting each year
                                                from 1976, in 5 year
                                                blocks    /1000    Ha/year
(first
                                                to element left as zero )
R LRPIN.KL=RCPIN.KL/PINPHA                      loss/felling rate, Ha/y
N LRPIN=PINA/PINGRR

A HPINA.K=TABHL(HPINAT,TIME.K,1981,1992,11)*1E3
T HPINAT=741/956   data from AusYB series: all coniferous

A NEWPINA.K=MAX(FIFGE(PINA.K-956E3,0,TIME.K,1997),0)  DC'97c
    new plantation will cut inro grazing land - see AAGRA

 === Plantations of Eucalypts & other native broadleaf species ===
 (Potential) Timber Stock in plantation
L  EUCSTK.K=EUCSTK.J+DT*(RGEUC.JK-RCEUC.JK)        total  standing  stock
/m3
N  EUCSTK=EUCA*EUCGRR*MGREUC/2                      assumes initial even
age
                                                   distribution
R RGEUC.KL=EUCA.K*MGREUC*FPEUC
R RCEUC.KL=DELAY3(RPEUC.K,EUCGRR)
C  EUCGRR=30                   mean felling age = age at which growth
saturates, y
                              rough average based on Borough et. al.  DC'96b
A RPEUC.K=PREUC.KL*EUCPHA
N EUCPHA=EUCGRR*MGREUC*FPEUC
C MGREUC=14                   rough average based on Borough et. al.  DC'96b
C  FPEUC=0.85                                               fraction of land
planted

 Forested Area
L EUCA.K=EUCA.J+DT*(PREUC.JK-LREUC.JK)
N EUCA=50E3                                      1992 data, AusYB'95 T16.2
Ha
R PREUC.KL=PR1EUC.KL+LREUC.KL                  additional planting and
                                                      replacement, Ha/y
R PR1EUC.KL=TABLE(PREUCT,TIME.K,1976,2051,5)*1000
T PREUCT=0,7.5,8.5,10,10,10,10,10,10,10,10,10,10,10,10,10
                                                total planting each year
                                                from 1976, in 5 year
                                                blocks    /1000    Ha/year
(first
                                                to element left as zero )
R LREUC.KL=RCEUC.KL/EUCPHA                      loss/felling rate, Ha/y
N LREUC=EUCA/EUCGRR

A HEUCA.K=TABHL(HEUCAT,TIME.K,1981,1992,11)*1E3
T HEUCAT=50/117    data from AusYB series: all broadleaves
```

```
A NEWEUCA.K=MAX(0,FIFGE(EUCA.K-117E3,0,TIME.K,1997))  DC'97c
    new Eucalypt plantation will cut into grazing land - see AAGRA

 === Summary of Timber Felling sectors ===
A WDSSTK.K=PINSTK.K+EUCSTK.K   harvestable stock, M3/y
A RGWDS.K=RGPIN.KL+RGEUC.KL    rate growth, m3/y
A RCWDS.K=RCPIN.KL+RCEUC.KL    rate cutting, m3/y
A WDSA.K=PINA.K+EUCA.K         plantation area, Ha/y
A PRWDS.K=PRPIN.KL+PREUC.KL    planting rate, Ha/y
A LRWDS.K=LRPIN.KL+LREUC.KL    loss rate plantations, Ha/y


 == Native (i.e. Non-Plantation) Forested Area ==
 Non plantation timber that generally does nothing, but, if felled, can
 contribute to supply of native timber.

A FA.K=RAINFA.K+NATPA.K+NATEA.K
   total native forests, ha
A HFA.K=HRAINFA.K+HNATPA.K+HNATEA.K

   native rainforests, ha
L RAINFA.K=RAINFA.J+dt*(NRFRFA.JK)
N RAINFA=1837*1E3
R NRFRFA.KL=TABHL(NRFRFAT,TIME.K,1981,2051,5)*1E3
T NRFRFAT=0/99/0/0/0/0/0/0/0/0/0/0/0/0/0
A HRAINFA.K=TABHL(HRAINFT,TIME.K,1981,2051,10)*1E3
T HRAINFT=1837/2332/2332/2332/2332/2332/2332/2332

   native cypress pine, ha
L NATPA.K=NATPA.J+dt*(NRFNPA.JK)
N NATPA=4377*1E3
R NRFNPA.KL=TABHL(NRFNPAT,TIME.K,1981,2051,5)*1E3
T NRFNPAT=0/-42/0/0/0/0/0/0/0/0/0/0/0/0/0
A HNATPA.K=TABHL(HNATPAT,TIME.K,1981,2051,10)*1E3
T HNATPAT=4377/4167/4167/4167/4167/4167/4167/4167

   native eucalypts & paperbark, ha
L NATEA.K=NATEA.J+dt*(NRFNEA.JK)
N NATEA=34653*1E3
R NRFNEA.KL=TABHL(NRFNEAT,TIME.K,1981,2051,5)*1E3
T NRFNEAT=0/-19.4/0/0/0/0/0/0/0/0/0/0/0/0/0
A HNATEA.K=TABHL(HNATEAT,TIME.K,1981,2051,10)*1E3
T HNATEAT=34653/34556/34556/34556/34556/34556/34556/34556

 Area of new forest regrowing & contributing to CO2 soak-up. This is
removed
 from accounts after 50 years, when forest matures & no longer a net
remover
 of atmospheric carbon  DC'96b
L NEWFA.K=NEWFA.J+dt*(RFNEWFA.JK-RDNEWFA.JK)
N NEWFA=0
R RFNEWFA.KL=REFORR.K
R RDNEWFA.KL=DELAY1(RFNEWFA.KL,MATURF)
I MATURF=50    age at which forest matures and stops accmulating woody
biomass
              average approximation  DC'96b
```

```
A DEFORR.K=-MIN(NRFRFA.KL,0)-MIN(NRFNPA.KL,0)-MIN(NRFNEA.KL,0)
   deforestation rate for additional timber supply: only registers -ve
values
A REFORR.K=MAX(NRFRFA.KL,0)+MAX(NRFNPA.KL,0)+MAX(NRFNEA.KL,0)
   reforestation rate for CO2 soakup equations only  DC'96b
A NWDSUP.K=DEFORR.K*WDPHA*(1-FCLEAR.K)
   native wood supply of timber from clear-felling, m3/y
A FCLEAR.K=TABHL(FCLEART,TIME.K,1981,2051,10)
T FCLEART=1/1/1/1/1/1/1/1
   fraction deforestation simply clearing of land, rather than use for
timber
   DC'96b
I WDPHA=250
   timber available per Ha after clear felling: 250m3/Ha is "ballpark"
figure
   based on Borough et al data for various Eucalypts


 === Timber Demand and Supply ===
A WDSOUT.K=(RCWDS.K+NWDSUP.K)*0.7              30% fractional wastage in
saw, M3/y
A WDSDEM.K=WDSIND.K+WDSBIO.K
                                            total demand for wood m3/y
A WDSIND.K=9.1E6*INDEX.K**0.4                       industrial demand for
timber DC'96b
                                            WR'95   T19.3   (FAO   data):
1979-81
                                            calc. as produc'n - (exports
+ fuel)
                                            8975E3 in 79-81; 10466E3 in
89-91
A WDSBIO.K=(BIODEM.K*FBIOWDS/PJPM3WD)*FWBPLAN.K
                                            wood   demand   as   biofuels,
m3/y
A FWBPLAN.K=TABHL(FWBPLAT,TIME.K,1981,2051,10)
T FWBPLAT=0.13/0.2/0.2/0.2/0.2/0.2/0.2/0.2
                                            fraction    fuelwood    from
plantation
                                            c.f.      native      forest;
empirical DC'96b
A WDSIMP.K=WDSDEM.K-WDSOUT.K               net imports timber, m3/y
A WDSIMPE.K=WDSIMP.K*GERWDS.K                 imports in embodied energy
units

I   PJPM3WD=6.4E-6 calorific value per m3 wood, PJ/m3
                     ABARE'94  p.48  gives  16GJ/t  &  nominal  average
density 0.4
                      (wood  ranges  from  0.35  poplar  to  >1  for  some
hardwoods)

 == Historical Timber Data ==
 Data from World Resources'95 T19.3 (source of data is FAO Forestry
Yearbook
 series). Data given for total production, exports and industrial/other
use.
 Although time series on fuel/charcoal given here, it doesn't relate
exactly
```

to model's WDSBIO, which includes bagasse, but doesn't include charcoal.
DC'96b

```
A HWDSOUT.K=TABHL(HWDTOUT,TIME.K,1980,1990,10)*1E3
T HWDTOUT=16400/19360
A HWDSIND.K=TABHL(HWDTIND,TIME.K,1980,1990,10)*1E3
T HWDTIND=8975/10466
A HWDSBIO.K=TABHL(HWDTBIO,TIME.K,1980,1990,10)*1E3
T HWDTBIO=1520/2890
A HWDSIMP.K=TABHL(HWDTIMP,TIME.K,1980,1990,10)*1E3
T HWDTIMP=-5905/-6004
A HWDSDEM.K=HWDSOUT.K+HWDSIMP.K
```

== Timber as Biomass Energy DC'96b
Covers Wood & Bagasse as listed in ABARE'93 at present. Ties in to BIO renewable electricity sector DC'96b

```
A
BIODEM.K=BIOAFF.K+BIOMIN.K+BIOIND.K+BIODOM.K+BIOSER.K+BIOTRA.K+BIOEL.K
PJ/y
I FBIOWDS=0.55      fraction biofuel demand as wood (rest is bagasse)
                    data from ABARE'94 table series 'A' DC'96b

A BIOAFF.K=TEDAFF.K*FBIOAFF  PJ/y
I FBIOAFF=0
A HBIOAFF.K=0

A BIOMIN.K=TEDMIN.K*FBIOMIN  PJ/y
I FBIOMIN=0
A HBIOMIN.K=0

A BIOIND.K=TEDIND.K*FBIOIND.K  PJ/y
A FBIOIND.K=TABHL(FBITIND,TIME.K,1981,2051,10)
T FBITIND=0.137/0.13/0.13/0.13/0.13/0.13/0.13/0.13 abare'93 data
A HBIOIND.K=TABHL(HBITIND,TIME.K,1981,1991,2)
T HBITIND=88.7/84.2/88.3/93/103.5/92.8

A BIODOM.K=TEDDOM.K*FBIODOM.K  PJ/y
A FBIODOM.K=TABHL(FBITDOM,TIME.K,1981,2051,10)
T FBITDOM=0.44/0.41/0.41/0.41/0.41/0.41/0.41/0.41 abare'93 data
A HBIODOM.K=TABHL(HBITDOM,TIME.K,1981,1991,2)
T HBITDOM=68.5/69.3/69.9/70.7/74.1/78.4

A BIOSER.K=TEDSER.K*FBIOSER.K  PJ/y
A FBIOSER.K=TABHL(FBITSER,TIME.K,1981,2051,10)
T FBITSER=0.02/0.01/0.01/0.01/0.01/0.01/0.01/0.01 abare'93 data
A HBIOSER.K=TABHL(HBITSER,TIME.K,1981,1991,2)
T HBITSER=1/.8/.8/.7/.7/.6

A BIOTRA.K=TEDTRA.K*FBIOTRA  PJ/y
I FBIOTRA=0
A HBIOTRA.K=0

A EREBIO.K=1+FBIOWDS*(GERWDS.K/PJPM3WD)
```

primary energy requirement per unit fuel wood is calorific value plus

```
      embodied  energy  content  from  forestry  operations  VPJ/PJ.  Only
timber
      is accounted for here; bagasse, as a waste product, is assigned
zero
      embodied energy content at present   DC'96b

 = 2.2.4 == Summary Statistics
A RCFAFF.K=RCFAGR.KL+RCFWDS.KL
A RDCAFF.K=RDCAGR.KL+RDCWDS.KL  DC'97B
A CSAFF.K=CSAGR.K+CSWDS.K
A TEDAFF.K=TEDAGR.K+TEDWDS.K
A EEDAFF.K=EEDAGR.K+EEDWDS.K
A RESAFF.K=RESAGR.K+RESWDS.K
A PEDAFF.K=PEDAGR.K+PEDWDS.K
A AFFOUTB.K=AGROUTB.K+FOROUTB.K  DC'97B
A AFFX.K=AFFOUTB.K/AFFOUTN     DC'97B
K AFFOUTN=AFFOUTB

 historical data for validation period
A HRCFAFF.K=TABHL(HRCFAT,TIME.K,1981,1992,1)*1E9*EII
                    historical  rate  of  capital  formation,  agriculture,
VPJ/y
T   HRCFAT=3.67/2.71/3.94/3.90/3.01/2.63/3.45/3.51/3.08/1.82/2.05/2.23
A HCSAFF.K=TABHL(HCSAT,TIME.K,1981,1992,1)*1E9*EII
                    historocal agricultural capital stock, VPJ
T
HCSAT=51.69/51.57/52.58/53.67/53.87/53.52/53.89/54.38/54.41/53.06/51.93
/ ^
     50.92          HRCF & HCS data from AusNA'92 T66,75,76
A HTEDAFF.K=TABHL(HTDAGRT,TIME.K,1981,1993,2)
                    historical agricultural thermal energy demand, PJ/y
T   HTDAGRT=47.9/49.6/47.2/47.7/49.1/49.3/53.5
                    PJ/y
A PTEDAFF.K=TABHL(PTETAFF,TIME.K,1993,2009,16)
T PTETAFF=53.5/70.3  ABARE'95 projections DC'97c

A HEEDAFF.K=TABHL(HEDAGRT,TIME.K,1981,1991,2)
                    historical  agricultural  electrical  energy  demand,
GWh/y
T   HEDAGRT=1556/1639/1833/2056/2361/2556
                    GWh/y HTED & HEED data from ABARE'92 Tables A5-11
A HPEDAFF.K=(HTEDAFF.K+(HEEDAFF.K*FEREL.K))*SYSGER.K


 == 2.3  Mining
 A broad sector, covering mining of Energy & Non-Energy resources

 == 2.3.1 Energy Reserves
 Divided into Oil, Gas & Coal only. Uranium isn't used indigenously, so
it
 isn't counted as a fuel here.

 = Mineral Oils
L CSOIL.K=CSOIL.J+DT*(RCFOIL.JK-RDCOIL.JK)
                    HMC of oil sector, VPJ
K   CSOIL=40.4E9*EII*(1-FNEN)*FMINOIL
                    HMC at initiation, VPJ
```

```
K   FMINOIL=HRPOIL/HRPFUL
                    fraction of energy mining initial CS allocated to
oil 22%
                    based on 1981 HRP data, assuming equal OCRs
R       RCFOIL.KL=FIFGE(FIFZE(RCFOIL2.K,RCFOIL1.K,FOILMKT),0,OILSTK.K,0)
DC'97c
                   rate of fixed CS formation, oil sector, VPJ/y
                   allows user-defined curbs on exports via RCFOIL2
DC'96b
A RCFOIL1.K=FIFGE(0,OILDEM.K*OILDEMF.K,EREOIL.K-EREME.K,ERECUT.K-1)
                   rate of fixed capital formation, oil sector, VPJ/y
oil
                    investment cuts out when gap between EREOIL & EREME
gets
                    too big
                   DEFAULT: free market exploitation of oil reserves,
                    assuming an export mkt
A RCFOIL2.K=MIN(RCFOIL1.K,DCSOIL.K-CSOIL.K+RDCOIL.KL)
                   ALTERNATIVE: postulate an upper limit on future oil
export
                    market
I    FOILMKT=1       policy variable: 1=assume unlimited export market
0=assume
                    limited exp. market, set by OILMKT.K
A DCSOIL.K=DRPOIL.K*CSPOIL
                   desired CS oil to meet indigenous demands plus
export
                    market, VPJ
A DRPOIL.K=OILDEM.K+OILMKT.K
                   desired rate of production: indigenous needs plus
export
                    market, PJ/y
A OILMKT.K=TABHL(OILMTT,TIME.K,1981,2051,10)*1E3
                   upper limit of export market for Australian oil,
PJ/y
T   OILMTT=122/131/131/131/131/131/131/131
                   BP'92 quotes world consumption 1981=2913e3mtoe,1991=
                    3141e3mtoe OILMTT data simply continues this latter
value:
                    user may insert other data
R RDCOIL.KL=CSOIL.K/LTMIN.K
                   depreciation of capital, VPJ/y
A OILDEMF.K=ODFN.K*EREOIL.K/EREME.K
                   demand-related factor determining level of
investment
A ODFN.K=TABHL(ODFNT,TIME.K,1981,1993,4)*1E-3
T  ODFNT=2.5/7/2.5/2.5      oil demand factor: empirically determined
DC'96b
                   variable regime reflecting changes in extraction
rate over
                   validation period  DC'96b
A PEROIL.K=RPOIL.KL*(EREOIL.K-1)
                   process energy req, oil extraction, PJ/y
A PEDOIL.K=PEROIL.K-RDCOIL.KL
                   direct primary energy demand, PJ/y
A TEDOIL.K=PEDOIL.K*FTEDOIL
                   thermal energy demand, oil sector, PJ/y
```

```
A EEDOIL.K=(PEDOIL.K*(1-FTEDOIL))/FEREL.K
                   electrical energy demand, oil sector, GWh/y
I   FTEDOIL=1        assume all energy input to resource extraction is
thermal
                    fuel

A HRPOIL.K=TABHL(HRPOIT,TIME.K,1981,1993,2)
                   historical oIl extraction rate, PJ/y
T   HRPOIT=909/1076/1280/1261/1284/1254/1161
                         1261/1284/1254
                   data to 85 from ABARE'93, from 87 from ABARE'95
DC'97c
A PRPOIL.K=TABHL(PRPOIT,TIME.K,1993,2009,16)
T   PRPOIT=1161/777
                   linear projection of ABARE'95 projection for 2009
DC'97c

A RCFGOL.K=RCFGAS.KL+RCFOIL.KL
                   RCF oil & gas, to check w. historical dataset
A HRCFGOL.K=TABHL(HRCFGOT,TIME.K,1981,1992,1)*1E6*EII
                   historical rate of capital formation, oil & gas
sectors,
                    VPJ/y
T   HRCFGOT=1241/1529/900/379/900/1400/1915/1528/1009/1038/1416/1371
                   data from BF_FAX_21APR95: deflated on 16MAY95
datasheet
A HGLDEMF.K=HRCFGOL.K/(HGASDEM.K+HOILDEM.K)
                   historical demand factor average, oil & gas  DC'96b

A OILDEM.K=(OILAFF.K+OILMIN.K+OILIND.K+OILDOM.K+OILSER.K+OILTRA.K)^
           *OILREF.K*EREOIL.K
                   demand for crude oil, PJ/y  AGR -> AFF DC'96b
A OILREF.K=1+FIFGE(TABHL(O2LREFT,TIME.K,1990,2050,10),^
          TABHL(OILREFT,TIME.K,1981,1993,12),TIME.K,1992)/100
                   factor determining fractional rate of
autoconsumption in
                    oil refining process
T   OILREFT=10/7
T   O2LREFT=7/7/7/7/7/7/7
                   ABARE'93 data on losses refinery factor, covering
losses in
                    conversion from crude to fuel plus 'other losses'
DC'96b

A OILAFF.K=TEDAFF.K*FOILAFF
K   FOILAFF=1-FGASAFF-FCOLAFF-FBIOAFF
                   fraction oil & gas to agriculture
A HOILAFF.K=TABHL(HOITAFF,TIME.K,1981,1991,2)
T HOITAFF=47.9/49.6/47.2/47.7/49.1/49.2

A OILMIN.K=1-FGASMIN.K-FCOLMIN.K-FBIOMIN
A HOILMIN.K=TABHL(HOITMIN,TIME.K,1981,1991,2)
T HOITMIN=25.1/23/25/28.1/37.8/40.4

A OILIND.K=TEDIND.K*FOILIND.K
A FOILIND.K=1-FGASIND.K-FCOLIND.K-FBIOIND.K
                   fraction oil & gas to industry
```

```
A HOILIND.K=TABHL(HOITIND,TIME.K,1981,1991,2)
T HOITIND=189.8/163.1/140/150.5/155.9/152.8

A OILDOM.K=TEDDOM.K*FOILDOM.K
A FOILDOM.K=1-FGASDOM.K-FCOLDOM.K-FBIODOM.K
                   fraction oil & gas to domestic sector
A HOILDOM.K=TABHL(HOITDOM,TIME.K,1981,1991,2)
T HOITDOM=24.6/20.1/18/16.5/16.7/17

A OILSER.K=TEDSER.K*FOILSER.K
A FOILSER.K=1-FGASSER.K-FCOLSER.K-FBIOSER.K
                   fraction oil & gas to services
A HOILSER.K=TABHL(HOITSER,TIME.K,1981,1991,2)
T HOITSER=16.6/11.3/10.6/10.6/11.2/11.7

A OILTRA.K=TEDTRA.K*FOILTRA.K
A FOILTRA.K=1-FGASTRA.K-FCOLTRA-FBIOTRA
                   fraction oil & gas to transport fractions thermal
fuel use
                    as oil, for demand-side sectors oil takes up the
shortfall
A HOILTRA.K=TABHL(HOITTRA,TIME.K,1981,1991,2)
T HOITTRA=837/851.8/891.4/950.1/994.8/1000.6

A HOILDEM.K=TABHL(HOITDEM,TIME.K,1981,1993,2)
                   historical demand for oil, PJ/y
T   HOITDEM=1360/1280/1270/1361/1448/1437/1516
                           1351/1493/1408
                   PJ/y: ABARE'93 & ABARE'95 data DC'97b
A POILDEM.K=TABHL(POITDEM,TIME.K,1993,2009,16)
T   POITDEM=1516/1860
                  linear projection of ABARE'95 projection for 2009
DC'97c

A OILIMP.K=(OILDEM.K-RPOIL.KL)/EREOIL.K
                   net import of oil, PJ/y
A HOILIMP.K=TABHL(HOITIMP,TIME.K,1981,1993,2)
                   historical net import of oil, PJ/y
T   HOITIMP=451/203/-10/89/209/158/358
                   net imports: ABARE'93 & abare'95 DC'97b
A POILIMP.K=TABHL(POITIMP,TIME.K,1993,2009,16)
T   POITIMP=358/1083
                  linear projection of ABARE'95 projection for 2009
DC'97c


 = Natural Gas
L CSGAS.K=CSGAS.J+DT*(RCFGAS.JK-RDCGAS.JK)
                   capital stock gas extraction, VPJ
K   CSGAS=40.4E9*EII*(1-FNEN)*FMINGAS
                   initial CS value, VPJ
K   FMINGAS=HRPGAS/HRPFUL
                    fraction of energy mining initial CS allocated to
gas 11%
                    based on 1981 HRP data, assuming equal OCRs
R       RCFGAS.KL=FIFGE(FIFZE(RCFGAS2.K,RCFGAS1.K,FGASMKT),0,GASSTK.K,0)
DC'97c
```

```
                        rate of fixed CS formation, gas sector, VPJ/y
                        allows user-defined curbs on exports via RCFGAS2
DC'96b
A RCFGAS1.K=FIFGE(0,GASDEM.K*GASDEMF.K,EREGAS.K,ERECUT.K)
                        DEFAULT: free market exploitation of gas reserves,
                         assuming an export mkt
A RCFGAS2.K=MIN(RCFGAS1.K,DCSGAS.K-CSGAS.K+RDCGAS.KL)
                        ALTERNATIVE: postulate an upper limit on future gas
export
                         market
I    FGASMKT=1            policy variable: 1=assume unlimited export market
0=assume
                         limited exp. market, set by GASMKT.K
A DCSGAS.K=DRPGAS.K*CSPGAS
                        desired CS gas to meet indigenous demands plus
export
                         market, VPJ
A DRPGAS.K=GASDEM.K+GASMKT.K
                        desired rate of production: indigenous needs plus
export
                         market, PJ/y
A GASMKT.K=TABHL(GASMTT,TIME.K,1981,2051,10)*1E3
                        upper limit of export market for Australian gas,
PJ/y
T   GASMTT=55/74/74/74/74/74/74/74
                        BP'92 quotes world consumption 1981=1315e3mtoe,1991=
                         1770e3mtoe GASMTT data simply continues this latter
value:
                         user may insert other data
                         Australia currently produces 1.5E3 PJ/y and exports
0.5E3
R RDCGAS.KL=CSGAS.K/LTMIN.K
                        depreciation of gas sector capital, VPJ/y
A GASDEMF.K=GDFN.K*EREGAS.K
                        demand-related factor determining level of
investment
A GDFN.K=TABHL(GDFNT,TIME.K,1981,1999,6)*1E-3
T GDFNT=5/5/12/8        gas demand factor: empirically determined  DC'96b
                        two-step regime reflecting changes in extraction
rate over
                        validation period (liberalisation of global gas
market in
                        late 1980's?)  DC'96b
A PERGAS.K=RPGAS.KL*(EREGAS.K-1)
                        process energy req, gas extraction, PJ/y
A PEDGAS.K=PERGAS.K-RDCGAS.KL
                        direct primary energy demand, PJ/y
A TEDGAS.K=PEDGAS.K*FTEDGAS
                        thermal fuel demand, gas sector, PJ/y
A EEDGAS.K=(PEDGAS.K*(1-FTEDGAS))/FEREL.K
                        electricity demand, gas sector, GWh/y
I    FTEDGAS=1            assume all energy input to resource extraction is
thermal
                         fuel
                        rate of extraction of gas, PJ/y
K   CSPGAS=CSGAS/HRPGAS
                        capital stoc req. per unit gas extracted
```

```
R DISCGAS.KL=TABHL(DISTGAS,TIME.K,1980,2050,10)
                   discovery of new gas reserves, PJ/y
T DISTGAS=2.2E3/2.2E3/1.51E3/1.51E3/1.51E3/1.51E3/1.51E3/1.51E3
                   default=0, as discovery unpredictable DC'96a
                   bdf 20/2/97 set at BRS average probability
                   BDF 12/10/97 NEW STOCKS MATCHING
A HGASSTK.K=TABHL(HGASSTT,TIME.K,1981,1994,1)*39^
         +TABHL(HLPGSTT,TIME.K,1981,1994,1)*26.5
T HGASSTT=644/624/629/616/691/691/832/1043/1030/941/950/978/999/1147
T HLPGSTT=126/123/112/85/85/88/97/85/128/106/108/133/134/144
 1981 data from ABARE'93 spreadsh

A HRPGAS.K=TABHL(HRPGAT,TIME.K,1981,1993,2)
                   historical gas extraction rate, PJ/y
T   HRPGAT=462/490/571/611/797/914/1054
                       610/797/931
                   data from ABARE'93 & ABARE'95 DC'97b
A PRPGAS.K=TABHL(PRPGAT,TIME.K,1993,2009,16)
T   PRPGAT=931/2218
                  linear  projection  of  ABARE'95  projection  for  2009
DC'97c

A
GASDEM.K=(GASAFF.K+GASMIN.K+GASIND.K+GASDOM.K+GASSER.K+GASTRA.K+GASEL.K
^
         +GASREF.K)*EREGAS.K*GASCONV.K
                   demand for gas, PJ/y
                   structure clarified DC'96b

A GASCONV.K=TABHL(GATCONV,TIME.K,1981,1993,12)
T GATCONV=1.06/1.032    ABARE data on gas used in conversion/processing
DC'96b

A GASAFF.K=TEDAFF.K*FGASAFF
I   FGASAFF=0       fraction of gas to agriculture
A HGASAFF.K=0

A GASMIN.K=TEDMIN.K*FGASMIN.K
A FGASMIN.K=TABHL(FGATMIN,TIME.K,1981,2051,10)
                   fraction of gas to industry
T   FGATMIN=0.49/0.54/0.61/0.61/0.61/0.61/0.61/0.61
                   ABARE'93 data for FGASMIN+ ABARE'95 DC'97c
A HGASMIN.K=TABHL(HGATMIN,TIME.K,1981,1991,2)
T HGATMIN=25.5/38.9/47.7/59/81.6/88.2  ABARE'93 data

A GASIND.K=TEDIND.K*FGASIND.K
A FGASIND.K=TABHL(FGATIND,TIME.K,1981,2051,10)
                   fraction of gas to industry
T   FGATIND=0.30/0.42/0.50/0.50/0.50/0.50/0.50/0.50  DC'96b
                   ABARE'93 data for FGASIND+ ABARE'95 DC'97c
A HGASIND.K=TABHL(HGATIND,TIME.K,1981,1991,2)
T HGATIND=193.6/203.2/253.7/276.1/288.8/297.5  ABARE'93 data

A GASDOM.K=TEDDOM.K*FGASDOM.K
A FGASDOM.K=TABHL(FGATDOM,TIME.K,1981,2051,10)
                   fraction of gas to domestic
T   FGATDOM=0.40/0.49/0.53/0.53/0.53/0.53/0.53/0.53
```

```
                    ABARE'93 data for FGASDOM + ABARE'95 DC'97c
A HGASDOM.K=TABHL(HGATDOM,TIME.K,1981,1991,2)
T HGATDOM=61.3/66/73/73/90/93.5   ABARE'93 data

A GASSER.K=TEDSER.K*FGASSER.K
A FGASSER.K=TABHL(FGATSER,TIME.K,1981,2051,10)
                    fraction of gas to services
T   FGATSER=0.49/0.69/0.69/0.69/0.69/0.69/0.69/0.69
                    ABARE'93 data for FGASSER
A HGASSER.K=TABHL(HGATSER,TIME.K,1981,1991,2)
T HGATSER=22.2/25.6/26.5/31/35/36.9   ABARE'93 data

A GASTRA.K=TEDROD.K*FGASROD.K
A FGASROD.K=NGV.K/TNV.K
                    fraction of gas to road transport
A FGASTRA.K=(TEDROD.K*FGASROD.K)/TEDTRA.K
                    fraction of gas to all transport services

A GASREF.K=RPOIL.KL*GASPORF.K
A GASPORF.K=TABHL(GATPORF,TIME.K,1981,1993,12)
T GATPORF=0.015/0.0072
    ABARE data on gas used in oil refineries DC'96b
A HGASREF.K=TABHL(HGATREF,TIME.K,1981,1993,12)
T HGATREF=14/9

A HGASDEM.K=TABHL(HGATDEM,TIME.K,1981,1993,2)
                    historical demand for gas, PJ/y
T   HGATDEM=462/490/571/611/688/688/733
                    PJ/y: ABARE'93 &'95 data DC'97c
A PGASDEM.K=TABHL(PGATDEM,TIME.K,1993,2009,16)
T   PGATDEM=733/1272
                    linear projection of ABARE'95 projection for 2009
DC'97c

A GASIMP.K=(GASDEM.K-RPGAS.KL)/EREGAS.K
                    net imports of gas, PJ/y
A HGASIMP.K=TABHL(HGATIMP,TIME.K,1981,1993,2)
                    historical net import of gas, PJ/y
T   HGATIMP=0/0/0/0/-110/-235/-321
                    net import, PJ/y: ABARE'93&'95 DC'97c
A PGASIMP.K=TABHL(PGATIMP,TIME.K,1993,2009,16)
T   PGATIMP=-321/-946.6
                    linear projection of ABARE'95 projection for 2009
DC'97c


 = Coal (black & brown)
L CSCOL.K=CSCOL.J+DT*(RCFCOL.JK-RDCCOL.JK)
                    capital stock, coal extraction, VPJ
K   CSCOL=40.4E9*EII*(1-FNEN)*FMINCOL
                    initial CS coal sector, VPJ
K   FMINCOL=HRPCOL/HRPFUL
                    fraction of energy mining initial CS allocated to
coal 67%
                    based on 1981 HRP data, assuming equal OCRs
R       RCFCOL.KL=FIFGE(FIFZE(RCFCOL2.K,RCFCOL1.K,FCOLMKT),0,COLSTK.K,0)
DC'97c
```

```
                    rate of fixed CS formation, coal sector, VPJ/y
A RCFCOL1.K=FIFGE(0,COLDEM.K*COLDEMF.K,ERECOL.K,ERECUT.K)
                    DEFAULT: free market exploitation of coal reserves,
                     assuming an export mkt
A RCFCOL2.K=MIN(RCFCOL1.K,DCSCOL.K-CSCOL.K+RDCCOL.KL)
                    ALTERNATIVE: postulate an upper limit on future coal
export
                     market
I    FCOLMKT=1        policy variable: 1=assume unlimited export market
0=assume
                     limited exp. market, set by COLMKT.K
A DCSCOL.K=DRPCOL.K*CSPCOL
    desired CS coal to meet indigenous demands plus export
                     market, VPJ
A DRPCOL.K=COLDEM.K+COLMKT.K
                    desired rate of production: indigenous needs plus
export
                     market, PJ/y
A COLMKT.K=TABHL(COLMTT,TIME.K,1981,2051,10)*1E3
                    upper limit of export market for Australian coal,
PJ/y
T   COLMTT=75/90/90/90/90/90/90/90
                    BP'92 quotes world consumption 1981=1800e3mtoe,1991=
                     2180e3mtoe COLMTT data simply continues this latter
value:
                     user may insert other data (Australia exports 7E3
PJ/y currently)
R RDCCOL.KL=CSCOL.K/LTMIN.K
                    depreciation of capital, VPJ/y
A COLDEMF.K=CDFN*ERECOL.K

   demand-related factor determining level of investment
I   CDFN=12E-3      initial value for COLDEMF
A PERCOL.K=RPCOL.KL*(ERECOL.K-1)
                    process energy req, coal extraction, PJ/y
A PEDCOL.K=PERCOL.K-RDCCOL.KL
                    direct primary energy demand, PJ/y
A TEDCOL.K=PEDCOL.K*FTEDCOL
                    thermal fuel demand, coal sector, PJ/y
A EEDCOL.K=(PEDCOL.K*(1-FTEDCOL))/FEREL.K
                    electricity demand, coal sector, GWh/y
I    FTEDCOL=1        assume all energy input to resource extraction is
thermal
                     fuel

A HRPCOL.K=TABHL(HRPCOT,TIME.K,1981,1993,2)
                    historical coal extraction rate, PJ/y
T   HRPCOT=2798/3143/3947/4035/4685/5177/5273
                    data from ABARE'93&'95 DC'97c
A PRPCOL.K=TABHL(PRPCOT,TIME.K,1993,2009,16)
T   PRPCOT=5273/7766
                   linear projection of ABARE'95 projection for 2009
DC'97c

A HRCFCOL.K=TABHL(HRCFCOT,TIME.K,1981,1992,1)*1E6*EII
                    historical rate of capital formation, coal sector,
VPJ/y
```

```
T   HRCFCOT=2296/2756/1470/879/840/800/752/449/745/939/580/1593
                    data   from   BF_FAX_21APR95:   deflated   on   16MAY95
datasheet

A
COLDEM.K=(COLAFF.K+COLMIN.K+COLIND.K+COLDOM.K+COLSER.K+COLTRA.K+COLEL.K
)^
          *ERECOL.K*COLCONV.K
                    demand for coal, PJ/y

A COLCONV.K=TABHL(COTCONV,TIME.K,1981,1993,12)
T COTCONV=1.046/1.02    ABARE data on losses during coking, briquette
manuf. etc
                        DC'96b

A COLAFF.K=TEDAFF.K*FCOLAFF
I   FCOLAFF=0       fraction coal to agriculture
A HCOLAFF.K=0

A COLMIN.K=TEDMIN.K*FCOLMIN.K
A FCOLMIN.K=TABHL(FCOTMIN,TIME.K,1981,2051,10)
                    fraction coal to industry
T   FCOTMIN=0.03/0.06/0.06/0.06/0.06/0.06/0.06/0.06
                    ABARE'93 data for FCOLMIN
A HCOLMIN.K=TABHL(HCOTMIN,TIME.K,1981,1991,2)
T HCOTMIN=1.7/2.2/3.1/5.4/8.4/8.3

A COLIND.K=TEDIND.K*FCOLIND.K
A FCOLIND.K=TABHL(FCOTIND,TIME.K,1981,2051,10)
                    fraction coal to industry
T   FCOTIND=0.27/0.24/0.12/0.12/0.12/0.12/0.12/0.12
                    ABARE'93 data for FCOLIND trend continued; ABARE'95
data
                    for 93-4 suggests 18.5% DC'97c
A HCOLIND.K=TABHL(HCOTIND,TIME.K,1981,1991,2)
T HCOTIND=174/155.3/175.7/170.9/173.8/167.8

A COLDOM.K=TEDDOM.K*FCOLDOM.K
A FCOLDOM.K=TABHL(FCOTDOM,TIME.K,1981,2051,10)
T   FCOTDOM=0.01/0/0/0/0/0/0/0   fraction coal to domestic
A HCOLDOM.K=TABHL(HCOTDOM,TIME.K,1981,1991,2)
T HCOTDOM=1.8/1.2/0.9/0.7/0.6/0.3

A COLSER.K=TEDSER.K*FCOLSER.K
A FCOLSER.K=TABHL(FCOTSER,TIME.K,1981,2051,10)
                    fraction coal to services
T   FCOTSER=0.13/0.09/0.09/0.09/0.09/0.09/0.09/0.09
                    ABARE'93 data for FCOLSER
A HCOLSER.K=TABHL(HCOTSER,TIME.K,1981,1991,2)
T HCOTSER=6.1/6.2/6/5.8/5.7/4.8

A COLTRA.K=TEDTRA.K*FCOLTRA
I   FCOLTRA=0       fraction coal to transport fractions thermal fuel
use as
                    gas, for demand-side sectors data taken from
ABARE'93
                    study: 1981-1991 average
```

```
A HCOLTRA.K=0

A HCOLDEM.K=TABHL(HCOTDEM,TIME.K,1981,1993,2)
                    historical demand for coal, PJ/y
T   HCOTDEM=1423/1228/1381/1431/1575/1643/1671
                            1100/1704/1622
                    PJ/y: ABARE'93 &'95 data DC'97c
A PCOLDEM.K=TABHL(PCOTDEM,TIME.K,1993,2009,16)
T   PCOTDEM=1671/2098
                   linear projection of ABARE'95 projection for 2009
DC'97c

A COLIMP.K=(COLDEM.K-RPCOL.KL)/ERECOL.K
                    net imports of coal, PJ/y
A HCOLIMP.K=TABHL(HCOTIMP,TIME.K,1981,1993,2)
                    historical net imp coal, PJ/y
T   HCOTIMP=-1373/-1916/-2566/-2935/-2982/-3524/-3684
                    net imports: ABARE'93
A PCOLIMP.K=TABHL(PCOTIMP,TIME.K,1993,2009,16)
T   PCOTIMP=-3684/-5666
                   linear projection of ABARE'95 projection for 2009
DC'97c
```

== Energy Resources Summary
The acronym FUL simply sums oil, gas & coal data: can help in determining
if deviations from historical data are due toerrors in thermal energy demand
terms of other sectors, or to internal misallocation between fuel types.

```
A RPFUL.K=RPOIL.KL+RPGAS.KL+RPCOL.KL
                    rate of production of fuels, PJ/y
A HRPFUL.K=HRPOIL.K+HRPCOL.K+HRPGAS.K   correction DC'96b
                    hist. rate of production of fuels, PJ/y
A PRPFUL.K=PRPOIL.K+PRPCOL.K+PRPGAS.K
                    ABARE'95 projection from 1993 data DC'97c
A FULDEM.K=OILDEM.K+GASDEM.K+COLDEM.K
                    fuel demand, PJ/y
A HFULDEM.K=HOILDEM.K+HGASDEM.K+HCOLDEM.K
                    historic fuel demand, PJ/y
A PFULDEM.K=POILDEM.K+PGASDEM.K+PCOLDEM.K
                    ABARE'95 projection from 1993 data DC'97c
A FULIMP.K=OILIMP.K+GASIMP.K+COLIMP.K
                    fuel imports, PJ/y
A HFULIMP.K=HOILIMP.K+HGASIMP.K+HCOLIMP.K
                    historic fuel imports, PJ/y
A PFULIMP.K=POILIMP.K+PGASIMP.K+PCOLIMP.K
                    ABARE'95 projection from 1993 data DC'97c
```

== 2.3.2 Non-Energy Resource Mining: stone, metals, minerals, etc.
All non-energy mining is lumped together here; includes metal ores, gold and
other minerals.

```
L CSMIN.K=CSMIN.J+dt*(RCFMIN.JK-RDCMIN.JK)
                     HMC in mining sector, VPJ
K   CSMIN=EII*40.436e9*FNEN
                     initial money value changed to VPJ
I   FNEN=0.5         fraction initial CSTMIN in non-energy sector
R RCFMIN.KL=FIFZE(HRCFMIN.K,DCSMIN.K-CSMIN.K+RDCMIN.KL,OPTMIN)
                     rate of fixed capital formation, VPJ/y
R RDCMIN.KL=CSMIN.K/LTMIN.K
                     rate of capital consumption, VPJ/y
A LTMIN.K=TABHL(LTMINT,TIME.K,1981,2051,10)
                     average lifetime of mining HMC, y
T   LTMINT=10/10/10/10/10/10/10/10
                     average value from BF_FAX_21APR95 data are 7.7 ->
9.7. Data
                      here slightly higher to match HRCFMIN
A DCSMIN.K=(MININD.K+MINOTH.K+DMINEXP.K)*CSPMIN.K
                     desired mining capital stock, VPJ
A CSPMIN.K=TABHL(CSPMINT,TIME.K,1981,2051,10)*CSPMINN
T   CSPMINT=1/1/1/1/1/1/1/1
    technological multiplier for non-energy mining  DC'96b
K   CSPMINN=CSMIN/(MININD+MINOTH+DMINEXP)
                     HMC required per unit output, VPJ/PJ

A MINOTH.K=(CSSER.K+CSDOM.K+CSUTL.K)*MICROTH.K
A MICROTH.K=TABHL(MICTOTH,TIME.K,1981,2051,10)*1E-11/EII
T MICTOTH=4.0/1.0/1.0/1.0/1.0/1.0/1.0/1.0
                     mining products other activities, PJ/y

A MININD.K=CSIND1.K*MICRIND.K
A MICRIND.K=TABHL(MICTIND,TIME.K,1981,2051,10)*1E-10/EII
T MICTIND=1.65/2.34/2.34/2.34/2.34/2.34/2.34/2.34
                     mining products, industry (from IO tables)  PJ/y



A TEDMIN.K=CSMIN.K*TICRMIN.K
                     thermal energy demand, mining, PJ/y
A TICRMIN.K=TABHL(TICTMIN,TIME.K,1981,2051,10)*1E-9/EII
T   TICTMIN=1.29/2.03/2.03/2.03/2.03/2.03/2.03/2.03
                     ABARE'93/94 average data for entire mining sector
A EEDMIN.K=CSMIN.K*EICRMIN.K
                     electrical energy demand, mining, GWh/y
A EICRMIN.K=TABHL(EICTMIN,TIME.K,1981,2051,10)*1E-7/EII
                     electricity demand per unit capital stock, GWh/y
T   EICTMIN=2.2/2.6/2.6/2.6/2.6/2.6/2.6/2.6  DC'97c
   T   EICTMIN=2.2/3.9/3.9/3.9/3.9/3.9/3.9/3.9
                     covering electricity demand for entire mining sector
DC'96b

A PEDMIN.K=(TEDMIN.K+(EEDMIN.K*FEREL.K))*SYSGER.K
                     primary energy demand, mining, PJ/y
A MINOUT.K=PEDMIN.K+RDCMIN.KL
                     embodied energy output, PJ/y
A MINOUT$.K=MINOUT.K/EII
                     money value of output using 'natural price', '89A$/y

A DMINEXP.K=TABHL(DMINEXT,TIME.K,1981,2051,10)
```

```
T   DMINEXT=12/92/92/92/92/92/92/92
                  model  computes  EE  of  output  as  ~70-190PJ  over
validation
                  period, using historic time series: IO tables show an
inc.
                  in exports from 16% to 49% of total output over this
time
                  DC'96b

 = Some historical data for non-energy mining ==
A HMINEXP.K=TABHL(HMINEXT,TIME.K,1981,1991,10)*EII
                   exports of mining output, based on IO/ABARE, VPJ/y
T   HMINEXT=11.7/21.3

A HMININD.K=TABHL(HMININT,TIME.K,1981,1991,10)*EII
                   sales  to  industry  of  mining  output,  based  on
IO/ABARE, VPJ/y
T   HMININT=20.3/36

A HMINOTH.K=TABHL(HMINOTT,TIME.K,1981,1991,10)*EII
                   sales to other sectors  of mining output, based on
IO, VPJ/y
T   HMINOTT=38.5/14

A HRCFMIN.K=TABHL(HRCFMT,TIME.K,1981,1992,1)*1E6*EII
                   historical  rate  of  capital  formation,  non-energy
mining,
                    VPJ/y
T   HRCFMT=5606/4240/2540/3039/2960/2890/2512/2666/2666/2733/2476/1833
                   from BF_FAX_21APR95 data:  85  &  86  filled  in  by
extrapolation


 == 2.3.3 Summary Mining Data
 Acronym TMIN sums energy and Non-energy mining activities
A RCFTMIN.K=RCFMIN.KL+RCFOIL.KL+RCFGAS.KL+RCFCOL.KL
                   total  rate  of  capital  formation  in  all  resource
sectors,
                    VPJ/y
A RDCTMIN.K=RDCMIN.KL+RDCOIL.KL+RDCGAS.KL+RDCCOL.KL  DC'97B
A CSTMIN.K=CSMIN.K+CSOIL.K+CSGAS.K+CSCOL.K
                   total HMC in all resource sectors, VPJ
A TEDTMIN.K=TEDMIN.K+TEDOIL.K+TEDGAS.K+TEDCOL.K
                   total rate of thermal enrgy demand in all resource
sectors,
                    PJ/y
A EEDTMIN.K=EEDMIN.K+EEDOIL.K+EEDGAS.K+EEDCOL.K
                   total rate of elec. demand in all resource sectors,
GWh/y
A MINDEX.K=CSTMIN.K/CSTMINN
                   index of mining activity: 1981=1
K   CSTMINN=CSMIN+CSOIL+CSGAS+CSCOL
                   HMC in resource sector at initiation, VPJ
A TRES.K=RESAFF.K+RESCO2.K
                   other non-energy resource demands not explicitly met
                   elsewhere (generally for chemicals/minerals): these
are
```

```
                    subtracted directly from INDOUT in TICFR equation
DC'96b


 historical data for validation
A HRCFTMN.K=TABHL(HRCFTMT,TIME.K,1981,1992,1)*1E9*EII
                    historical rate of capital formation, all mining
sectors,
                     VPJ/y
T   HRCFTMT=9.24/8.53/4.91/4.30/4.6/4.9/5.18/4.64/4.42/4.71/4.47/4.80
                    historical rate of capital formation, PJ/y !
BF_FAX_21APR95
                     data: 85 & 86 data filled in by linear
extrapolation
A HCSTMIN.K=TABHL(HCSMT,TIME.K,1981,1992,1)*1E9*EII
                    historical total capital stock in mining sectors,
VPJ
T
HCSMT=40.44/44.80/47.13/48.93/51.19/53.87/56.77/59.40/62.04/64.88/67.37
/ ^
     70.24          HRCF & HCS data from AusNA'92 T66,75,76

A HTEDMIN.K=TABHL(HTDMINT,TIME.K,1981,1993,2)
                    historic thermal fuel demand, resource sector, PJ/y
T   HTDMINT=52.3/64.1/75.8/92.5/127.8/136.9/158
                    data, PJ/y
A PTEDMIN.K=TABHL(PTETMIN,TIME.K,1993,2009,16)
T PTETMIN=158/253  ABARE'95 projections DC'97c

A HEEDMIN.K=TABHL(HEDMINT,TIME.K,1981,1991,2)*1E3
                    historic electricity demand, resource sector, GWh/y
T   HEDMINT=5.2/5.4/6.5/7.1/9.7/10.2
                    data GWh/y HTED & HEED data from ABARE'92 Tables A5-
11


 == 2.4  Industry - inc. Manufacturing, Construction
L CSIND.K=CSIND.J+dt*(RCFIND.JK-RDCIND.JK)
                    capital stock industry, VPJ
K   CSIND=EII*123.096e9
                    initial money value changed to VPJ
R RCFIND.KL=FIFZE(HRCFIND.K,DELAY3(RCFIND1.K,2),OPTIND)
                    rate of fixed capital formation, VPJ/y
R RDCIND.KL=CSIND.K/LTIND
                    rate of depreciation of fixed capital, VPJ/y
I   LTIND=24        lifetime of capital: derived from AusNA'92 data


 index of growth of industrial CS DC'97B
A RCFINDX.K=RCFIND.KL/RCFINDN
K RCFINDN=RCFIND

 historical data for validation purposes
A HRCFIND.K=TABHL(HRCFIT,TIME.K,1981,1992,1)*1E9*EII
                    historic rate oc capital formation in industry,
VPJ/y
T   HRCFIT=9.20/8.06/7.43/7.36/7.56/8.74/9.88/9.97/10.95/8.91/8.01/8.15
```

```
                   data
A HCSIND.K=TABHL(HCSIT,TIME.K,1981,1992,1)*1E9*EII
                   historic HMC in industry, VPJ
T
HCSIT=123.10/126.27/128.53/130.97/133.08/136.24/140.24/144.32/149.22/ ^
     151.84/153.55/155.13
                   data HRCF & HCS data from AusNA'92 T66,75,76

  capital productivity changes, affecting INDOUTB DC'95a
  If CSIND becomes more productive, can expect ceteris paribus more
inputs per
  unit of CS, assuming that input:output ratio maintained. CSIND1 is a
  "productivity-corrected" measure of this, designed to drive TEDIND,
etc.
A CAPINDF.K=TABHL(CAPINT,TIME.K,1981,2051,10)
T CAPINT=1/1/1/1/1/1/1/1
A CSIND1.K=CSIND.K/CAPINDF.K   productivity-corrected CSIND DC'95a

A TEDIND.K=CSIND1.K*TICRIND.K  DC'95a
                   thermal energy demand, industry, PJ/y
A TICRIND.K=TABHL(TICTIND,TIME.K,1981,2051,10)*1E-12/EII
T   TICTIND=5240/4630/4630/4630/4630/4630/4630/4630      DC'95a
                   PJ/PJ.y
A EEDIND.K=CSIND1.K*EICRIND.K  DC'95a
                   electrical energy demand, industry, GWh/y
A EICRIND.K=TABHL(EICTIND,TIME.K,1981,2051,10)*1E-7/EII
                   electricity demand per unit capital stock, GWh/y
T   EICTIND=2.6/3.6/3.1/2.6/2.6/2.6/2.6/2.6    DC'97c
            new series derived from ABARE'95 data
            2.6/3.6/3.6/3.6/3.6/3.6/3.6/3.6    DC'95a
                   GWh/PJ.y
A RESIND.K=MININD.K+(WATIND.K*GERUWT.K)
                   non-energy resource demand: minerals + water, PJ/y
DC'96b


A PEDIND.K=(TEDIND.K+(EEDIND.K*FEREL.K))*SYSGER.K
                   primary energy demand associated with fuel & elec.
                    consumption, PJ/y

 historical data for validation purposes
A HTEDIND.K=TABHL(HTDINDT,TIME.K,1981,1993,2)
                   historical industry fuel consumption, PJ/y
T   HTDINDT=646.1/605.8/657.7/690.5/722.0/710.9/920
                   PJ/y
A PTEDIND.K=TABHL(PTETIND,TIME.K,1993,2009,16)
T PTETIND=920/1155  ABARE'95 projections DC'97c

A HEEDIND.K=TABHL(HEDINDT,TIME.K,1981,1991,2)*1E3
                   historical industry electricity demand, GWh/y
T   HEDINDT=31.6/36.3/42.3/48.2/53.3/54.4
                   GWh/y HTED & HEED data from ABARE'92 Tables A5-11


 == 2.5  Utility Industries
 This sector divided into Electricity generation (coal/gas, hydro,
other
```

renewables), water supply and gas supply. At present, only the electricity
sector is fully operational: other two utility sectors have operational
structures but no real data at present

```
 aggregate utilities historical data
A HRCFUTL.K=HRCFEL.K+HRCFGSD.K+HRCFWAT.K
                   historical rate of capital formation in utilities,
VPJ/y
A HCSUTL.K=TABHL(HCSUT,TIME.K,1981,1992,1)*1E9*EII
                   historical total CS in utilities sectors, VPJ
T   HCSUT=122/127/130/134/136/139/140/142/144/145/146/147
                   HCS data from AusNA'92 T76,78
A CSUTL.K=CSCOEL.K+CSHYD.K+CSREN.K+CSGASD.K+CSWAT.K
                   total capital stock in utilities sector, VPJ
A RCFUTL.K=RCFEL.K+RCFGASD.KL+RCFWAT.K  DC'97B
A RDCUTL.K=RDCEL.K+RDCGASD.KL+RDCWAT.K  DC'97B

A UTLOUTB.K=PEDUTLB.K+RDCUTL.K  DC'97B
A PEDUTLB.K=PEDELB.K+PEDGSDB.K+PEDWATB.K
A UTLX.K=UTLOUTB.K/UTLOUTN
K UTLOUTN=UTLOUTB

A PTEDUTL.K=TABHL(PTETUTL,TIME.K,1993,2009,16)
T PTETUTL=1123/1470  ABARE'95 projections DC'97c

 == 2.5.1 Electricity Generation
 aggregate electricity utilities historical data
A HRCFEL.K=TABHL(HRCFET,TIME.K,1981,1992,1)*1E6*EII
                   historical rate of capital formation, electricity
sectors,
                    VPJ/y
T   HRCFET=4800/4800/5100/3800/3600/3500/3300/3100/3000/2500/2800/3300
                   rounded data from BF_FAX_21APR95 p.3, using public
gdfcf
                    deflators pre-85, private post-89. 85-88 data not
                    published, filled in by linear interpolation
A HEP.K=TABHL(HEPT,TIME.K,1986,1992,1)*1E3
                   electricity generated, GWh/y
T   HEPT=130/137/145/152/154/156/160
                   BF_FAX_21APR95 p.3
A HEPCOEL.K=HEP.K-HEPHYD.K
                   during validation period, all EP either fossil or
hydro
                   DC'96b
A RDCEL.K=RDCCOEL.K+RDCHYD.K+RDCBIO.K+RDCREN.K
```

= Electricity generation using coal (and other fossil fuels! DC'97c)
New separation between conventional plant (COEL) and closed cycle turbine
(CCT). Both are capable of using either coal or gas. DC'97c

Five generating technologies are avaiable post-95: conventional fossil (COEL), closed-cycle turbine fossil (CCT), solar/wind renewable (REN), hydro-electric (HYD) and bio-fuel (BIO). The table functions FUPXXX denote the fractional uptake of these technologies as the market expands (FUPCOEL is determined as the residual here).

Each technology will expand its generating capacity to meet the fraction of additional supply required, and will increase its load factor above the default value to meet supply in the short term. Similarly, if market is shrinking, these sectors will reduce capacity and load factors using the same formula. DC'97c

```
 fractional uptake terms
A FUPCOEL.K=1-FUPCCT.K-FUPREN.K-FUPHYD.K-FUPBIO.K
A FUPCCT.K=TABHL(FUTCCT,TIME.K,1985,2050,5)
T  FUTCCT=0/0/0/0/0/0/0/0/0/0/0/0/0/0       default  BAU  -  COEL  future
DC'97c
        0/0/0/0.5/1/1/1/1/1/1/1/1/1/1   alternative 'default' with CCT
DC'97c
A FUPHYD.K=TABHL(FUTHYD,TIME.K,1985,2050,5)
T FUTHYD=0/0/0/0/0/0/0/0/0/0/0/0/0/0
A FUPREN.K=TABHL(FUTREN,TIME.K,1985,2050,5)
T FUTREN=0/0/0/0/0/0/0/0/0/0/0/0/0/0
A FUPBIO.K=TABHL(FUTBIO,TIME.K,1985,2050,5)
T FUTBIO=0/0/0/0/0/0/0/0/0/0/0/0/0/0

 total uptake in electricity required
A DAEP.K=EED.K-EEP1.K
  desired additional EP to be met by technology of choice
A EEP1.K=EPCOEL1.K+EPCCT1.K+EPHYD1.K+EPREN1.K+EPBIO1.K
  electricity generated when all technologies running at their desired
  load factor

A DEPFOS.K=EED.K-EPREN.K-EPHYD.K
                   desired fossil electricity from whatever source
A FCCT.K=TABHL(FCCTT,TIME.K,1981,2051,10)
T FCCTT=0/0/0/0/0/0/0/0
                   fraction of required EP generated by CCT

 = Conventional combustion Plants
 USER defines desired load factor for COEL system as a whole, and
growth then
 triggered to meet shortfall in electricity supply. Simplification of
OZ96A
 structure, which created oscillations. DC'96b.
L COELMW.K=COELMW.J+DT*(RBCOEL.JK-RDCOEL.JK)
                   generating capacity, MW
N    COELMW=17E3      initial coal generating capacity, MW from YB'82
Hydro@
                    5500MW is currently 25% of installed capacity
R RBCOEL.KL=DCOELMW.K-COELMW.K+FIFGE(RDCOEL.KL,0,FUPCOEL.K,0.001)
```

```
                   rate of building generating capacity, MW/y
                   only maintain by adding RDC if FUP>0 i.e. still an
interest
                   in using this technology DC'97c
R RDCOEL.KL=COELMW.K/LTCOEL
                   deprec'n of gen cap, MW/y
I   LTCOEL=25      ! lifetime of generating capital, y
A DCOELMW.K=EPCOEL.K/(8760E-3*DLFCOEL)
                   desired generating capacity, MW
I   DLFCOEL=0.52   ! desired load factor
A LFCOEL.K=MIN(0.9,EPCOEL.K/(COELMW.K*8760E-3))
                   actual load factor of coal-fired plant
A EPCOEL1.K=COELMW.K*8760E-3*DLFCOEL
                   output available with all capacity at DLF, DC'97c
A EPCOEL.K=EPCOEL1.K+DAEP.K*(FUPCOEL.K)
                   electricity generated, GWh/y

A FUELCOE.K=EPCOEL.K*3.6E-3/EFFCOEL.K
                   coal consumed in generation, PJ/y
A EFFCOEL.K=TABHL(EFFCOET,TIME.K,1981,2051,10)
T EFFCOET=0.317/0.335/0.335/0.335/0.335/0.335/0.335/0.335
                   thermal efficiency of plant, from HEP & HFUELEL
DC'96b
                   +ABARE'95 p33   DC'97c

A COLCOEL.K=FUELCOE.K*FCOECOL.K
                   coal consumed, PJ/y
A GASCOEL.K=FUELCOE.K*(1-FCOECOL.K)
                   gas consumed, PJ/y
A FCOECOL.K=TABHL(FCOECOT,TIME.K,1981,2051,10)
T FCOECOT=0.9/0.91/0.86/0.86/0.80/0.80/0.80/0.80
     fraction of fuel is coal from HGASEL & HCOLEL  DC'96b
     ABARE'95 projects 14% GAS by 2009/10 DC'97c

 = Closed Cycle Coal & Gas Plants
 The main difference cf. COEL is in the thermal efficiency DC'97c
L CCTMW.K=CCTMW.J+DT*(RBCCT.JK-RDCCT.JK)
                   generating capacity, MW
N   CCTMW=0E3    initial CCT generating capacity, MW
R RBCCT.KL=DCCTMW.K-CCTMW.K+FIFGE(RDCCT.KL,0,FUPCOEL.K,0.001)
                   rate of building generating capacity, MW/y
                   only maintain by adding RDC if FUP>0 i.e. still an
interest
                   in using this technology DC'97c
R RDCCT.KL=CCTMW.K/LTCCT
                   deprec'n of gen cap, MW/y
I   LTCCT=25       ! lifetime of generating capital, y
A DCCTMW.K=EPCCT.K/(8760E-3*DLFCCT)
                   desired generating capacity, MW

I   DLFCCT=0.9      ! desired load factor DC'97c
A                                 LFCCT.K=MIN(0.95,FIFGE(EPCCT.K/(8760E-
3*(CCTMW.K+0.001)),0,EPCCT.K,0))
  a little 'fudge-factor' number 0.0001 inserted to avoid division by
zero
  DC'97c
A EPCCT1.K=CCTMW.K*8760E-3*DLFCCT
```

```
A EPCCT.K=EPCCT1.K+DAEP.K*FUPCCT.K
                    electricity generated, GWh/y

A FUELCCT.K=EPCCT.K*3.6E-3/EFFCCT.K
                    coal consumed in generation, PJ/y
A EFFCCT.K=TABHL(EFFCCTT,TIME.K,1981,2051,10)
T EFFCCTT=0.358/0.358/0.358/0.358/0.358/0.358/0.358/0.358
                    thermal  efficiency  of  plant,  from  ABARE'95  p33
DC'97c

A COLCCT.K=FUELCCT.K*FELCCT.K
                    coal consumed, PJ/y
A GASCCT.K=FUELCCT.K*(1-FELCCT.K)
                    gas consumed, PJ/y
A FELCCT.K=TABHL(FELCTT,TIME.K,1981,2051,10)
T FELCTT=0.86/0.86/0.86/0.8/0.74/0.68/0.60/0.54
     fraction of fuel is coal: default zero DC'97c
     ABARE'95 projects 14% GAS by 2009/10 assume a linear continuation
of
     that trend beyond 2010DC'97c

A FUELEL.K=FUELCOE.K+FUELCCT.K
                    fuel consumed, PJ/y
A PEDELB.K=FUELEL.K*SYSGERN  DC'97B
A COLEL.K=COLCOEL.K+COLCCT.K
                    coal consumed, PJ/y
A GASEL.K=GASCOEL.K+GASCCT.K
                    gas consumed, PJ/y
A FELCOL.K=COLEL.K/FUELEL.K
     fraction of fuel is coal  DC'97c

A HCOLEL.K=TABHL(HCOTEL,TIME.K,1981,1991,2)
                    historical demand for coal by electriciy, PJ/y
T   HCOTEL=917/961/1042/1161/1274/1357
                    ABARE'93 data
A PCOLEL.K=TABHL(PCOTEL,TIME.K,1994,2009,5)
T PCOTEL=1389/1596/1731/1783  abare'95 projections T16  DC'97c

A HGASEL.K=TABHL(HGATEL,TIME.K,1981,1993,1)
                    historical demand for coal by electriciy, PJ/y
T
HGATEL=104/117.8/123.3/128.9/134.4/137.1/139.8/150.7/161.5/121.5/131.9/
^
          136.4/147.9
                    ABARE'94 data, interpolated where nec. DC'96b
A PGASEL.K=TABHL(PGATEL,TIME.K,1994,2009,5)
T PGATEL=148/204/226/286  abare'95 projections T16  DC'97c

A HFUELEL.K=HGASEL.K+HCOLEL.K
                    historical  total  fuel  demand  for  electricity  PJ/y
DC'96b
A PFUELEL.K=PGASEL.K+PCOLEL.K
A HFELCOL.K=HCOLEL.K/(HCOLEL.K+HGASEL.K)
                    historical fuel mix, electricity DC'96b

A CSCOEL.K=COELMW.K*CSPMWC
                    capital stock of generating plant, VPJ
```

```
A RCFCOEL.K=RBCOEL.KL*CSPMWC
                   rate cap formation, VPJ/y
A RDCCOEL.K=RDCOEL.KL*CSPMWC
                   rate cap depreciation, VPJ/y
I   CSPMWC=17E-3   embodied energy of cap per MW, VPJ/MW approx. value
                   (A$2.3million per MW)

 = Electricity generation using hydro-electricity
 YB'95  states  that  most  of  hydro  capacity  in  Australia  is  already
developed,
 therefore this sector simply maintained at current level
L HYDMW.K=HYDMW.J+DT*(RBHYD.JK-RDHYD.JK)
                   generating capacity, MW
N   HYDMW=5500     YB'82 p.441-9
R RBHYD.KL=DHYDMW.K-HYDMW.K+RDHYD.KL
                   FIFGE(RDHYD.KL,0,FUPHYD.K,0.001)
                   increase in gen cap, MW/y
                   maintain by adding RDC in all cases - hydro unlikely
to
                   expand because of hydrological constraints, but will
not
                   be wound down  DC'97c
A DHYDMW.K=EPHYD.K/(8760E-3*DLFHYD) DC'97c
   TABHL(DHYDT,TIME.K,1981,2051,10)
   T DHYDT=5500/5500/5500/5500/5500/5500/5500/5500
                   user-definable expansion of hydro-electric  DC'96b
R RDHYD.KL=HYDMW.K/LTHYD
                   deprec'n of gen cap, MW/y
I   LTHYD=70       1ifetime of generating capital, y
A EPHYD1.K=HYDMW.K*DLFHYD*8760E-3
                   electricity generated, GWh/y
A EPHYD.K=EPHYD1.K+DAEP.K*FUPHYD.K DC'97c
K    DLFHYD=0.31      load factor: calculated from initial capacity &
HEPHYD
                    average
A LFHYD.K=MIN(0.5,EPHYD1.K/(8760E-3*HYDMW.K)) DC'97c

A HEPHYD.K=TABHL(HEPHYT,TIME.K,1981,1991,2)*1E3
                   historical  electricity  generatoon  by  hydro-electric
sector,
                    GWh/y
T   HEPHYT=14.6/12.9/15.5/15.0/14.9/15.3

A CSHYD.K=HYDMW.K*CSPMWH
                   capital stock of generating plant, VPJ
A RCFHYD.K=RBHYD.KL*CSPMWH
                   rate cap formation, VPJ/y
A RDCHYD.K=RDHYD.KL*CSPMWH
                   rate cap depreciation, VPJ/y
I   CSPMWH=28E-3   embodied energy of cap per MW, VPJ/MW approx. value
                    (A$3.8million per MW)

 = Electricity generation using other renewables (Wind & Solar)
 Building  of  other  renewables  set  by  User  policy  -  alter  value  of
RENPOL
 Default rate of introduction is zero
L RENMW.K=RENMW.J+DT*(RBREN.JK-RDREN.JK)
```

```
                    generating capacity, MW
N   RENMW=0         initial value
R RBREN.KL=DRENMW.K-RENMW.K+FIFGE(RDREN.KL,0,FUPREN.K,0.001)  DC'97c
                    only maintain by adding RDC if FUP>0 i.e. still an
interest
                    in using this technology DC'97c
   FIFGE(RENPOL.K,0,TIME.K,1995)+RDREN.KL  increase in gen cap, MW/y
A DRENMW.K=EPREN.K/(8760E-3*DLFREN) DC'97c
R RDREN.KL=RENMW.K/LTREN
                    deprec'n of gen cap, MW/y
I   LTREN=20        ! lifetime of generating capital, y
   A RENPOL.K=TABHL(RENPOLT,TIME.K,1991,2051,10)
   T    RENPOLT=0/0/0/0/0/0/0          renewables policy: how many MW/y
post-'94?

A EPREN1.K=RENMW.K*DLFREN*8760E-3
                    electricity generated, GWh/y
A EPREN.K=EPREN1.K+DAEP.K*FUPREN.K
I   DLFREN=0.15      !!
A LFREN.K=MIN(0.3,FIFGE(EPREN.K/(8760E-3*(RENMW.K+0.001)),0,EPREN.K,0))
  a little 'fudge-factor' number 0.0001 inserted to avoid division by
zero
  assume extreme upper limit of 30%
  DC'97c

A CSREN.K=RENMW.K*CSPMWR
                    capital stock of generating plant, VPJ
A RCFREN.K=RBREN.KL*CSPMWR
                    rate cap formation, VPJ/y
A RDCREN.K=RDREN.KL*CSPMWR
                    rate cap depreciation, VPJ/y
I   CSPMWR=30E-3    !! embodied energy of cap per MW, VPJ/MW


 = Biomass Electricity Generation (timber) ==
 Building of biomass renewables set by User policy - alter value of
BIOPOL
 Default rate of introduction is zero
L BIOMW.K=BIOMW.J+DT*(RBBIO.JK-RDBIO.JK)
                    generating capacity, MW
N   BIOMW=0         initial value
R RBBIO.KL=DBIOMW.K-BIOMW.K+FIFGE(RDBIO.KL,0,FUPBIO.K,0.001) DC'97c
                    only maintain by adding RDC if FUP>0 i.e. still an
interest
                    in using this technology DC'97c
   FIFGE(BIOPOL.K,0,TIME.K,1995)+RDBIO.KL  increase in gen cap, MW/y
R RDBIO.KL=BIOMW.K/LTBIO
                    deprec'n of gen cap, MW/y
A DBIOMW.K=EPBIO.K/(8760E-3*DLFBIO)

I   LTBIO=20        ! lifetime of generating capital, y
   A BIOPOL.K=TABHL(BIOPOLT,TIME.K,1991,2051,10)
   T   BIOPOLT=0/0/0/0/0/0/0        biorenewables policy: how many MW/y
post-'94?

A EPBIO1.K=BIOMW.K*DLFBIO*8760E-3
                    electricity generated, GWh/y
```

```
A EPBIO.K=EPBIO1.K+DAEP.K*FUPBIO.K
I   DLFBIO=0.15     !!
A LFBIO.K=MIN(0.5,FIFGE(EPBIO.K/(8760E-3*(BIOMW.K+0.001)),0,EPBIO.K,0))
  a little 'fudge-factor' number 0.0001 inserted to avoid division by
zero
  DC'97c

A HEPBIO.K=0         ABARE'94 notes no use of wood/bagasse by elec gen
sector
                    DC'96b

A BIOEL.K=EPBIO.K*3.6E-3/EFFBIO.K
                     timber required for bio-electricity, PJ/y
A EFFBIO.K=TABHL(EFFTBIO,TIME.K,1981,2051,10)
T   EFFTBIO=0.15/0.15/0.2/0.2/0.3/0.35/0.35/0.35
                     thermal efficiency bio-fuel generators, data from
Babu
                     (1995): current technology 15-20%, advanced cycles
35-40%
                     DC'96b

A CSBIO.K=BIOMW.K*CSPMWR
                    capital stock of generating plant, VPJ
A RCFBIO.K=RBBIO.KL*CSPMWR
                    rate cap formation, VPJ/y
A RDCBIO.K=RDBIO.KL*CSPMWB
                    rate cap depreciation, VPJ/y
I    CSPMWB=30E-3    !! embodied energy of cap per MW, VPJ/MW set equal
to other
                    renewables at present DC'96b


 = Aggregate Electricity Statistics
A
EEDFD.K=EEDAFF.K+EEDTMIN.K+EEDIND.K+EEDDOM.K+EEDSER.K+EEDTRA.K+EEDCO2.K
                    Aggregate Demand for Electricity at final demand,
GWh/y
A EED.K=EEDFD.K*EPLOSS.K
                    Aggregate Demand for Electricity at the Bus-bar,
GWh/y
A HEEDFD.K=TABHL(HEEDFT,TIME.K,1981,1991,2)*1E3
                    historical EEDFD, GWh/y change in name to reflect
meaning
                    (i.e. FD = final demand) DC'96b
T   HEEDFT=87.14/95.53/106.2/119.0/134.2/138.2
                    ABARE'93
A EPLOSS.K=TABHL(EPLOST,TIME.K,1981,2051,10)
T EPLOST=1.185/1.13/1.12/1.12/1.12/1.12/1.12/1.12
                     factors in fractional losses & autoconsumption in
                     generation & transmission average figures based on
                     HEEDFD & HEP data over 86-91  DC'96b
                     use ABARE'95 estimate from 2009 (fig H, P.32)
DC'97c

A EEP.K=EPCOEL.K+EPCCT.K+EPHYD.K+EPREN.K+EPBIO.K   DC'96b
                    Aggregate Supply of Electricity
A EEPNF.K=EEP.K-EPCOEL.K-EPCCT.K
```

```
                    Aggregate non-foosil electricity supply DC'96b
A EEPNC.K=EPHYD.K+EPREN.K
                    Aggregate non-Carbon electricity supply DC'96b
A TOTMW.K=COELMW.K+CCTMW.K+HYDMW.K+RENMW.K+BIOMW.K
                    Total installed capacity in MW bdf 10-2-97


 == 2.5.2 Gas Distribution - this sector is dormant at present, fitted
with
                              "dummy" zero values, denoted "!!!"
L CSGASD.K=CSGASD.J+DT*(RCFGASD.JK-RDCGASD.JK)
                    fixed capital, gas supply, VPJ
N    CSGASD=EII*5e9 ! rough estimate from quoted assets of sales of
major
                    pipelines scaled up to rough length of entire system
                    source: El Paso Energy Corp, emailed by BF 19.12.96
                    VPJ DC'96b
R RCFGASD.KL=FIFZE(HRCFGSD.K,DCSGASD.K-CSGASD.K+RDCGASD.KL,OPTGASD)
                    rate of cap formation, VPJ/y
R RDCGASD.KL=CSGASD.K/LTGASD
                    rate of cap depreciation, VPJ/y
I   LTGASD=24       ! estimated lifetime of gas supply cap (=LTIND), y
A DCSGASD.K=GASDEM.K*CSPGASD
                    required CSGASD, VPJ
K   CSPGASD=CSGASD/HGASDEM
                    CS req'd per unit gas supplied, VPJ/PJ
A TEDGASD.K=0
A EEDGASD.K=0
A PEDGSDB.K=(TEDGASD.K+(EEDGASD.K*FEREL.K))*SYSGER.K
      no data as yet DC'97B

A HRCFGSD.K=TABHL(HRCFGDT,TIME.K,1981,1992,1)*1E6*EII
                    historical rate of capital formation, gas supply
system,
                     VPJ/y
T   HRCFGDT=300/770/800/520/450/370/300/220/150/160/160/220
                    rounded data from BF_FAX_21APR95 p.3, using public
gdfcf
                     deflators pre-85, private post-89. 85-88 data not
                     published, filled in by linear interpolation


 == 2.5.3 Water Supply - Australia is commonly referred to as a water-
limited
  territory. Given that current controlled supplies exceed demand, key
to
  understanding this statement is variability of Australian water
regime, both
  spatially and temporally. Heathcote & Mabbutt, p21 identify many of
built-up
  areas as using over 90% of available surface water, including most of
the
  Murray-Darling system. The CSPWATT table attempts to take account of
this
  variability, rather than just summing national supply and demand
values.
  DC'96b
```

```
 = Water supply summary data ==
 CS is subdivided into urban and rural supply systems UWT & AWT
respectively.
 WAT acronym summarises sector as a whole.
A CSWAT.K=CSUWT.K+CSAWT.K
A RCFWAT.K=FIFZE(HRCFWAT.K,RCFUWT.KL+RCFAWT.KL,OPTWAT)
A RDCWAT.K=RDCUWT.KL+RDCAWT.KL

A TEDWAT.K=TEDUWT.K
A EEDWAT.K=EEDUWT.K
A PEDWATB.K=(TEDWAT.K+(EEDWAT.K*FERELN))*SYSGERN  DC'97B

 = Urban centre water supply ==
L CSUWT.K=CSUWT.J+DT*(RCFUWT.JK-RDCUWT.JK)
                    fixed capital, water supply, VPJ
K   CSUWT=HCSWAT*FWURB    VPJ
I FWURB=0.86  fraction CSWAT in urban supply system
     based on data from Johnson & Rix "Water in Australia" (pluto
press)
     Their data for 1989-90 quotes 81.6billion A$ water & sewage
assets, which
     is quite a bit over ABS figures (60-odd). Breakdown is METRO 44.6,
     NON-METRO  27.5  &  IRRIGATION  9.8.  Assume  non-metro  still
urban/mains, then
     rural covers ~14% of total.  DC'96b
R RCFUWT.KL=DCSUWT.K-CSUWT.K+RDCUWT.KL rate of cap formation, VPJ/y
R RDCUWT.KL=CSUWT.K/LTUWT
                    rate of cap depreciation, VPJ/y
I    LTUWT=60          !!! estimated lifetime of urban water supply CS
(=LTIND), y

A DCSUWT.K=WATURB.K*CSPUWT.K
                    required water supply CS, VPJ
A CSPUWT.K=CSPUWN*ACCUWT.K
K CSPUWN=CSUWT/WATURB
                    fixed CS req'd per gigalitre supplied, VPJ/Gl
                    baseline value is altered by table function as
volume of
                    demand increases: see section 1.2.1   DC'96b

A
ACCUWT.K=(FUSW.K*(CSPUWF.K*FSWFSH.K+CSPUWM.K*FSWMGN.K+CSPUWS.K*FSWSEA.K
)^
          +(1-
FUSW.K)*(CSPUWF.K*FGWFSH.K+CSPUWM.K*FGWMGN.K+CSPUWS.K*FGWSEA.K))
   index of accessibility of water, based on ground vs. surface & water
quality
   considerations. Used to drive CS & energy requirements  DC'96b

A CSPUWF.K=TABHL(CSPUWFT,TIME.K,1981,2051,10)
T CSPUWFT=1/1/1/1/1/1/1/1
A CSPUWM.K=TABHL(CSPUWMT,TIME.K,1981,2051,10)
T CSPUWMT=4/4/4/4/4/4/4/4
A CSPUWS.K=TABHL(CSPUWST,TIME.K,1981,2051,10)
T CSPUWST=50/50/50/37.5/25/25/25/25
```

```
                    3 grades of water quality: fresh (2GJ/Ml surf,
4GJ/Ml grd),
                    marginal-saline (8GJ/Ml) & sea water (280GJ/Ml); GER
data
                    from Slesser et al. As individual states become
short of
                    water, average GER of Australian water will rise,
ahead of
                    time predicted by an aggregated national data
survey. DC'96b
                    see OZWATER.XLS for calculations

A SWURB.K=WATURB.K*FUSW.K      urban surface water demand, m3/l
A GWURB.K=WATURB.K*(1-FUSW.K)  urban ground water demand, m3/l

A FUSW.K=TABHL(FUSWT,TIME.K,1981,2051,10)
T FUSWT=1/1/1/1/1/1/1/1
     fraction aff water from surface sources, based on AWRC'87 data
DC'96b

A TEDUWT.K=CSUWT.K*TICRWAT*ACCUWT.K
K TICRWAT=HTEDUWT/CSUWT

A EEDUWT.K=CSUWT.K*EICRWAT*ACCUWT.K
K EICRWAT=HEEDUWT/CSUWT

 actual embodied energy per unit urban water supplied, PJ/Gl
 (service corrected terms computed under RESINDB section DC'96b
A PEDUWT.K=(TEDUWT.K+(EEDUWT.K*FEREL.K))*SYSGER.K
A GERUWT.K=(PEDUWT.K+(RDCUWT.KL/REDEII.K))/WATURB.K



 = Agricultural/rural water supply ==
 Capital costs only: TED & EED not disaggregated from AGR values DC'96b
L CSAWT.K=CSAWT.J+DT*(RCFAWT.JK-RDCAWT.JK)
                    fixed capital, water supply, VPJ
K   CSAWT=HCSWAT*(1-FWURB)         VPJ
R RCFAWT.KL=DCSAWT.K-CSAWT.K+RDCAWT.KL rate of cap formation, VPJ/y
R RDCAWT.KL=CSAWT.K/LTAWT
                    rate of cap depreciation, VPJ/y
I    LTAWT=60          !!! estimated lifetime of agric water supply CS
(=LTIND), y

A DCSAWT.K=WATAFF.K*CSPAWT.K
                    required water supply CS, VPJ
A CSPAWT.K=CSPAWN*ACCAWT.K
                    fixed CS req'd per gigalitre supplied, VPJ/Gl
                    baseline value is altered by table function as
volume of
                    demand increases: see section 1.2.1   DC'96b
K CSPAWN=CSAWT/WATAFF

A
ACCAWT1.K=(FASW.K*(CSPAWF.K*FSWFSH.K+CSPAWM.K*FSWMGN.K+CSPAWS.K*FSWSEA.
K)^
```

```
          +(1-
FASW.K)*(CSPAWF.K*FGWFSH.K+CSPAWM.K*FGWMGN.K+CSPAWS.K*FGWSEA.K))
K ACCAWTN=(FASW*(CSPAWF*FSWFSH+CSPAWM*FSWMGN+CSPAWS*FSWSEA)^
          +(1-FASW)*(CSPAWF*FGWFSH+CSPAWM*FGWMGN+CSPAWS*FGWSEA))
L ACCAWT.K=ACCAWT.J+dt*(RFACAWT.JK-RDACAWT.JK)
N ACCAWT=1
R RFACAWT.KL=ACCAWT1.K/ACCAWTN
R RDACAWT.KL=ACCAWT.K
   simultaneous equations avoided by writing ACCAWT as a level
   index of accessibility of water, based on ground vs. surface & water
quality
   considerations. Used to drive CS & energy requirements Additional
indexing
   equations ACCAWT1 & ACCAWTN normalise to initial value of 1, as
initial
   AFF supply a mixture of fresh & marginal, and of ground & surface
    Note the effects of this variable on agriculture: as water becomes
scarcer,
   agriculture for export decreases: see VSSA & ASSA  DC'96b
A CSPAWF.K=TABHL(CSPAWFT,TIME.K,1981,2051,10)
T CSPAWFT=2.4/2.4/2.4/2.4/2.4/2.4/2.4/2.4
A CSPAWM.K=TABHL(CSPAWMT,TIME.K,1981,2051,10)
T CSPAWMT=8/8/8/8/8/8/8/8
A CSPAWS.K=TABHL(CSPAWST,TIME.K,1981,2051,10)
T CSPAWST=100/100/100/75/50/50/50/50
                  3 grades of water quality: fresh (2GJ/Ml surf,
4GJ/Ml grd),
                  marginal-saline (8GJ/Ml) & sea water (100GJ/Ml); GER
data
                  from Slesser et al. As individual states become
short of
                  water, average GER of Australian water will rise,
ahead of
                  time predicted by an aggregated national data
survey. DC'96b
                  see OZWATER.XLS for calculations. These figures are
already
                  adjusted to baseline condition of 84% fresh, 16%
marginal
                  water use.

A SWAFF.K=SWAFF1.K-(SWDEM1.K*DSWSEA.K)
   WATAFF.K*FASW.K        agric surface water demand, m3/1
A GWAFF.K=GWAFF1.K-(GWDEM1.K*DGWSEA.K)
   WATAFF.K*(1-FASW.K)  agric ground water demand, m3/1

A FASW.K=TABHL(FASWT,TIME.K,1981,2051,10)
T FASWT=0.8/0.8/0.8/0.8/0.8/0.8/0.8/0.8
     fraction aff water from surface sources, based on AWRC'87 data
DC'96b

  No TEDAWT or EEDAWT at present, as this data cannot be disaggregated
from
  TEDAFF & EEDAFF at present. DC'96b
```

```
 = 2.5.3.1 Water Demand == mostly driven by capital stocks. Exception
is
   irrigation, which is driven by Slesser equation terms PERAN &
PERVEG. The
   logic is that as agriculture intensifies, more irrigation needed in
step w.
   other artificial inputs: a rough and ready solution DC'96b.
    Most demand data based on Australian Water Resources Council survey
1987,
   with data appplying to 1985-7 period. Coefficients have been
corrected to
   fit data to 1985 values in model. DC'96b

A WATDEM.K=WATURB.K+WATAFF.K
                   total water demand, Gl/y  AGR -> AFF DC'96b
A WATDEMF.K=WATDEM.K/WATDEMN
K WATDEMN=WATDEM
                   index of total water demand

A WATURB.K=WATIND.K+WATMAIN.K
                   urban area water demand, Gl/y
A WATURBF.K=WATURB.K/WATURBN
K WATURBN=WATURB
                   index of urban water demand

A UWTEFF.K=TABHL(UWTEFFT,TIME.K,1981,2051,10) water efficiency policy
T  UWTEFFT=1/1/0.95/0.9/0.85/0.8/0.75/0.7                user defined
efficiency data
                                                    DC'96b

A WATIND.K=CSIND.K*WATPIND*UWTEFF.K
                   industrial water demand, Gl/y
K   WATPIND=650/CSIND    data (790Gl) from AWRC'87  DC'96b
                   coefficient corrected for 1981 start

A WATMAIN.K=WATDOM.K+WATSER.K
                   mains water demand, Gl/y

A WATDOM.K=HOUSHLD.K*WATPHOU.K
                   household water demand, Gl/y
A HOUSHLD.K=TPOP.K/CAPPHH.K
A CAPPHH.K=TABHL(CAPPHT,TIME.K,1981,2051,10)
T CAPPHT=3/2.6/2.6/2.6/2.6/2.6/2.6/2.6
   capita per household: data from BF_email 28/1/97  DC'96b
A WATPHOU.K=TABHL(WATPHOT,TIME.K,1981,2051,10)*1E-6
T WATPHOT=300/300/300/300/300/300/300/300
   water per household: data from BF_email 28/1/97 (114kl/cap/y, 1994)
DC'96b


A WATSER.K=CSSER.K*WATPSER*UWTEFF.K
                   services water demand, Gl/y
K   WATPDOM=1250/CSDOM    data (1790Gl) from AWRC'87
                   coefficient corrected for 1981 start
K   WATPSER=350/CSSER     data (481Gl) from AWRC'87
                   coefficient corrected for 1981 start
```

```
A WATAFF.K=WATIRR.K+WATOAFF.K
                      actual agricultural water demand, Gl/y   AGR -> AFF
DC'96b
A WATIRR.K=WATIRR1.K-FIFZE(NAVSW.K+NAVGW.K,0,DESAL)
                      if DESAL=0, will cut back on irrigation to allow
other
                      water demands to grow, without opting for
desalination
                      DC'96b

  available supplies of surface & ground water excluding desalination
A AVSW.K=SWDEM1.K*(DSWFSH.K+DSWMGN.K)
A AVGW.K=GWDEM1.K*(DGWFSH.K+DGWMGN.K)
  non-available water i.e. extent of cutback on irrigation if DESAL=0
A NAVSW.K=MAX(0,SWDEM1.K-AVSW.K)
A NAVGW.K=MAX(0,GWDEM1.K-AVGW.K)

I DESAL=0               policy variable: desalination option is pursued if
DESAL=1
                      otherwise cutback on irrigation water before going
for the
                      expensive techno-fix option (DESAL=0 is default)
DC'96b

 = Hypothetical calculations of unconstrained irrigation demand used to
assess
   pressure that would be placed on saline water resources DC'96b

   ground water demand & index
A GWDEM1.K=GWURB.K+GWAFF1.K
A GWAFF1.K=WATAFF1.K*(1-FASW.K)
A GWDEMF1.K=GWDEM1.K/GWDEM1N
K GWDEM1N=GWDEM1

   surface water demand & index
A SWDEM1.K=SWURB.K+SWAFF1.K
A SWAFF1.K=WATAFF1.K*FASW.K
A SWDEMF1.K=SWDEM1.K/SWDEM1N
K SWDEM1N=SWDEM1

A WATAFF1.K=WATIRR1.K+WATOAFF.K
                      desired agric water demand if no desalination
cutback
A WATIRR1.K=DIRRAN.K+DIRRVEG.K
                      desired water for irrigation, Gl/y
L RIRRF.K=RIRRF.J+dt*(RFRIRRF.JK-RDRIRRF.JK)
N RIRRF=1
R RFRIRRF.KL=WATIRR.K/WATIRR1.K
R RDRIRRF.KL=RIRRF.K
   A RIRRF.K=WATIRR.K/WATIRR1.K
     reduction in irrigation factor: indicator only  DC'96b

A DIRRAN.K=PERAN.K*DIRRPAN
K DIRRPAN=4480/PERAN     pasture irrigation, Gl/y
                      coefficient corrected for 1981 start
A DIRRVEG.K=PERVEG.K*DIRRPVG
K DIRRPVG=4550/PERVEG  crop/horticulture irrigation, Gl/y
```

```
                    coefficient corrected for 1981 start


A WATOAFF.K=CSAFF.K*WATPAFF  non-irrigation rural water demands, Gl/y
K WATPAFF=1340/CSAFF
                    AWRC'87   data   irrigation   5180Gl   pasture,   5060Gl
crops/veg
                     plus 1340Gl other rural demands DC'96b

  index of surface water usage rate
A SWDEM.K=FIFZE(MIN(SWDEM1.K,AVSW.K),SWDEM1.K,DESAL)
K SWDEMN=SWDEM
A SWDEMF.K=SWDEM.K/SWDEMN

  index of ground water usage rate
A GWDEM.K=FIFZE(MIN(GWDEM1.K,AVGW.K),GWDEM1.K,DESAL)
K GWDEMN=GWDEM
A GWDEMF.K=GWDEM.K/GWDEMN

 Historical data for validation
A HCSWAT.K=TABHL(HCSWTT,TIME.K,1981,1995,1)*1E9*EII
T
HCSWTT=53.9/55.4/56.9/58.2/59.8/61.2/62.8/64.2/65.3/66.6/67.7/68.9/69.9
^
          /70.7/71.9
            ABS data supplied by BF 13.12.96 DC'96b
A HRCFWAT.K=TABHL(HRCFWTT,TIME.K,1981,1992,1)*1E6*EII
                    historical  rate  of  capital  formation,  water  supply,
VPJ/y
T   HRCFWTT=6310/4760/2300/3240/2770/2300/1830/1360/890/1250/1100/350
                    from   BF_FAX_21APR95,   85-88   filled   in   by   linear
interpolation

 energy data for urban supply only: ABS category 37 "water sewerage &
drainage"
A HTEDUWT.K=TABHL(HTEDWTT,TIME.K,1982,1994,1)
T  HTEDWTT=.8/.8/.8/.7/.8/.9/.8/.8/.9/.9/.9/.9/.9     abare'95.1   TabC1
p.111 DC'96b
A HEEDUWT.K=TABHL(HEEDWTT,TIME.K,1982,1994,1)/3.6E-3
T HEEDWTT=5.0/5.0/5.0/4.8/4.6/4.3/4.4/4.5/4.9/4.9/4.6/5.0/5.0
          abare'95.1 TabC1 p.111 data quoted in PJ @ 1GWh=3.6E-3PJ i.e.
          simple heat equivalent c.f. FEREL-type calculation DC'96b
A HPEDUWT.K=(HTEDUWT.K+(HEEDUWT.K*FEREL.K))*SYSGER.K

 = 2.6  Domestic - inc. ownership of dwellings
 Rate of investment in dwellings determined empirically as a log-linear
 function of MSOLF, the affluence index
L CSDOM.K=CSDOM.J+dt*(RCFDOM.JK-RDCDOM.JK)
                    capital stock dwellings, VPJ
K   CSDOM=EII*372e9
                    initial money value changed to VPJ
R RCFDOM.KL=FIFZE(HRCFDOM.K,(MSOLF.K**RCFD2)*RCFD1+RDCDOM.KL,OPTDOM)
                    rate of capital investment in dwellings, VPJ/y
I    RCFD1=110         parameters governing RCFDOM have been calibrated
with
I   RCFD2=0.4      OPTDOM=1, all other OPT's=0, i.e. MSOLF reaches ~1.5
by 1991
```

```
R RDCDOM.KL=CSDOM.K/LTDOM
                   rate of capital depreciation, dwellings, VPJ/y
I   LTDOM=140       ! sounds very large (75 might be a better estimate,
one'd
                   think), but this value matches CSDOM & HCSDOM when
using
                   OPT=0 (i.e. RCFDOM = HRCFDOM)  DC'96b

 historical data for validation purposes
A HRCFDOM.K=TABHL(HRCFDT,TIME.K,1981,1992,1)*1E9*EII
                   historic rate of of capital formation in dwellings,
VPJ/y
T   HRCFDT=17.5/14.1/15.2/16.9/17.2/15.6/15.9/19.5/19.5/17.5/17.1/19.5
                   data
A HCSDOM.K=TABHL(HCSDT,TIME.K,1981,1992,1)*1E9*EII
                   historic HMC stock in dwellings, VPJ
T   HCSDT=372/385/399/414/426/440/454/472/489/504/518/534
                   HRCF & HCS data from AusNA'92 T66,67,68,75,76,78

A TEDDOM.K=CSDOM.K*TICRDOM.K
                   thermal energy demand PJ/y
A TICRDOM.K=TABHL(TICTDOM,TIME.K,1981,2051,10)*1E-12/EII
T   TICTDOM=420/400/350/300/300/300/300/300  DC'97c
  some increase in efficiency inline with ABARE'95 projections
                   PJ/PJ.y
A EEDDOM.K=CSDOM.K*EICRDOM.K
                   electrical energy demand, PJ/y
A EICRDOM.K=TABHL(EICTDOM,TIME.K,1981,2051,10)*1E-8/EII
                   electricity demand per unit capital stock, GWh/y
T   EICTDOM=8.6/8.0/7.2/6.4/6.4/6.4/6.4/6.4  DC'97c
            new series derived from ABARE'95 data
            8.6/8.0/8.0/8.0/8.0/8.0/8.0/8.0  DC'95a
                   GWh/PJ.y

 historical data for validation purposes
A HTEDDOM.K=TABHL(HTDDOMT,TIME.K,1981,1993,2)
                   historical fuel cons
T   HTDDOMT=157.5/158.4/164.3/163.6/184.4/192.6/202
                   PJ/y
A PTEDDOM.K=TABHL(PTETDOM,TIME.K,1993,2009,16)
T PTETDOM=202/252  ABARE'95 projections DC'97c

A HEEDDOM.K=TABHL(HEDDOMT,TIME.K,1981,1991,2)*1E3
                   historical elec cons
T   HEDDOMT=32.0/32.6/34.5/36.2/38.6/39.4
                   GWh/y HTED & HEED data from ABARE'92 Tables A5-11


 = 2.7  Services - inc. Wholesale & retail trade
                      Transport, storage & communications
                      Finance, property & business services
                      Community services
                      Recreation, personal & other services
 Services by private and government concerns all aggregated into single
sector
L CSSER.K=CSSER.J+dt*(RCFSER.JK-RDCSER.JK)
                   capital stock VPJ
```

```
K   CSSER=EII*461e9
                     initial money value changed to VPJ
R RCFSER.KL=FIFZE(HRCFSER.K,DCSSER.K-CSSER.K+RDCSER.KL,OPTSER)
                     rate of fixed capital investment, VPJ/y
R RDCSER.KL=CSSER.K/LTSER
                     rate of fixed capital depreciation, VPJ/y
I   LTSER=35           service sector CS lifetime: derived from AusNA'92
data

 historical data for validation purposes
A HRCFSER.K=TABHL(HRCFST,TIME.K,1981,1992,1)*1E9*EII
                     historic  rate  of  capital  formation  in  services,
VPJ/y
T   HRCFST=27.0/25.2/27.7/31.7/35.8/36.6/37.8/41.4/42.9/38.9/34.2/33.1
                     data
A HCSSER.K=TABHL(HCSST,TIME.K,1981,1992,1)*1E9*EII
                     historic HMC, services, VPJ
T   HCSST=462/474/489/507/524/547/569/595/621/643/661/675
                     data HRCF & HCS data from AusNA'92 T66,75,76

A TEDSER.K=CSSER.K*TICRSER.K
                     thermal energy demand, PJ/y
A TICRSER.K=TABHL(TICTSER,TIME.K,1981,2051,10)*1E-12/EII
T   TICTSER=100/84/84/84/84/84/84/84
                     PJ/PJ.y
A EEDSER.K=CSSER.K*EICRSER.K
                     electrical energy demand, GWh/y
A EICRSER.K=TABHL(EICTSER,TIME.K,1981,2051,10)*1E-8/EII
                     electricity demand per unit capital stock, GWh/y
T   EICTSER=3.8/4.8/4.25/3.7/3.7/3.7/3.7/3.7
              new series derived from ABARE'95 data DC'97c
              3.8/4.8/4.8/4.8/4.8/4.8/4.8/4.8
                     GWh/PJ.y

A PEDSER.K=(TEDSER.K+(EEDSER.K*FEREL.K))*SYSGER.K
                     primary energy demand associated with fuel & elec.
                      consumption, PJ/y

 historical data for validation purposes
A HTEDSER.K=TABHL(HTDSERT,TIME.K,1981,1993,2)
                     historical services fuel demand, PJ/y
T   HTDSERT=45.9/43.9/45.9/48.1/52.6/54.0/58.0
                     PJ/y
A PTEDSER.K=TABHL(PTETSER,TIME.K,1993,2009,16)
T PTETSER=58/96  ABARE'95 projections DC'97c

A HEEDSER.K=TABHL(HEDSERT,TIME.K,1981,1991,2)*1E3
                     historical services electricity demand, GWh/y
T   HEDSERT=17.5/18.4/20.9/23.9/27.3/28.9
                     GWh/y HTED & HEED data from ABARE'92 Tables A5-11

A SEROUT.K=PEDSER.K+(RDCSER.KL/REDEII.K)
                     embodied energy output, PJ/y  DC'96b
A HSEROUT.K=(HTEDSER.K+(HEEDSER.K*FEREL.K))*SYSGER.K+(HCSSER.K/LTSER)
                     SEROUT calculated on basis of historical data

 index of service sector activity
```

```
A SERDEX.K=SEROUTB.K/SEROUTN
                    index of services activity: 1981=1
K   SEROUTN=SEROUTB initial value of services output, PJ/y

A DCSSER.K=DSEROUT.K*MCRSER.K
                    desired CS of sector, VPJ/y
A MCRSER.K=CSSER.K/SEROUT.K
                    marginal capital requirement, VPJ/VPJ
```

Services output destination is explicitly recorded for all sectors which purchase more than 5% of output in '81 or '89 combined use matrix. These sectors are: Industry (6.5 - 13.3%: $11.3 - 39.6 billion)
Services (34.3 - 43.0%: $59.8 - 128.5 billion)
Domestic (15.4 - 35.8%: $26.9 - 107.0 billion)
Exports (39.4 - 2.8%: $68.8 - 8.3 billion)
Note the considerable structural change in services output occurring over the period 1981-89.

In addition, desired indigenous output is determined by FSERIMP, the fraction of services output bought in from abroad (0 - 2.5%; negligible).

```
A DSEROUT.K=(DSOTIND.K+DSOTSER.K+DSOTDOM.K+SEREXP.K)
                    desired services sector output, VPJ/y
A FSERIND.K=DSOTIND.K/DSEROUT.K
                    fraction service output -> IND
A FSERSER.K=DSOTSER.K/DSEROUT.K
                    fraction service output -> SER
A FSERDOM.K=DSOTDOM.K/DSEROUT.K
                    fraction service output -> DOM

A DSOTIND.K=CSIND.K*SERPCSI.K
                    SEROUT demand by IND, VPJ/y
A SERPCSI.K=FIFGE(TABHL(S2RPCTI,TIME.K,1992,2052,10),^
            TABHL(SERPCTI,TIME.K,1981,1992,11),TIME.K,1993)*1E-12/EII
                    services output demand per unit industrial capital, VPJ/VPJ
T   SERPCTI=250/650
T   S2RPCTI=650/650/650/650/650/650/650
                    SEROUT demand per CSIND

A DSOTSER.K=CSSER1.K*SERPCSS.K
                    SEROUT demand by SER, VPJ/y
A SERPCSS.K=FIFGE(TABHL(S2RPCTS,TIME.K,1992,2052,10),^
            TABHL(SERPCTS,TIME.K,1981,1992,11),TIME.K,1993)*1E-12/EII
                    services output demand per unit services capital, VPJ/VPJ
T   SERPCTS=470/610
T   S2RPCTS=610/610/610/610/610/610/610
                    SEROUT demand per CSSER CS serving non-industry sectors:
                     level variable to avoid simultaneous equations
L CSSER1.K=CSSER1.J+dt*(RCFS1.JK-RDCS1.JK)
                    CSSER serving non-service sectors, VPJ
K   CSSER1=CSSER*0.66
```

```
R                    RCFS1.KL=CSSER.K*((DSOTIND.K+DSOTDOM.K+SEREXP.K)*(1-
FSERIMP))/DSEROUT.K
                   instantaneous value of CSSER1
R RDCS1.KL=CSSER1.K
                   old value of CSSER1: for internal calculations


A DSOTDOM.K=CSDOM.K*SERPCSD.K
                   SEROUT demand by DOM, VPJ/y
A SERPCSD.K=FIFGE(TABHL(S2RPCTD,TIME.K,1992,2052,10),^
            TABHL(SERPCTD,TIME.K,1981,1992,11),TIME.K,1993)*1E-12/EII
                   services output demand per unit domestic capital,
VPJ/VPJ
T   SERPCTD=170/350
T   S2RPCTD=350/350/350/350/350/350/350
                   SEROUT demand per CSDOM

A SEREXP.K=SEROUT.K*(FSEREXP.K-FSERIMP)
                   SEROUT exported, VPJ/y
A FSEREXP.K=FIFGE(TABHL(FS2REXT,TIME.K,1992,2052,10),^
            TABHL(FSEREXT,TIME.K,1981,1992,11),TIME.K,1993)
                   fraction services exported
                   (1992/3 data replaces 89/90's 3% DC'96b)
T   FSEREXT=0.4/0.14
T   FS2REXT=0.14/0.14/0.14/0.14/0.14/0.14/0.14
                   data from IO tables (see above)
C   FSERIMP=0      fraction of desired output met by imports, policy
```

== 3.0 PERSONAL CONSUMPTION OF GOODS

The rate of consumption is linked to the rate of reinvestment in industry,
which is viewed as a broad indicator of economic activity. Put another way,
residual HMC availability is split between consumption and reinvestment in
industry, on the basis of the RGC term. While rather crude in many ways, this
consumption function generates a tight feedback between increased wealth
creation and consumption, both directly through CONS, and less directly
through MSOL (see 3.1)

```
A CONS.K=RCFIND1.K*RGC.K*REDEII.K    DC'95b
                   rate of consumption of goods, VPJ/y
A RGC.K=FIFGE(TABHL(RGCT2,TIME.K,1990,2050,10),^
        TABHL(RGCT,TIME.K,1981,1991,5),TIME.K,1993)
                   ratio of consumption to industrial reinvestment
T   RGCT=11/11/11     approx. average value of HCONS/HRCFIND over 81-92
T   RGCT2=11/11/11/11/11/11/11
     revised values get best poss. fit for both CONS & RCFIND w.
     historical time series DC'96b

 historical data for validation
A HCONS.K=TABHL(HCONST,TIME.K,1981,1992,1)*1E9*EII
                   VPJ/y
```

```
T
HCONST=93.1/93.4/94.4/97.7/101.5/100.1/102.8/107.1/111.7/111.5/114.5/ ^
     117.2          table 53, AusNA'92: food, tobacco, alcohol, clothing
total,
                    durables total, purch & op of vehicles, books,
etc., goods
                    summed, other categories fall into SEROUT or RCFs:
                    tabulated data is 89$billion
A HRGC.K=HCONS.K/HRCFIND.K
                   historically accurate estimate of RGC term

 = 3.1 MATERIAL STANDARD OF LIVING
 WARNING: indicative of affluence, not quality of life. Mainly used as
a
 driver in this respect, also useful as an indicator in its own right
 NOTE: GMSOL expressed in VPJ/y, but MSOL IN VGJ/y, to give a more
"friendly"
 unit of measurement
 NOTE: Now measured in constant functionality/VPJ   DC'95a

 GMSOL treated as a level variable to avoid simultaneous equations
L GMSOL.K=GMSOL.J+dt*(RFGMSOL.JK-RDGMSOL.JK)
                   gross affluence VPJ/y
K   GMSOL=HSEROUT*FSERDOM+FIFZE(HCONS,CONS,OPTMSOL)
R RFGMSOL.KL=DSOTDOM.K+FIFZE(HCONS.K,CONS.K,OPTMSOL)
                   total material living standard, VPJ/y
R RDGMSOL.KL=GMSOL.K
                   old value of GMSOL: for internal calculations
A MSOL1.K=GMSOL.K*1E6/TPOP.K
A MSOL.K=MSOL1.K+RQXBPC.K
                   DC'95b     per cap affluence, VPJ/y
A MSOLF.K=MSOL.K/MSOLN FIFGE(MSOL.K/MSOL83,1,TIME.K,1983)
                   indexed value
K MSOLN=MSOL

A HMSOL.K=(HSEROUT.K*FSERDOM.K+HCONS.K)*1E6/HPOP.K
  historical msol term  DC'96b

 * State Benefit payments to people
A HBEN.K=TABHL(HBENT,TIME.K,1981,1992,1)*1E9*EII
T HBENT=23.5/25.8/28.2/29.9/29.8/29.8/31.4/31.1/33.4/36.3/39.7/42.1
  AusNA'92 T53-4 Personal benefit payments to residents, and domestic
final
  demand deflator from T3  VPJ/y DC'95b
A HBENPC.K=HBEN.K*1E6/HPOP.K  VGJ/y for comparison w. MSOLF  DC'95b
A HEMP.K=TABHL(HEMPT,TIME.K,1981,1992,1)*1E3
T HEMPT=6538/6433/6478/6684/6956/7114/7327/7619/7900/7851/7705/7699
  AusNA'92 T5 total persons employed DC'95b
A FPOPWA.K=FIFGE(TABHL(FP2PWAT,TIME.K,1990,2050,10),^
          TABHL(FPOPWAT,TIME.K,1991,1996,1),TIME.K,1997)
T FPOPWAT=0.60/0.60/0.60/0.60/0.60/0.60
T FP2PWAT=0.6/0.6/0.6/0.6/0.6/0.6/0.6
  fraction pop of working age (18-65) derived from AusPopT&P'92
Table5.1
A POPWA.K=TPOP.K*FPOPWA.K   pop of working age DC'95b
A UNEMPR.K=(POPWA.K-EMP.K)/POPWA.K  unemployment rate DC'95b
A EMP.K=HEMP.K  DC'95b
```

```
* Additional benefits payments to prevent drop in MSOL  DC'95b
L DMSOL.K=DMSOL.J+dt*RFDMS.JK   desired (non-declining) MSOL
N DMSOL=MSOL1
R RFDMS.KL=MAX(0,MSOL1.K-DMSOL.K)
  desired MSOL is the higher of current or previous value DC'95b
A                                     RQXBPC.K=FIFGE(FIFGE(MAX(0,DMSOL.K-
MSOL1.K),0,TIME.K,1992),0,BENPOL,0.5)
                                        VGJ/y
                                        required extra per cap benefit
L RQXBEN.K=RQXBEN.J+dt*(RFXBEN.JK-RDXBEN.JK)
N RQXBEN=0
R RFXBEN.KL=RQXBPC.K*1E-6*TPOP.K
R RDXBEN.KL=RQXBEN.K
   A  RQXBEN.K=RQXBPC.K*1E-6*TPOP.K              total  required  extra
benefit VPJ/y
                                        DC'95b
I BENPOL=0    0=no additional benefit payments   DC'95b
              1=payments to try to match previous MSOL if declining


 == 3.2  TRANSPORTATION
 Very simple transport sector, dealing with four classes of transport:
road,
 rail, water & air. From IO tables for 89/90, major users of transport
 sector   have   been   identified   as   mining,   industry,   services,
consumption.
 ('81/2  tables  not  used  because  large  "stocks"  term  in  output
ambiguous, and
 CONS terms seemed very low indeed.)
 TED & EED equations are driven directly by these terms.

 Simple  stocks  of  road  vehicles  recorded,  for  purpose  of  monitoring
changes
 from oil to gas powered vehicles: CRV=conventional road vehicles
                                   NGV=natural gas vehicles
I TIMNGV=3000    time at which transfer from conv road vehicles to NGV
begun

L CRV.K=CRV.J+dt*(RFCRV.JK-RDCRV.JK-CONNGV.JK)
   stock of conventional road vehicles, cars
N CRV=7917.6E3
   initial value of conv road vehicle fleet
R RFCRV.KL=FIFGE(0,NEWV.K+RDCRV.KL,TIME.K,TIMNGV)
   replacement and expansion of CRV fleet
R RDCRV.KL=CRV.K/LTCRV.K
   depreciation of road fleet stock
A LTCRV.K=FIFGE(TABHL(LTCRVT2,TIME.K,1990,2050,10),^
          TABHL(LTCRVT,TIME.K,1981,1993,2),TIME.K,1994)
   average lifetime of road vehicles
T LTCRVT=9.8/9.8/9.8/9.8/9.8/9.8/10.4
T LTCRVT2=10.4/10.4/10.4/10.4/10.4/10.4/10.4
   data from AusYB series T21.3 for 91 & 93 only
A HCRV.K=TABHL(HCRVT,TIME.K,1981,1993,1)*1E3
T
HCRVT=7917.6/8217.7/8589.9/8770/8959.7/9290.5/9373.7/9544.4/9806.1/1008
0.6^
```

```
        /9934.1/10246.9/10431.5
   data from AusYB series: 1981-3 from YB85 P450; 85 from YB88 P753;
86-89
    from YB91 P594; 90-93 from YB95 P643

L NGV.K=NGV.J+dt*(RFNGV.JK-RDNGV.JK+CONNGV.JK)
   stock of natural gas powered vehicles
N NGV=0
   initial value of NGV fleet
R RFNGV.KL=FIFGE(NEWV.K+RDNGV.KL,0,TIME.K,TIMNGV)
   replacement and expansion of NGV fleet
R RDNGV.KL=NGV.K/LTNGV.K
   depreciation of NGV fleet stock
A LTNGV.K=LTCRV.K
   average NGV lifetime: set equal to CRV for now

R
CONNGV.KL=FIFGE(TABHL(CONNGVT,TIME.K,1990,2050,10)*CRV.K,0,TIME.K,TIMNG
V)
T CONNGVT=0/0/0/0/0/0/0
   conversion rate of CRV to NGV, fraction remaining CRV per year

A RCFNGV.K=(RFNGV.KL*RCFNGV1+CONNGV.KL*RCFNGV2)*EII
              investment required in infrastructure modifications for
NGV's,
              VPJ/y
I RCFNGV1=0    capital investment in infrastructure req. per new NGV,
A$/y
I RCFNGV2=0    capital investment in infrastructure req. per converted
NGV, A$/y
   "guesstimate" values at present: given higher costs of conversions
c.f.
   original equipment manufactured (OEM) vehicles, RCFNGV2 > RCFNGV1

A TNV.K=CRV.K+NGV.K

 Saturation levels introduced for all classes of vehicle.
 Sat levels set to twice current usage rates, but, due to VGRF exponent
< 1,
 these saturation levels won't be reached anyway. DC'96b
A DNV.K=DNVMIN.K+DNVIND.K+DNVSER.K+DNVCON.K
A DNVMIN.K=MIN(V81*FMINROD*MINDEX.K**VGRFMIN,CSTMIN.K*SATMVEH)
A DNVIND.K=MIN(V81*FINDROD*INDEX.K**VGRFIND,CSIND.K*SATIVEH)
A DNVSER.K=MIN(V81*FSERROD*SERDEX.K**VGRFSER,CSSER.K*SATSVEH)
A DNVCON.K=MIN(V81*FCONROD*MSOLF.K**VGRFCON,TPOP.K*SATPVEH)

I VGRFCON=0.6      average private vehicle growth rate factor DC'96a
I VGRFIND=0.7      average industrial vehicle growth rate factor DC'96a
I VGRFMIN=0.85     average mining vehicle growth rate factor DC'96a
I VGRFSER=0.85     average commercial vehicle growth rate factor DC'96a
                   value altered DC'97c

A NEWV.K=MAX(0,DNV.K-TNV.K)   increase in no. vehicles
K V81=NGV+CRV

A TVEHPC.K=TNV.K/TPOP.K           vehicles (all classes) per cap. -
indicator
```

```
A VEHPC.K=DNVCON.K/TPOP.K      passenger vehicles per cap.
I SATPVEH=0.5                     user-defined saturation/upper limit on
private
                               car ownership DC'96b

A VEHPM.K=DNVMIN.K/CSTMIN.K  mining vehicles per unit CS mining DC'96b
I SATMVEH=2800                    user-defined saturation/upper limit on
mining
                               vehicle requirements DC'96b

A VEHPI.K=DNVIND.K/CSIND.K    industrial vehicles per unit CS industry
DC'96b
I SATIVEH=8600                    user-defined saturation/upper limit on
ind.
                               vehicle requirements DC'96b

A VEHPS.K=DNVSER.K/CSSER.K     service vehicles per unit CS services
DC'96b
I SATSVEH=800                     user-defined saturation/upper limit on
service
                               vehicle requirements DC'96b


A TEDROD.K=CRV.K*TEDPCRV+NGV.K*TEDPNGV
K TEDPCRV=649.5/CRV
K TEDPNGV=TEDPCRV

A EEDROD.K=0         electrical energy consumption, road transport, GWh/y

I   FMINROD=0.05   fractional use by mining
I   FINDROD=0.46   fractional use by industry
I   FSERROD=0.16   fractional use by services
I    FCONROD=0.33    fractional use by private sector fractions derived
from
                      1989 IO table

A TEDRAL.K=MINTRAL.K+INDTRAL.K+SERTRAL.K+CONTRAL.K
                     thermal energy consumption, road transport, PJ/y
A EEDRAL.K=MINERAL.K+INDERAL.K+SERERAL.K+CONERAL.K
                     electrical energy consumption, road transport, GWh/y
A MINTRAL.K=FMINRAL*27.9*MINDEX.K**0.4
                     reference TEDRAL used by mining, PJ/y
A INDTRAL.K=FINDRAL*27.9*INDEX.K**0.4
                     reference TEDRAL used by industry, PJ/y
A SERTRAL.K=FSERRAL*27.9*SERDEX.K**0.4
                     reference TEDRAL used by services, PJ/y
A CONTRAL.K=FCONRAL*27.9*MSOLF.K**0.4
                     reference TEDRAL used by priv, PJ/y
A MINERAL.K=FMINRAL*806*MINDEX.K**0.4
                     reference EEDRAL used by mining, GWh/y
A INDERAL.K=FINDRAL*806*INDEX.K**0.4
                     reference EEDRAL used by industry, GWh/y
A SERERAL.K=FSERRAL*806*SERDEX.K**0.4
                     reference EEDRAL used by services, GWh/y
A CONERAL.K=FCONRAL*806*MSOLF.K**0.4
                     reference EEDRAL used by priv, GWh/y
I   FMINRAL=0.04   fractional use by mining
```

```
I   FINDRAL=0.21   fractional use by industry
I   FSERRAL=0.05   fractional use by services
I    FCONRAL=0.70    fractional use by private sector fractions derived
from
                     1989 IO table

A TEDWTR.K=MINTWAT.K+INDTWAT.K+SERTWAT.K+CONTWAT.K
                    thermal energy consumption, road transport, PJ/y
A EEDWTR.K=MINEWAT.K+INDEWAT.K+SEREWAT.K+CONEWAT.K
                    electrical energy consumption, road transport, GWh/y
A MINTWAT.K=FMINWTR*73.7*MINDEX.K**0.4
                    reference TEDWTR used by mining, PJ/y
A INDTWAT.K=FINDWTR*73.7*INDEX.K**0.4
                    reference TEDWTR used by industry, PJ/y
A SERTWAT.K=FSERWTR*73.7*SERDEX.K**0.4
                    reference TEDWTR used by services, PJ/y
A CONTWAT.K=FCONWTR*73.7*MSOLF.K**0.4
                    reference TEDWTR used by priv, PJ/y
A MINEWAT.K=FMINWTR*83*MINDEX.K**0.4
                    reference EEDWTR used by mining, GWh/y
A INDEWAT.K=FINDWTR*83*INDEX.K**0.4
                    reference EEDWTR used by industry, GWh/y
A SEREWAT.K=FSERWTR*83*SERDEX.K**0.4
                    reference EEDWTR used by services, GWh/y
A CONEWAT.K=FCONWTR*83*MSOLF.K**0.4
                    reference EEDWTR used by priv, GWh/y
I   FMINWTR=0.05   fractional use by mining
I   FINDWTR=0.15   fractional use by industry
I   FSERWTR=0.21   fractional use by services
I    FCONWTR=0.59    fractional use by private sector fractions derived
from
                     1989 IO table

A TEDAIR.K=MINTAIR.K+INDTAIR.K+SERTAIR.K+CONTAIR.K
                    thermal energy consumption, road transport, PJ/y
A EEDAIR.K=MINEAIR.K+INDEAIR.K+SEREAIR.K+CONEAIR.K
                    electrical energy consumption, road transport, GWh/y
A MINTAIR.K=FMINAIR*86.4*MINDEX.K**0.4
                    reference TEDAIR used by mining, PJ/y
A INDTAIR.K=FINDAIR*86.4*INDEX.K**0.4
                    reference TEDAIR used by industry, PJ/y
A SERTAIR.K=FSERAIR*86.4*SERDEX.K**0.4
                    reference TEDAIR used by services, PJ/y
A CONTAIR.K=FCONAIR*86.4*MSOLF.K**0.4
                    reference TEDAIR used by priv, PJ/y
A MINEAIR.K=FMINAIR*139*MINDEX.K**0.4
                    reference EEDAIR used by mining, GWh/y
A INDEAIR.K=FINDAIR*139*INDEX.K**0.4
                    reference EEDAIR used by industry, GWh/y
A SEREAIR.K=FSERAIR*139*SERDEX.K**0.4
                    reference EEDAIR used by services, GWh/y
A CONEAIR.K=FCONAIR*139*MSOLF.K**0.4
                    reference EEDAIR used by priv, GWh/y
I   FMINAIR=0.04   fractional use by mining
I   FINDAIR=0.07   fractional use by industry
I   FSERAIR=0.36   fractional use by services
```

```
I    FCONAIR=0.53    fractional use by private sector fractions derived
from
                     1989 IO table

A TEDTRA.K=TEDROD.K+TEDRAL.K+TEDAIR.K+TEDWTR.K
                    fuel consumption by transport, PJ/y
A EEDTRA.K=EEDROD.K+EEDRAL.K+EEDAIR.K+EEDWTR.K
                    electricity consumption by transport, GWh/y
A PEDTRA.K=(TEDTRA.K+(EEDTRA.K*FEREL.K))*SYSGER.K
                    primary energy demand associated with fuel & elec.
                     consumption, PJ/y
A FTRAIND.K=FIFGE(TABHL(FTR2IND,TIME.K,1990,2050,10),^
            TABHL(FTRTIND,TIME.K,1981,1989,8),TIME.K,1990)
                    fraction of transport output used by industry
T   FTRTIND=0.13,0.23
T   FTR2IND=0.23/0.23/0.23/0.23/0.23/0.23/0.23
                    IO tables data

 historical data from ABARE'92
A HTEDTRA.K=HTEDROD.K+HTEDRAL.K+HTEDAIR.K+HTEDWTR.K
                    historical fuel consumption by transport, PJ/y
A PTEDTRA.K=TABHL(PTETTRA,TIME.K,1993,2009,16)
T PTETTRA=1070/1404  ABARE'95 projections DC'97c

A HEEDTRA.K=HEEDROD.K+HEEDRAL.K+HEEDAIR.K+HEEDWTR.K
                    historical   electricity   consumption   by   transport,
GWh/y
A HTEDROD.K=TABHL(HTETROD,TIME.K,1981,1991,2)
                    HTED by road transport, PJ/y
T   HTETROD=649.5/676.8/719.4/760.1/808.9/800.7
A HTEDRAL.K=TABHL(HTETRAL,TIME.K,1981,1991,2)
                    HTED by rail transport, PJ/y
T   HTETRAL=27.9/27.2/27.5/28/25/25.2
A HTEDAIR.K=TABHL(HTETAIR,TIME.K,1981,1991,2)
                    HTED by air transport, PJ/y
T   HTETAIR=86.4/83.5/93.3/106.9/109/130.6
A HTEDWTR.K=TABHL(HTETWTR,TIME.K,1981,1991,2)
                    HTED by water transport, PJ/y
T   HTETWTR=73.7/68.3/54.9/59.1/55.8/48.3
A HEEDROD.K=TABHL(HEETROD,TIME.K,1981,1991,2)
                    HEED by road transport, GWh/y
T   HEETROD=0/0/0/0/0/0
A HEEDRAL.K=TABHL(HEETRAL,TIME.K,1981,1991,2)
                    HEED by rail transport, GWh/y
T   HEETRAL=806/944/1111/1306/1583/1639
A HEEDAIR.K=TABHL(HEETAIR,TIME.K,1981,1991,2)
                    HEED by air transport, GWh/y
T   HEETAIR=139/83/83/83/83/83
A HEEDWTR.K=TABHL(HEETWTR,TIME.K,1981,1991,2)
                    HEED by water transport, GWh/y
T   HEETWTR=83/83/111/139/139/167


 == 4 ENVIRONMENTAL POLLUTION

 = 4.1 CARBON DIOXIDE EMISSIONS
 CO2 accounting done in three ways, each a refinement of previous one.
```

```
 (I)   CO2GEN - CO2 generated by burning of fossil fuels
 (II)  CO2EMM - actual emissions, i.e. subtract 'scrubbed' or otherwise
               techno-fixed captured carbon
 (III) NETCO2 - net emissions accounting for other indirect impacts on
the
               carbon cycle, such as vegetation cover changes, etc.
DC'96b

A
CO2GEN.K=OILDEM.K*CO2POIL+GASDEM.K*CO2PGAS+(COLDEM.K+BIODEM.K)*CO2PCOL
  Anthropogenic Carbon Dioxide Generation from fossil fuel combustion,
  tonnes Carbon/y
  BIODEM added DC'97c
I   CO2POIL=70E3      revised estimate in line with US EIA data DC'97c
           64.33E3    tonnes Carbon/PJ combusted
I   CO2PGAS=51.08E3   tonnes Carbon/PJ combusted
I   CO2PCOL=92.64E3   tonnes Carbon/PJ combusted
 new data inserted by DC 7.11.95 from 1990 GHG inventory supplied by BF

 NOTE NGGI & ABARE data (latter used to calibrate OzEcco fuel demands)
do not
 match exactly on fuel demand/apparent consumption. Overall, ABARE data
is
 28PJ higher (+77PJ coal, -22PJ gas, -28PJ oil) for 1990. This accounts
for
 the discrepancy between HCO2GEN & CO2GEN: a second HCO2GEN, based on
NGGI
 emission factors and ABARE demand data, is given for comparison
DC'96b

A CO2EMM.K=CO2GEN.K-CO2REM.K  CO2 actually emitted, T C/y

A NGGICO2.K=CO2EMM.K+COSGOIL.K-CO2SOAK.K
                             net CO2 emissions, allowing for forest
soak-up
                             as defined in Net Greenhouse Gas inventory
(NGGI)
                             Pasture & grassland conversion terms from
                             NGGI aren't yet factored in: t C/y  DC'96b
A NETCO2.K=NGGICO2.K+CO2RELS.K
                             NGGI calculation extended to cover
estimates of
                             releases of CO2 from forestry/timber
activities,
                             following Mohrens & Gabbour's analyses
DC'96b
A NCO2FOR.K=CO2RELS.K-COSGOIL.K-CO2SOAK.K
                             net CO2 impact of forestry, T C/y  DC'96b

 = Historical data on generation & net emissions from NGGI
A HCO2GEN.K=TABHL(HCO2GT,TIME.K,1988,1994,1)*1E6
T HCO2GT=240.4/258.6/262.6/269.1/267.4/270.5/273.9
A HCO2GN1.K=FIFGE(HCO2GN2.K,^
           HOILDEM.K*CO2POIL+HGASDEM.K*CO2PGAS+HCOLDEM.K*CO2PCOL,^
           TIME.K,1994)
A HCO2GN2.K=TABHL(HCO2GT2,TIME.K,1993,1995,1)*1E6
T HCO2GT2=290/314/339
```

```
  second historical emissions term based on NGGI 1990 average fuel
carbon
  contents and ABARE fuel demand data (which disagrees with NGGI
estimates)
  DC'96b
  The post-93 data her is a linear extrapolation to 95/6 ABARE estimate
A PCO2GEN.K=TABHL(PCOTGEN,TIME.K,1995,2009,14)*1E6
T PCOTGEN=339/428
  linear extrapolation to ABARE'95 2009/10 projections DC'97c
A HCO2SOK.K=TABHL(HCO2SOT,TIME.K,1988,1994,1)*1E6
T HCO2SOT=24.1/21.6/22.4/24.9/25.5/23.2/19.5
A HCOSGOL.K=-TABHL(HCOSGOT,TIME.K,1988,1994,1)*1E6
T HCOSGOT=3.4/3.5/3.8/4.3/4.5/4.2/4.3
A HNGICO2.K=HCO2GEN.K+HCOSGOL.K-HCO2SOK.K

 == Per Capita Indicators
A CO2GPC.K=CO2GEN.K/TPOP.K  Per Cap generation rate DC'96b
A CO2EPC.K=CO2EMM.K/TPOP.K  Per Cap emissions rate DC'96b
A CO2NPC.K=NETCO2.K/TPOP.K   net per cap emissions, t C/y

 == Breakdown by fuel type
A CO2COL.K=COLDEM.K*CO2PCOL
A CO2OIL.K=OILDEM.K*CO2POIL
A CO2GAS.K=GASDEM.K*CO2PGAS

A FCO2COL.K=CO2COL.K/CO2GEN.K
A FCO2OIL.K=CO2OIL.K/CO2GEN.K
A FCO2GAS.K=CO2GAS.K/CO2GEN.K

 == Sectoral Breakdown of Emissions DC'97c
A CO2ELG.K=COLEL.K*CO2PCOL+GASEL.K*CO2PGAS

 Direct CO2 per sector: only counting fuels burnt there
A DCO2AFF.K=OILAFF.K*CO2POIL+GASAFF.K*CO2PGAS+COLAFF.K*CO2PCOL
A DCO2IND.K=OILIND.K*CO2POIL+GASIND.K*CO2PGAS+COLIND.K*CO2PCOL
A DCO2DOM.K=OILDOM.K*CO2POIL+GASDOM.K*CO2PGAS+COLDOM.K*CO2PCOL
A DCO2SER.K=OILSER.K*CO2POIL+GASSER.K*CO2PGAS+COLSER.K*CO2PCOL
A DCO2TRA.K=OILTRA.K*CO2POIL+GASTRA.K*CO2PGAS+COLTRA.K*CO2PCOL

 Fraction of direct Carbon Dioxide emissions attributable to sectors
A FDCELG.K=CO2ELG.K/CO2GEN.K
A FDCAFF.K=DCO2AFF.K/CO2GEN.K
A FDCIND.K=DCO2IND.K/CO2GEN.K
A FDCDOM.K=DCO2DOM.K/CO2GEN.K

A FDCSER.K=DCO2SER.K/CO2GEN.K
A FDCTRA.K=DCO2TRA.K/CO2GEN.K

 Total CO2 per sector includes induced emissions from electricity
A CO2PKWH.K=CO2ELG.K/EEDFD.K
A TCO2AFF.K=DCO2AFF.K+EEDAFF.K*CO2PKWH.K
A TCO2IND.K=DCO2IND.K+EEDIND.K*CO2PKWH.K
A TCO2DOM.K=DCO2DOM.K+EEDDOM.K*CO2PKWH.K
A TCO2SER.K=DCO2SER.K+EEDSER.K*CO2PKWH.K
A TCO2TRA.K=DCO2TRA.K+EEDTRA.K*CO2PKWH.K

 Fraction of direct Carbon Dioxide emissions attributable to sectors
```

```
A FTCAFF.K=TCO2AFF.K/CO2GEN.K
A FTCIND.K=TCO2IND.K/CO2GEN.K
A FTCDOM.K=TCO2DOM.K/CO2GEN.K
A FTCSER.K=TCO2SER.K/CO2GEN.K
A FTCTRA.K=TCO2TRA.K/CO2GEN.K
```

== 4.1.1 Technical Fix to remove CO2: MonoEthanolomine (MEA) technology
(see Turkenburg et. al.)

Emmission reduction acheived by building MEA systems, at capital cost of
38.4e4 GJ/ MW generating capacity handled.

This module considers the case of carbon dioxide removal from coal fired electricity generation using monoethanolamine (MEA) technology, followed by high pressure compression and injection into used gas wells. Note that other technologies e.g. dolomite rock-based, may also be treated by the model, where appropriate data is available. MEA is presented here as an example.

The effect is to reduce the OVERALL efficiency of electricity generation, since 160 MW of electrical power are required for removal of CO2 per 600 MW output. At the same time the capital cost/MW delivered will rise. Turkenberg et. al. estimate costs rise by a factor of (2000+1600)/2000 =1.8. Since estimates of CS for coal fired generation is 17e-3, that for MEA technology is 13.6e-3 PJ/MW treated.

It is estimated that 90 % CO2 is removed. CO2 is disposed by injection into used gas wells, requiring 77+13=80 kWh/ T CO2, added to electricity demand.

Policy is activated by setting FMWMEA (Fraction fossil MW treated by MEA) table to non-zero values. Because it would be pointless to power these devices using C-fired electricity generation (emitting more CO2), there is a control device that cuts off activity if no non-fossil electricity available. DC'96b

```
A DFMWMEA.K=TABHL(FMWMEAT,TIME.K,1981,2051,10)
T FMWMEAT=0/0/0/0/0/0/0/0
   desired fraction of fossil-fired MW to be treated (default is none)
A FMWMEA.K=(CSMEA.K/CSMEAMW)/COELMW.K
```

```
   actual fraction treated: less than desired if no source of carbon
free elec
   DC'96b

A RCFCO2.K=RCFMEA.KL     generic CO2 sector term: redundant at present,
but
                         useful if range of tech. options present DC'96b

L CSMEA.K=CSMEA.J+DT*(RCFMEA.JK-RDCMEA.JK)   CS for CO2 tech.fix, VPJ
K CSMEA=0
R RCFMEA.KL=DCSMEA.K-CSMEA.K+RDCMEA.KL
                         RCF in MEA technology, VPJ/y
R RDCMEA.KL=CSMEA.K/LTMEA
                         depreciation rate MEA tech., VPJ/y

A DCSMEA.K=MWMEA.K*CSMEAMW
                         desired capital stock MEA technology, VPJ/y
                         limited  by  policy  (FMWMEA)  or  by  non-C
electricity
                         supply DC'96b
A MWMEA.K=MIN(DMWMEA.K,AVMWMEA.K)  actual capacity MEA, MW
A DMWMEA.K=(COELMW.K+CCTMW.K)*DFMWMEA.K  DC'97c
                         desired MW capacity treated, MW
A AVMWMEA.K=EEPNC.K/MEPPMW.K   available MEA as limited by non-carbon
elect'y
                                supply DC'96b
A MEPPMW.K=3.186                 EP req per MW active MEA inc. injection
DC'96b
                                (8760E-3*0.36)+(1320*24.5E-6)

I CSMEAMW=13.6E-3        additional CS per MW treated, VPJ/MW
I LTMEA=25               lifetime of fixed capital MEA technology, y

A CO2REM.K=MWMEA.K*1320
                                T  CO2/y  removed;  TURKENBURG,  TABLE  1
(4850T CO2)

L  EEDCO2.K=EEDCO2.J+DT*(RBEDCO2.JK-RDEDCO2.JK)  level  to  avoid  sim  aux
DC'97c
N EEDCO2=0
R RBEDCO2.KL=EEDINJ.K+EEDMEA.K
R RDEDCO2.KL=EEDCO2.K
   A   EEDCO2.K=EEDINJ.K+EEDMEA.K      additional   electricity   for   co2
removal
A EEDMEA.K=MWMEA.K*8760E-3*0.36 (.36=160 MW used per 600 MW)
A EEDINJ.K=CO2REM.K*24.5E-6
                                GWh per t C injected into old gas wells
                                 (Turkenburg; 90e-6GWh/T CO2)

A RESCO2.K=RESMEA.K      generic CO2 sector term: redundant at present,
but
                         useful if range of tech. options present DC'96b
A RESMEA.K=CO2REM.K*47E-9
                         Resource  operating  req.  for  MEA  (12.7e-9PJ/T
CO2),
                         VPJ/y
```

=== 4.1.2 CO2 banking by Forest Growth (& other indirect factors) ===
A number of indirect causes of CO2 (& other greenhouse gases) are identified
in recent greenhouse gas inventories for Australia (1993), including, for the
year 1990; industrial processes (1.6% of total), land-use change & forestry
(31% of total), and fugitive emissions of uncombusted fuels in oil & gas
extraction systems (1%). The main part of this section is an assessment of the
land use change/forestry component. DC'96b

```
A CO2SOAK.K=COSWDS.K+COSNF.K+COSRFOR.K
      rate of C take-up by indirect factors, T C/year
A CO2RELS.K=COSTIMB.K+COSWST.K+COSBIO.K+COSSCB.K+COSGOIL.K
      rate of CO2 release by indirect factors, T C/year

A COSWDS.K=RGPIN.KL*SUFPIN+RGEUC.KL*SUFEUC
      positive soak-up from growth of new woods (plantation)
A COSNF.K=COSRF.K+COSNE.K+COSNP.K
A COSRF.K=RAINFA.K*SUFRF
A COSNE.K=NATEA.K*SUFNE
A COSNP.K=NATPA.K*SUFNP
      positive annual soak-up from mature native forests
A COSRFOR.K=NEWFA.K*MGRNF*SUFNF
      positive soak-up from growth of new woods (native)
A COSTIMB.K=RDTIMB.KL*SUFTIMB
      negative soak-up from scrapped timber products
A COSWST.K=RDWAST.KL*SUFWST
      negative soak-up from waste biomass not used as timber products
A COSBIO.K=BIOEL.K*SUFTIMB
      negative soak-up for burning of timber & other biofuels
A COSSCB.K=DISSCB.KL*SUFSCB
      negative soak-up for scrub vegetation displaced by plantations
A COSGOIL.K=(RPOIL.KL+RPGAS.KL)*1945
      negative soak-up from fugitive emissions from oil/gas systems
      (1990 estimate of 4086Gg CO2 = 4E6T C & HRP(OIL+GAS,1990)=2100PJ)
      DC'96b

L STORETI.K=STORETI.J+DT*(RCWDS.J+NWDSUP.J-RDTIMB.JK-BIOEL.J+WDSIMP.J)
                                      store of cut wood as products
K STORETI=DTST*RCWDS
R RDTIMB.KL=STORETI.K/DTST            rate of release from store, m3/y
C DTST=10                                 average time of wood products
between
                                      felling and burning; weighted
average of
                                      energy, paper & packwood,
particle board
                                      & panel products and sawn timber
carbon
                                      residence times as quoted by
Mohrens &
                                      Gabbour (2.5,20 & 35 y resp.) No
use of
```

```
                                           embodied Carbon in trade here;
exported
                                           wood not accounted for. Note that
BIOFUEL
                                           for electricity also taken out
separately
                                           If big bio electric programme
brought in,
                                           average residence time inc.
energy usage
                                           would change considerably: best
to leave
                                           it separately here  DC'96b

L STOREWS.K=STOREWS.J+DT*(RWPLANT.JK+RWNFOR.JK-RDWAST.JK)
                                           store of waste biomass decaying,
m3
K STOREWS=DTSW*RCWDS
R RWPLANT.KL=RCWDS.K*1.5
    NGGI 1990 quotes total biomass removed in commercial forestry as
2.5 times
    the value of HWDSOUT data => for every m3 timber, 1.5m3 waste
biomass left
    to decay. Note that this is bigger than 30% wastage figure quoted
for
    conversion of RCWDS to WDSOUT: that refers to wastage of potential
timber
    only, based on MGR figures for commercially harvestable wood
DC'96b
R RWNFOR.KL=DEFORR.K*WDPHA*(FCLEAR.K*2.5+(1-FCLEAR.K)*1.5)
    deforested areas where timber not removed counted using factor of
2.5 as
    above: where timber removed, factor of 1.5 accounts for other
biomass
R RDWAST.KL=STOREWS.K/DTSW                 rate of release from store, m3/y
C DTSW=50                                   average decay time of waste wood
in soil

 = soak-up factors for forests use NGGI 1990 data of estimated average
tonnes
   Carbon per Ha, converted to tonnes per m3. For plantations, All
carbon
   soak-up is assumed to come from rapid growth of new immature
biomass:
   felling of these handled separately under COSTIMB term. Mature
forest
   soak-up based on mechanisms of mature forest (COSNF) as well as de-
and
   re-forestation terms. Displaced scrub and ave. nat forest content in
timber
   use estimate of 0.45tC/t dry mass,and assumed density of vegetation
0.4t/m3
   DC'96b
K SUFPIN=7.28/(MGRPIN*FPPIN)          C stored per m3 of pine plantation
K SUFEUC=5.68/(MGREUC*FPEUC)          C stored per m3 of euc plantation
```

```
K SUFRF=29/2332                            C store rate per m3 of mature nat
rainforest
                                        NGGI 1990 179E3tC: AusYB 2332E3Ha in
91
                                        estimate 150E3tC accounted for by
REFORR
K SUFNE=12584/34556                        C store rate per m3 of mature nat
eucalyptus
                                        (average for NGGI types 1-3)
                                        NGGI 1990 12584E3tC: AusYB 34556E3Ha
in 91
K SUFNP=355/4167                           C store rate per m3 of mature nat
pine/conif
                                        NGGI 1990 355E3tC: AusYB 4167E3Ha in
91

K SUFNF=0.4*0.45                             C store/release rate for mature
forest wood
K SUFTIMB=0.4*0.45                      average C release factor for timber
K SUFWST=0.4*0.45                         average C release factor for waste
biomass
K SUFSCB=0.4*0.45                       C per m3 of scrub


R DISSCB.KL=(RGWDS.K+REFORR.K-DEFORR.K)*MGRSCB
I MGRSCB=1                        displaced scrub marginal growth/year in
m3/hectare
                                  estimated small value  DC'96b
I MGRNF=5                           marginal growth rate of expanding forest,
estimate


 = 4.2 SULPHUR DIOXIDE EMISSIONS
A SO2.K=OILDEM.K*SO2POIL+GASDEM.K*SO2PGAS+COLDEM.K*SO2PCOL
                    Anthropogenic Sulphur Dioxide Emissions, tonnes/y
I   SO2POIL=20E3    tonnes/PJ combusted
I   SO2PGAS=0       tonnes/PJ combusted
I   SO2PCOL=15E3    tonnes/PJ combusted


 == 5 Indicators
 = Potential for Change (after Howell & Slesser, 1973, UNESCO, 1983;
   Slesser et. al, 1994
A    STES1.K=TACFR.K/(RDCIND.KL+RCFOS.K)        short    term    economic
sustainability
A VAINT.K=VAGRA.K/TPOP.K                         cereal/vegetable arable
intensity
A POTFCH1.K=STES1.K*VAINT.K              potential for change indicator

 = 5.1 == GDP Analogues & Historical Series

* Historical data series from AusNA'92/3 Tl
  Average GDP estimate (1993-96 from OECD web site
A HGDPA.K=TABHL(HGDPAT,TIME.K,1981,1996,1)*1E9
```

```
T
HGDPAT=282.2/275.2/290.3/305.4/317.9/324.6/341.4/357.8/369.5/367.4/369.
9^
         /380.9/390/405.9/418.9/435.0
  Income-based GDP estimate
A HGDPI.K=TABHL(HGDPIT,TIME.K,1981,1992,1)*1E9
T
HGDPIT=280.5/275.7/292.4/307.3/318.9/326.9/343.9/360.5/370.9/369.2/371.
1^
         /382.9
  Expenditure-based GDP estimate
A HGDPE.K=TABHL(HGDPET,TIME.K,1981,1992,1)*1E9
T
HGDPET=284.6/278.4/293.6/307.1/320.9/327.2/342.8/354.9/366.5/365.3/371.
5^
         /382.0
  Production-based GDP estimate
A HGDPP.K=TABHL(HGDPPT,TIME.K,1981,1992,1)*1E9
T
HGDPPT=281.5/271.4/284.9/301.7/313.9/319.9/337.6/358.1/370.9/367.8/367.
2^
         /377.8

* Breakdown of GDP(P) by sector, from AusNA'92/3 T4
A HGPAFF.K=TABHL(HGTAFF,TIME.K,1981,1992,1)*1E9
T HGTAFF=12.7/9.9/14.2/14.3/13.9/14.4/13.8/13.9/15.1/16.1/15.3/16.1
A HGPMIN.K=TABHL(HGTMIN,TIME.K,1981,1992,1)*1E9
T HGTMIN=9.638/10.097/10.961/12.488/13.764/12.934/14.665/15.056/16.266^
         /16.995/17.323/17.507
A HGPIND.K=TABHL(HGTIND,TIME.K,1981,1992,1)*1E9
T HGTIND=77.1/69.9/70.7/75.1/77.2/77.2/81.5/86.6/86.5/83.5/79.6/82.3
A HGPSER.K=TABHL(HGTSER,TIME.K,1981,1992,1)*1E9
T
HGTSER=151.4/149.7/156.3/165/172.4/178/189.1/202.3/210.1/207.4/209.9/21
5.9
A HGPDOM.K=TABHL(HGTDOM,TIME.K,1981,1992,1)*1E9
T HGTDOM=27.5/28.1/28.7/29.4/30.4/31.4/32.4/33.5/34.7/35.8/36.7/37.8
A HGPUTL.K=TABHL(HGTUTL,TIME.K,1981,1992,1)*1E9
T HGTUTL=8.6/8.8/9.2/9.7/10.1/10.3/10.8/11.3/11.9/12.2/12.3/12.5

 Some GP terms initialised using average historical values from 1981-3
 to avoid problem w. initial downturn in 1981-2
A GPAFF.K=GPAFFN*AFFX.K
K GPAFFN=12.3E9
A GPMIN.K=GPMINN*MINDEX.K
K GPMINN=HGPMIN
A GPIND.K=GPINDN*RCFINDX.K
K GPINDN=HGPIND
A GPSER.K=GPSERN*SERDEX.K
K GPSERN=152.5E9
A GPDOM.K=GPDOMN*DOMX.K
K GPDOMN=HGPDOM
A DOMX.K=CSDOM.K/CSDOMN
K CSDOMN=CSDOM
A GPUTL.K=GPUTLN*UTLX.K
K GPUTLN=HGPUTL
A GPTRAD.K=TABHL(GPTRAT,TIME.K,1981,1992,1)*1E9
```

```
T GPTRAT=-1.6/-2.3/-2.8/-3.0/-3.0/-3.3/-3.8/-4.5/-3.5/-6.2/-7.8/-10.0
  combined import duties and imputed bank service charge on GDPP,
AusNA92/3 T4
  DC'97B

A       GDPP.K=GPAFF.K+GPMIN.K+GPIND.K+GPSER.K+GPDOM.K+GPUTL.K+GPTRAD.K
DC'97B

 = Growth in GDP
A GDPGR.K=(GDPP.K-DELAY1(GDPP.K,1))*100/GDPP.K
   annual growth rate of GDP, %pa

A PGDPGR.K=TABHL(PGDPGT,TIME.K,1992,2009,1)
T PGDPGT=3.0/3.9/4.5/4.3/3.7/3.5/3.0/3.0/2.8/2.8/2.8/2.8/2.8^
        /2.5/2.5/2.5/2.5/2.5
   projected growth in GDP, ABARE'95 T13 DC'97c

L PGDP.K=PGDP.J+DT*RGPGDP.JK
N PGDP=HGDPP
R RGPGDP.KL=PGDP.K*PGDPGR.K/100
  projected GDP determined from growth rate DC'97c

 5.2 = ENERGY BALANCE EQUATIONS ================
 These serve as a set of checks/indicators on the consistency of the
model's
 accounting framework (with primary energy, fuel, embodied and
service-
 corrected embodied measures all using PJ units, things can get a
little
 confusing!) The total energy into and out of the economy are both
represented
 here in primary energy terms. Energy input is easy to describe; as it
is the
 actual energy content combusted in the economy. Energy notionally
leaves the
 economy on the output side when the service that it has been
dissipated to
 produce (i.e. the service in which the energy is 'embodied') is done -
in
 practical terms this is the depreciation of fixed HMC, use & export of
 non-fixed HMC and other services.  DC'97B

A TOTEIN.K=RPOIL.KL+RPGAS.KL+RPCOL.KL+OILIMP.K+GASIMP.K+COLIMP.K

 HMC entering and leaving the system at each timestep logged here in
terms
 of it's real embodied energy content rather than service-corrected
measure
L HMC.K=HMC.J+DT*(HMCIN.JK-HMCOUT.JK)
K HMC=CSAFF+CSTMIN+CSIND+CSUTL+CSDOM+CSSER
R HMCIN.KL=INDOUT.K
 rate of input of HMC equals embodied energy of industrial output
R HMCOUT.KL=(RDCAFF.K+RDCTMIN.K+RDCIND.KL+RDCUTL.K+RDCDOM.KL+RDCSER.KL^
          +CONS.K+NETXPGD.K+RQXBEN.K+TRES.K)/REDEII.K
 rate of output of HMC equals sum of RDC's and uses of transitory HMC
plus
```

```
 exports, corrected using REDEII to give actual embodied energy at
current
 replacement cost
A HMCB.K=CSAFF.K+CSTMIN.K+CSIND.K+CSUTL.K+CSDOM.K+CSSER.K
 for comparison, the total CS in service-corrected terms

 Energy dissipated by the system without an intermediate accumulation:
this
 is calculated both as a difference and from individual usages
A DISSE1.K=TOTEIN.K-HMCIN.KL
 energy disspated by system without being accumulated as HMC (even for
nominal
 zero-length time period, e.g. CONS) equals total energy input minus
HMC input
A DISSE2.K=(TEDAFF.K*(1-FAGRIND.K)+TEDMIN.K*(1-FMININD.K)^
           +TEDGAS.K+TEDOIL.K+TEDCOL.K^
           +(FUELEL.K+BIOEL.K)*(1-FELIND.K)+TEDGASD.K^
           +TEDWAT.K*(1-FWATIND.K)+TEDDOM.K^
           +TEDSER.K*(1-FSERIND.K)+TEDTRA.K*(1-FTRAIND.K))*SYSGER.K
 energy dissipated by the system equals sum of fuel inputs that don't
end up
 in the INDOUT equation
A FMININD.K=MININD.K/(MININD.K+MINOTH.K+DMINEXP.K)
A FWATIND.K=WATIND.K/WATDEM.K
A FELIND.K=(EEDIND.K+EEDAFF.K*(FAGRIND.K)+EEDMIN.K*(FMININD.K)^
           +EEDWAT.K*(FWATIND.K)+EEDSER.K*(FSERIND.K)^
           +EEDTRA.K*(FTRAIND.K))/EEDFD.K
A TOTEOT1.K=DISSE1.K+HMCOUT.KL
A TOTEOT2.K=DISSE2.K+HMCOUT.KL
```

Appendix 3 Source Code Listings for CarteSim Model

The CarteSim model was implemented in MicroSoft Visual Basic v3 for 16-bit Windows. In addition to the main simulation program, a model editor and a map editor were developed.

The Visual Basic code was stored in a number of modues reflecting the modular construction of the GUI (graphical user's interface). Most of the code included in these modules simply dealt with event handling, file input and output, and other mundane functions. The simulation algorithms were centralised in a main module *MAP_SIM.BAS*, and two ancillary modules *SIM_FRAC.BAS* for computing fractal dimensions of shapes, and *SENSOVER.BAS* for statistically analysing the 'overlay' maps. The code for these three modules is given below. A fourth module *FILE_IO.BAS* centralised file handling activities (the code for which is not included here).

MAP_SIM.BAS

```
' global constants for cmdialog from c:\vb\constant.txt
Global Const OFN_OVERWRITEPROMPT = &H2&
Global Const PD_PRINTSETUP = &H40&

Global current As Integer    ' bookmark variable for dealing with arrays
Global cfrom As Integer      ' bookmarks current rule selection
Global cto As Integer
Global ceff As Integer
Global rule_loaded                 ' toggle 0=rules viewers not loaded,
1=table only, 2=table+ed
Global viewmap As Integer      ' determines which maps are viewed during
simulation
                             '  0=none  1=land  use  only  2=tp's  only
3=both

Rem surface type, with characteristic dimensions
Type surface
  x As Integer         ' length
  y As Integer         ' width
  d As Integer         ' no. dimensions (1 or 2:y=1 if d=1)
End Type

'Rem neighbourhood template type
Type nt
  r As Integer         ' radius
  rf As Single         ' radius factor for "cutting corners"
  d As Integer          ' dimension of surface upon which nt is mapped
(=s.d)
End Type

Global nclass As Integer          ' no. land-use classes
Global  land_use_type()  As  String    '  names  of  land-use  classes,
dimension nclass
```

```
Global land_use_col() As Long     ' color scheme for land-use types
Global nt As nt                   ' nt used for transition rules
Global  rule_poss()  As  Integer         '  dimensions  nclass,nclass:
0=forbidden, 1=allowed
Global base_w() As Single         ' weight functions for transp
                                  '                          dimensions
nclass,nclass,nclass,nt.r

Global s As surface         '  map
Global cell() As Integer    ' cells on map, dimension s.x,s.y
Global    t_mask()    As    Single          '    transition    masks    dim
nclass,nclass,nclass,x,y

Global transp() As Single  ' deterministic transition potentials
                          ' dimensions s.x,s.y,nclass
Global s_tp() As Single ' stochastic transition potential term
                          ' dimensions s.x,s.y,nclass

Global stp_bw As Integer  ' toggle for tp display:=0 for white high, =1
for black high
Global view_tp_type As Integer  'toggle: =0 if view dtp's, =1 if view
stp's

Global best_x() As Integer    ' record position and value of best site
for
Global best_y() As Integer    ' each land use type
Global best_stp() As Single  ' dimensions 1 to nclass

Global mapfile As Integer  ' flags saying whether *.map and *.mod files
Global modfile As Integer  ' loaded (=1 if so): otherwise won't run

Global t As Integer        ' timestep counter
Global running As Integer  ' flag if simulation n progress=1
                           ' 0 = not yet running: need to initiate tp's
                           '  1  =  mid-running  (or  -1  if  running
backwards in playback mode)
                           ' 2 = frozen: able to continue or cancel

Rem simulation input parameters from input forms (see simulate menu)
Rem can be varied in sensitivity analyses
Global alpha As Single     ' random noise parameter
Global seed As Single      ' seed for randomising
Global sens_ct$             ' string representation of alpha + seed for
sens runs
Global  sens_run%                 '  =0  if  running  normally,  =1  for
sensitivity runs

Rem results saving management files
Global mapname$            ' name of current map file (w/out extension)
Global root$               ' root name for results files
Global cdir$               ' current results storage directory
Global first As Integer    ' first time-step at which results saved
Global map_save As Integer ' regular interval for saving .map file
Global dtp_save As Integer ' regular interval for saving .dtp file
Global stp_save As Integer ' regular interval for saving .stp file
Global stop_time As Integer' pre-set stopping point for simulation
Global map_bmp_sav As Integer
```

```
Global tp_bmp_sav As Integer

Global pb_list$()          ' list of files for movie playback
Global play_ready As Integer ' toggle =1 if list of playbacks ready to
run
Global pb_dir$
Global pb_place As Integer
Global pb_run As Integer

Global newcell() As Integer     ' growth rates for new cells dim 1 to
nclass
Global replacell() As Integer  'no. cells 'overwritten' and in need of
replacement

Sub advance_current ()
  On Error Resume Next
  current = current + 1
  If current > nclass Then current = 1
  If replacell(current) < 0 Then
    advance_current
    If Err = 28 Then
      retval% = MsgBox("No active land-use classes in model. Closing
transition potential viewer.", 48)
      viewmap = viewmap - 2
      tp_see.WindowState = 1
    End If
    Exit Sub
  End If
  tp_see.tpv_pict.BackColor = land_use_col(current)
  tp_see.tpv_text.Caption = land_use_type(current)
  Call draw_tpmap(current)
End Sub

Sub advance_rule_ed ()
  ceff = ceff + 1
  If ceff > nclass Then ceff = ceff - nclass
  rule_ed.grultitl_eff.BackColor = land_use_col(ceff)
  For a% = 1 To nt.r
    rule_ed.rule_graph_label(a%).Caption  =  CStr(base_w(ceff,  cfrom,
cto, a%))
  Next a%
  scale_rule_ed
End Sub

Function di_si% (x As Integer, y As Integer, sx As Integer)
  ' converts x and y coordinates to single index for s_tp sorting
  di_si% = ((y - 1) * sx) + x
End Function

Sub draw_legend (showgrow As Integer)
Rem if showgrow=1 then widen form and show growth rates
If showgrow = 1 Then legend.setup.Value = True
legend.WindowState = 0
If showgrow = 0 Then
  legend.Width = 2580
Else
  legend.Width = 4200
```

```
End If

legend.Height = 1115 + 360 * nclass

For a% = 1 To nclass
  legend.leg_pict(a%).Visible = True
  legend.leg_pict(a%).Top = 50 + 360 * a%
  legend.leg_pict(a%).Left = 120
  legend.leg_pict(a%).BackColor = land_use_col(a%)
  legend.leg_pict(a%).BorderStyle = 0
  legend.leg_text(a%).Visible = True
  legend.leg_text(a%).Top = 50 + 360 * a%
  legend.leg_text(a%).Left = 720
  legend.leg_text(a%).Caption = land_use_type(a%)
  If showgrow = 1 Then
    If replacell(a%) >= 0 Then
      legend.leg_grow(a%).Visible = True
      legend.leg_grow(a%).Enabled = True
      legend.leg_grow(a%).Top = 50 + 360 * a%
      legend.leg_grow(a%).Left = 2520
      legend.leg_grow(a%).Text = CStr(newcell(a%))
    Else
      legend.leg_grow(a%).Enabled = False
      legend.leg_grow(a%).Visible = False
    End If
  End If
Next a%

End Sub

Sub draw_map ()
' draw land-use map
If viewmap = 1 Or viewmap = 3 Then
  map_see.WindowState = 0
  If s.d = 2 Then
    For a% = 1 To s.x
      For b% = 1 To s.y
        Call draw_map_cell(a%, b%, cell(a%, b%))
      Next b%
    Next a%
  ElseIf s.d = 1 Then
    For a% = 1 To s.x
      Call draw_map_cell(t, a%, cell(a%, 1))
    Next a%
  End If
End If

End Sub

Sub draw_map_cell (x As Integer, y As Integer, L As Integer)
  map_see.map.Line (x, y)-Step(1, 1), land_use_col(L), BF
End Sub

Sub draw_rule_ed ()
  If rule_loaded < 2 Then
    Load rule_ed
    rule_loaded = 2
```

```
  End If
  rule_ed.WindowState = 0
  rule_ed.Height = 4260
  rule_ed.Width = 3735 + 495 * (nt.r - 6)
  If rule_ed.Width < 3735 Then rule_ed.Width = 3735

Rem size and place controls
For a% = 1 To nt.r
  rule_ed.rules_graph(a%).Visible = True
  rule_ed.rules_graph(a%).Width = 495
  rule_ed.rules_graph(a%).Height = 2055
  rule_ed.rules_graph(a%).Left = 600 + 495 * (a% - 1)
  rule_ed.rules_graph(a%).Top = 720
  rule_ed.rules_graph(a%).BackColor = QBColor(7)

  rule_ed.rule_graph_label(a%).Visible = True
  rule_ed.rule_graph_label(a%).Width = 495
  rule_ed.rule_graph_label(a%).Left = 600 + 495 * (a% - 1)
  rule_ed.rule_graph_label(a%).Top = 3120
  rule_ed.rule_graph_label(a%).Height = 285
  rule_ed.rule_graph_label(a%).Caption = CStr(base_w(ceff, cfrom, cto,
a%))
  rule_ed.rule_graph_label(a%).TabIndex = a% + 2
Next a%

Rem rescale graphs
rule_ed.grul_yhigh.Caption = "1"
rule_ed.grul_ylow.Caption = "-1"
scale_rule_ed

rule_ed.scale_high.Left = rule_ed.rule_graph_label(nt.r).Left
rule_ed.grultitl_eff.BackColor = land_use_col(ceff)
rule_ed.grultitl_from.BackColor = land_use_col(cfrom)
rule_ed.grultitl_to.BackColor = land_use_col(cto)

End Sub

Sub draw_rule_table ()
  If rule_loaded = 0 Then
    Load rule_table
    rule_loaded = 1
  End If
  rule_table.WindowState = 0
  rule_table.Width = 840 + 240 * nclass
  rule_table.Height = 2460 + 240 * nclass
  If rule_table.Width < 2535 Then rule_table.Width = 2535
  If rule_table.Height < 3420 Then rule_table.Height = 3420

  rule_table.from_label.Top = 1200 + 120 * (nclass - 4)
  rule_table.from_label.Left = 120
  rule_table.to_label.Top = 600
  rule_table.to_label.Left = 720 + 120 * (nclass - 1)

  rule_leg_height% = 2280 + 240 * (nclass - 4)
  If rule_leg_height% < 2280 Then rule_leg_height% = 2280
  rule_table.leg_cap1.Top = rule_leg_height%
  rule_table.leg_box1.Top = rule_leg_height%
```

```
  rule_table.leg_box1.BackColor = QBColor(7)
  rule_table.leg_cap2.Top = rule_leg_height% + 360
  rule_table.leg_box2.Top = rule_leg_height% + 360
  rule_table.leg_box2.BackColor = QBColor(2)

  For a% = 1 To nclass
    rule_table.rulmat_from(a% - 1).Visible = True
    rule_table.rulmat_from(a% - 1).Top = 960 + a% * 240
    rule_table.rulmat_from(a% - 1).Left = 360
    rule_table.rulmat_from(a% - 1).BackColor = land_use_col(a%)

    rule_table.rulmat_to(a% - 1).Visible = True
    rule_table.rulmat_to(a% - 1).Top = 840
    rule_table.rulmat_to(a% - 1).Left = 480 + a% * 240
    rule_table.rulmat_to(a% - 1).BackColor = land_use_col(a%)
    For b% = 1 To nclass
      rule_table.rule_grid(di_si%(a%, b%, nclass)).Visible = True
      rule_table.rule_grid(di_si%(a%, b%, nclass)).Height = 230
      rule_table.rule_grid(di_si%(a%, b%, nclass)).Width = 230
      rule_table.rule_grid(di_si%(a%, b%, nclass)).Left = 480 + b% *
240
      rule_table.rule_grid(di_si%(a%, b%, nclass)).Top = 960 + a% * 240
      If rule_poss(a%, b%) = 0 Then rule_table.rule_grid(di_si%(a%, b%,
nclass)).BackColor = QBColor(7)
      If rule_poss(a%, b%) = 1 Then rule_table.rule_grid(di_si%(a%, b%,
nclass)).BackColor = QBColor(2)
      rule_table.rule_grid(di_si%(a%, b%, nclass)).BorderStyle = 0
    Next b%
  Next a%
  rule_table.rule_grid(di_si%(cto, cfrom, nclass)).BorderStyle = 0

End Sub

Sub draw_tpmap (L As Integer)
'draw s_tp map shading active s_tp's in order
If viewmap > 1 Then
  tp_see.WindowState = 0
If view_tp_type = 1 Then
  shadeincr! = 200 / best_stp(L)
  If s.d = 2 Then
    For a% = 1 To s.x
      For b% = 1 To s.y
        If s_tp(a%, b%, L) = -1000 Then
          shade% = 0
        Else
          If stp_bw = 0 Then
            shade% = 56 + CInt(s_tp(a%, b%, L) * shadeincr!)
          Else
            shade% = 256 - CInt(s_tp(a%, b%, L) * shadeincr!)
          End If
          If shade% < 0 Then shade% = 0
        End If
        tp_see.tpv_map.Line (a%, b%)-Step(1, 1), RGB(shade%, shade%,
shade%), BF
      Next b%
    Next a%
  Else
```

```
    ' rescale and white-out view window
    tp_see.tpv_map.Scale (-best_stp(L), 0)-(best_stp(L), s.x)
    tp_see.tpv_map.Line (-best_stp(L), 0)-(best_stp(L), s.x), RGB(255,
255, 255), BF
    For a% = 1 To s.x
      If s_tp(a%, 1, L) <> -1000 Then
        If stp_bw = 0 Then
          tp_see.tpv_map.Line (0, a%)-Step(s_tp(a%, 1, L), 1),
land_use_col(L), BF
        Else
          tp_see.tpv_map.Line (0, a%)-Step(s_tp(a%, 1, L), 1), RGB(0,
0, 0), BF
        End If
      End If
    Next a%
  End If
Else
  ' draw map of deterministic tp's
  For a% = 1 To s.x
    For b% = 1 To s.y
      If transp(a%, b%, L) >= best_dtp Then best_dtp = transp(a%, b%,
L)
    Next b%
  Next a%
  shadeincr! = 200 / best_dtp
  If s.d = 2 Then
    For a% = 1 To s.x
      For b% = 1 To s.y
        If s_tp(a%, b%, L) = -1000 Then
          shade% = 0
        Else
          If stp_bw = 0 Then
            shade% = 56 + CInt(transp(a%, b%, L) * shadeincr!)
          Else
            shade% = 256 - CInt(transp(a%, b%, L) * shadeincr!)
          End If
          If shade% < 0 Then shade% = 0
        End If
        tp_see.tpv_map.Line (a%, b%)-Step(1, 1), RGB(shade%, shade%,
shade%), BF
      Next b%
    Next a%
  Else
    ' rescale and white-out view window
    tp_see.tpv_map.Scale (-best_dtp, 0)-(best_dtp, s.x)
    tp_see.tpv_map.Line (-best_dtp, 0)-(best_dtp, s.x), RGB(255, 255,
255), BF
    For a% = 1 To s.x
      If stp_bw = 0 Then
        tp_see.tpv_map.Line (0, a%)-Step(transp(a%, 1, L), 1),
land_use_col(L), BF
      Else
        tp_see.tpv_map.Line (0, a%)-Step(transp(a%, 1, L), 1), RGB(0,
0, 0), BF
      End If
    Next a%
  End If
```

```
End If

End If
End Sub

Sub find_best_stp (L As Integer)
  ' deals with possibility of more than one 'best' value
  ' by storing all candidates' x,y in an array bestvals(1 to 2, 1 to
candidate_number): will
  ' randomly select one at end of search
  Call say("Searching for best site for " + land_use_type(L))
  ReDim bestvals(1 To 2, 1 To 1)
  best_stp(L) = s_tp(1, 1, L)  ' start out w. first cell as best value
  bestvals(1, 1) = 1
  bestvals(2, 1) = 1
  For a% = 1 To s.x
    For b% = 1 To s.y
      If s_tp(a%, b%, L) > best_stp(L) Then
        ' won't select a cell if a higher-up land-use class has
selected it
        can% = 1
        For c% = L + 1 To nclass
          If best_x(c%) = a% And best_y(c%) = b% Then can% = 0
        Next c%
        If can% = 1 Then
          If UBound(bestvals, 2) > 1 Then ReDim bestvals(1 To 2, 1 To
1)
          bestvals(1, 1) = a%
          bestvals(2, 1) = b%
          best_stp(L) = s_tp(a%, b%, L)
        End If
      ElseIf s_tp(a%, b%, L) = best_stp(L) Then
        ' won't select a cell if a higher-up land-use class has
selected it
        can% = 1
        For c% = L + 1 To nclass
          If best_x(c%) = a% And best_y(c%) = b% Then can% = 0
        Next c%
        If can% = 1 Then
          candno% = UBound(bestvals, 2) + 1
          ReDim Preserve bestvals(1 To 2, 1 To candno%)
          bestvals(1, candno%) = a%
          bestvals(2, candno%) = b%
        End If
      End If
    Next b%
  Next a%
  ' randomly select one of bestvals candidates
  candsel% = Int((UBound(bestvals, 2) - LBound(bestvals, 2) + 1) * Rnd
+ LBound(bestvals, 2))
  best_x(L) = bestvals(1, candsel%)
  best_y(L) = bestvals(2, candsel%)

  Call say("Idle")
End Sub
```

```
Sub init_map (s As surface)
Rem calculate deterministic transition potentials for map
Rem and call to init_stp's and sort them by order

  On Error GoTo 0

  Call say("Calculating map's transition potentials")

  If s.d = 1 Then
    ntryl% = 1
    ntryh% = 1
  Else
    ntryl% = -nt.r
    ntryh% = nt.r
  End If
  For c% = 1 To nclass
    If replacell(c%) >= 0 Then
      For a% = 1 To s.x
        For b% = 1 To s.y
          If rule_poss(cell(a%, b%), c%) = 1 Then
            transp(a%, b%, c%) = 0    ' reset to zero before counting up
contributions
            For d% = -nt.r To nt.r
              For e% = ntryl% To ntryh%
                cc% = 1  ' default vacant site if off the map
                If a% + d% > 0 And a% + d% <= s.x Then
                  If s.d = 2 Then
                    If b% + e% > 0 And b% + e% <= s.y Then
                      cc% = cell(a% + d%, b% + e%)      ' correct if not
off map
                    End If
                  Else
                    cc% = cell(a% + d%, 1)      ' correct if not off map
                  End If
                End If
                transp(a%, b%, c%) = transp(a%, b%, c%) + t_mask(cc%,
cell(a%, b%), c%, d%, e%)
              Next e%
            Next d%
          Else
            transp(a%, b%, c%) = -1000
          End If
        Next b%
      Next a%
      tp_see.WindowState = 0
      Call init_stp_from_dtp(c%)
    End If
  Next c%

  If viewmap < 2 Then tp_see.WindowState = 1
  running = 1
  Call say("Idle")

End Sub

Sub init_stp_from_dtp (L As Integer)
' where transp already calculated, resets and resorts stochastic terms
```

```
On Error GoTo 0

Call say("Adding random noise to tp's for " + land_use_type(L))
For a% = 1 To s.x
  For b% = 1 To s.y
    If transp(a%, b%, L) = -1000 Then
      s_tp(a%, b%, L) = -1000
    Else
      s_tp(a%, b%, L) = (transp(a%, b%, L) + 1) * (1 + ((-Log(Rnd) /
.4343) ^ alpha))
    End If
  Next b%
Next a%

'refresh viewer if opened
If tp_see.WindowState <> 1 And current = L Then Call draw_tpmap(L)

'sort stp's
Call find_best_stp(L)

Call say("Idle")
End Sub

Sub init_transition_masks (s As surface)
Rem set up transition masks containing coefficients for transition
rules
Rem for each possible transformation

Call say("Initialising transition potential masks")

Erase t_mask
If s.d = 1 Then
  ydiml% = 1
  ydimh% = 1
ElseIf s.d = 2 Then
  ydiml% = -nt.r
  ydimh% = nt.r
End If
' t_mask has indices effector class,old class, new class, x, y of eff
rel to old->new
ReDim t_mask(1 To nclass, 1 To nclass, 1 To nclass, -nt.r To nt.r,
ydiml% To ydimh%)

' for 1D maps, prompt whether ordinary or squared weights to be used
If s.d = 1 Then
  retval% = MsgBox("Map is one-dimensional. Treat weights as
numerically equal to 2D case by pressing 'YES', or equivalent inertia
factor by pressing 'NO'", 68)
  If retval% = 6 Then tm_1d = 0 Else tm_1d = 1
End If

For a% = 1 To nclass
  For b% = 1 To nclass
    If rule_poss(a%, b%) > 0 Then
      For c% = 1 To nclass
        If s.d = 1 Then
```

```
          For d% = -nt.r To nt.r
            If d% <> 0 Then
              If tm_1d = 0 Then
                t_mask(c%, a%, b%, d%, 1) = base_w(c%, a%, b%, Abs(d%))
' use same weights as 2d map
              Else
                If base_w(c%, a%, b%, Abs(d%)) < 0 Then sg% = -1 Else
sg% = 1
                t_mask(c%, a%, b%, d%, 1) = sg% * Sqr(base_w(c%, a%,
b%, Abs(d%))) ' use squared root weights for equivalent inertia
              End If
            End If
          Next d%
        ElseIf s.d = 2 Then
          For d% = -nt.r To nt.r
            For e% = -nt.r To nt.r
              If d% + e% <> 0 Then
                dist! = Sqr(CSng(d% ^ 2) + CSng(e% ^ 2))
                next_low_dist! = Int(dist!)
                If CInt(dist! + nt.rf) <= nt.r Then
                  next_up_dist! = next_low_dist! + 1
                  If next_up_dist! > nt.r Then next_up_dist! = nt.r
                  low_base! = base_w(c%, a%, b%, next_low_dist!)
                  high_base! = base_w(c%, a%, b%, next_up_dist!)
                  t_mask(c%, a%, b%, d%, e%) = low_base! + (high_base!
- low_base!) * (dist! - next_low_dist!)
                End If
              End If
            Next e%
          Next d%
        End If
      Next c%
    End If
  Next b%
Next a%
Call say("Idle")
End Sub

Sub playback ()
  ' call playback selecter
  overlay.Caption = "Movie Playback Selecter"
  overlay.Show (1)
  If play_ready = 1 Then
    ' open map viewer and maximise
    pb_view.Show
    map_sim.top_bar.Visible = False
    map_sim.low_bar.Visible = False
    map_sim.pb_bar.Visible = True
    pb_view.WindowState = 2
    ' load first bitmap
    pb_view.pb_map.Picture = LoadPicture(pb_dir$ + "\" + pb_list$(1))
    map_sim.file_nam.Caption = pb_list$(1)
  End If
End Sub

Sub redraw_tpv ()
  ' update tp viewer to show tp's or overlays
```

```
  If tp_see.Caption = "TP Viewer" Then
    Call draw_tpmap(current)
  Else
    Call draw_overlay(c_over)
  End If
End Sub

Sub reset_grow ()
  For a% = 1 To nclass
    legend.leg_grow(a%).Text = CStr(newcell(a%))
  Next a%
End Sub

Sub reset_pb ()
  overlay.dir_name.Text = cdir$
  overlay.dir_list.Path = overlay.dir_name.Text
  overlay.file_name.Text = "*.bmp"
  overlay.file_list.Pattern = overlay.file_name.Text
  overlay.select_list.Clear
  overlay.x_dim.Caption = "1"
  overlay.y_dim.Caption = "1"
  play_ready = 0
  map_sim.menu_file.Enabled = True
  If modfile = 1 Then map_sim.menu_mod.Enabled = True
  If modfile = 1 And mapfile = 1 Then map_sim.menu_sim.Enabled = True
  If modfile = 1 And mapfile = 1 Then map_sim.menu_an.Enabled = True
  If modfile = 1 And mapfile = 1 Then map_sim.menu_view.Enabled = True
End Sub

Sub reset_rand ()
  sim_parm.alpha.Text = CStr(alpha)
  sim_parm.seed.Text = "1"
End Sub

Sub reset_simfile ()
  sim_file.rootname.Text = root$
  sim_file.cdirname.Text = cdir$
  sim_file.first.Text = CStr(first)
  sim_file.map_save.Text = CStr(map_save)
  sim_file.dtp_save.Text = CStr(dtp_save)
  sim_file.stp_save.Text = CStr(stp_save)
  sim_file.stop_time.Text = CStr(stop_time)
  sim_file.map_bmp_save.Text = CStr(map_bmp_sav)
  sim_file.tp_bmp_save.Text = CStr(tp_bmp_sav)
End Sub

Sub say (message As String)
  If message = "Idle" Then
    screen.MousePointer = 1
  Else
    screen.MousePointer = 11
  End If
  map_sim.low_bar_label.Caption = message
  map_sim.low_bar_label.Refresh
End Sub

Sub scale_rule_ed ()
```

```
Rem reset axis scale to cover all values
minval! = -1
maxval! = 1
For a% = 1 To nt.r
  If base_w(ceff, cfrom, cto, a%) > maxval! Then maxval! = base_w(ceff,
cfrom, cto, a%)
  If base_w(ceff, cfrom, cto, a%) < minval! Then minval! = base_w(ceff,
cfrom, cto, a%)
Next a%
rule_ed.grul_yhigh.Caption = CStr(Int(maxval!))
rule_ed.grul_ylow.Caption = CStr(Int(minval!))
Rem redraw graph elements
For a% = 1 To nt.r
  rule_ed.rules_graph(a%).Scale  (0,  CSng(rule_ed.grul_yhigh.Caption))-
(1, CSng(rule_ed.grul_ylow.Caption))
  rule_ed.rules_graph(a%).Cls
  rule_ed.rules_graph(a%).Line  (0,  0)-(1,  base_w(ceff,  cfrom,  cto,
a%)), QBColor(2), BF
  rule_ed.rules_graph(a%).Line (0, 0)-(1, 0), QBColor(0)
Next a%
End Sub

Sub set_grow (gr() As Integer)
  If UBound(gr) = nclass And LBound(gr) = 1 Then
    For a% = 1 To nclass
      newcell(a%) = gr(a%)
    Next a%
  End If
End Sub

Sub set_map ()
  ' automatically open display windows in order to change sizes
  map_see.WindowState = 0
  tp_see.WindowState = 0
  If s.d = 2 Then
    yy% = s.y
  ElseIf s.d = 1 Then
    yy% = s.x / 2
  End If
  If s.x > yy% Then maxdim% = s.x Else maxdim% = yy%
  mapscal% = Int(4000 / maxdim%)
  tpscal% = Int(2500 / maxdim%)
  If s.d = 2 Then
    map_see.Height = 405 + s.y * mapscal%
    map_see.Width = 120 + s.x * mapscal%
    map_see.map.Height = s.y * mapscal%
    map_see.map.Width = s.x * mapscal%
    tp_see.Height = 885 + s.y * tpscal%
    tp_see.Width = 120 + s.x * tpscal%
    tp_see.tpv_map.Height = s.y * tpscal%
    tp_see.tpv_map.Width = s.x * tpscal%
    map_see.map.Scale (1, 1)-(s.x + 1, s.y + 1)
    tp_see.tpv_map.Scale (1, 1)-(s.x + 1, s.y + 1)
  ElseIf s.d = 1 Then
    map_see.Height = 405 + s.x * mapscal%
    map_see.Width = 120 + yy% * mapscal%
    map_see.map.Height = s.x * mapscal%
```

```
    map_see.map.Width = yy% * mapscal%
    tp_see.Height = 885 + s.x * tpscal%
    tp_see.Width = 120 + yy% * tpscal%
    tp_see.tpv_map.Height = s.x * tpscal%
    tp_see.tpv_map.Width = yy% * tpscal%
    map_see.map.Cls
    tp_see.tpv_map.Cls
    map_see.map.Scale (1, 1)-(101, s.x + 1)
    tp_see.tpv_map.Scale (1, 1)-(101, s.x + 1)
  End If
  tp_see.tpv_pict.Top = tp_see.tpv_map.Height + 120
  tp_see.tpv_text.Top = tp_see.tpv_map.Height + 120
  tp_see.tpv_pict.BackColor = land_use_col(current)
  tp_see.tpv_text.Caption = land_use_type(current)
  'iconise unwanted display windows
  If mapview < 2 Then tp_see.WindowState = 1
  If mapview = 0 Or mapview = 2 Then map_see.WindowState = 1
End Sub

Sub set_rand (a As Single, s As Single)
  If alpha <> a And mapfile = 1 Then
    alpha = a
    retval% = MsgBox("Value of alpha has changed. Do you wish to
recalculate random terms in map?", 36)
    If retval% = 6 Then
      For aa% = 1 To nclass
        Call init_stp_from_dtp(aa%)
      Next aa%
    End If
  End If
  seed = s
  Randomize s
End Sub

Sub set_simfile (r$, d$, f%, ms%, ds%, ss%, st%, bm%, bt%)
  root$ = r$
  cdir$ = d$
  first = f%
  map_save = ms%
  dtp_save = ds%
  stp_save = ss%
  stop_time = st%
  map_bmp_sav = bm%
  tp_bmp_sav = bt%
End Sub

Function si_dix% (i As Integer, x As Integer)
  ' extracts x-value from single index as used by s_tp
  si_dix% = i - (x * (si_diy%(i, x) - 1))
End Function

Function si_diy% (i As Integer, x As Integer)
  ' extracts x-value from single index as used by s_tp
  si_diy% = Int((i - 1) / x) + 1
End Function

Sub sim_step (s As surface, newcell() As Integer)
```

```
Rem each element of newcell details number of new cells
Rem of each land_use_type to add that step

Rem cells updated in reverse order of legend classes for moment, as
this
Rem avoids clash of interests in "when93" model, where a hierarchy of
Rem transition potentials operates

On Error GoTo 0

' if no stp or dtp loaded then look for them
If running = 0 Then Call open_transp(mapname$)

' save current results in storage directory if relevant
If t = first Then Call save_during_sim(sens_run%)

Call say("Simulating")

' set second dimension of t_mask scanning routine before entering loops
If s.d = 2 Then
  mine% = -nt.r
  maxe% = nt.r
  indx_add% = 0
Else
  mine% = 0
  maxe% = 0
  indx_add% = 1
End If

' set replacement terms to zero
For a% = 1 To nclass
  If replacell(a%) > 0 Then replacell(a%) = 0
Next a%

'run through in reverse order filling in new cells
For a% = UBound(newcell) To LBound(newcell) Step -1
  If replacell(a%) >= 0 And newcell(a%) + replacell(a%) > 0 Then
    For b% = 1 To newcell(a%) + replacell(a%)
      ' variable indicating current cell of interest
      cypos% = best_y(a%)
      cxpos% = best_x(a%)
      Call  say("Cell  [" + CStr(cxpos%) + "," + CStr(cypos%) + "]
changing to " + land_use_type(a%))
      ' if 'overwriting' a non-vacant cell, add extra cell to new list
for overwritten class
      If replacell(cell(cxpos%, cypos%)) >= 0 Then
        replacell(cell(cxpos%,    cypos%))    =    replacell(cell(cxpos%,
cypos%)) + 1
      End If
      ' overwrite cell with new type
      oldcell% = cell(cxpos%, cypos%)
      cell(cxpos%, cypos%) = a%
      ' update all relevant transps, and reset s_tp's
      For c% = -nt.r To nt.r
        For e% = mine% To maxe%
          If Sqr((c% ^ 2) + (e% ^ 2)) <= nt.r Then
            For d% = 1 To nclass
```

```
                ccxpos% = cxpos% + c%
                ccypos% = cypos% + e%
                If ccxpos% > 0 And ccxpos% <= s.x Then
                  If ccypos% > 0 And ccypos% <= s.y Then
                    If rule_poss(cell(ccxpos%, ccypos%), d%) = 1 Then
                      ch_tr! = -t_mask(oldcell%, cell(ccxpos%, ccypos%),
d%, c%, e% + indx_add%) + t_mask(a%, cell(ccxpos%, ccypos%), d%, c%, e%
+ indx_add%)
                      If ch_tr! <> 0 Then
                        transp(ccxpos%, ccypos%, d%) = transp(ccxpos%,
ccypos%, d%) + ch_tr!
                        s_tp(ccxpos%, ccypos%, d%) = (transp(ccxpos%,
ccypos%, d%) + 1) * (1 + ((-Log(Rnd + 1E-50) / .4343) ^ alpha))
                      End If
                    ElseIf transp(ccxpos%, ccypos%, d%) > -1000 Then
                      ' correct cells that have newly become unavailable
for transition
                      ' typically where ccxpos=cxpos and ccypos=cypos
                      transp(ccxpos%, ccypos%, d%) = -1000
                      s_tp(ccxpos%, ccypos%, d%) = -1000
                    End If
                  End If
                End If
              Next d%
            End If
          Next e%
        Next c%
        ' find new best value for each active class, for next iteration
of b%
        For f% = 1 To nclass
          If replacell(f%) >= 0 Then Call find_best_stp(f%)
        Next f%
        '  on 2D map, update each cell as it changes
        If s.d = 2 Then Call draw_map_cell(cxpos%, cypos%, a%)
      Next b%
    End If
Next a%
t = t + 1
' on 1D map, update next layer at end of sim_step
If s.d = 1 Then draw_map
draw_tpmap (current)
map_sim.top_bar_ct.Caption = CStr(t)
save_during_sim (sens_run%)

DoEvents

Call say("Idle")

End Sub

Sub stop_sim ()
  running = 2
End Sub

Sub update_dyn_controls (old_nclass As Integer, new_nclass As Integer,
old_ntr As Integer, new_ntr As Integer)
```

```
If old_nclass <> new_nclass Then
  If new_nclass > old_nclass Then
    For a% = old_nclass + 1 To new_nclass
      Load legend.leg_pict(a%)
      Load legend.leg_text(a%)
      Load legend.leg_grow(a%)
      If rule_loaded >= 1 Then Load rule_table.rulmat_from(a% - 1)
      If rule_loaded >= 1 Then Load rule_table.rulmat_to(a% - 1)
    Next a%
    For b% = (old_nclass ^ 2) + 1 To (new_nclass ^ 2)
      If rule_loaded >= 1 Then Load rule_table.rule_grid(b%)
    Next b%
  ElseIf old_nclass > new_nclass Then
    For a% = new_nclass + 1 To old_nclass
      Unload legend.leg_pict(a%)
      Unload legend.leg_text(a%)
      Unload legend.leg_grow(a%)
      If rule_loaded >= 1 Then Unload rule_table.rulmat_from(a% - 1)
      If rule_loaded >= 1 Then Unload rule_table.rulmat_to(a% - 1)
    Next a%
    For b% = (new_nclass ^ 2) + 1 To (old_nclass ^ 2)
      If rule_loaded >= 1 Then Unload rule_table.rule_grid(b%)
    Next b%
  End If
End If

If rule_loaded >= 1 Then
  If old_ntr <> new_ntr Then
    If new_ntr > old_ntr Then
      For a% = old_ntr + 1 To new_ntr
        Load rule_ed.rules_graph(a%)
        Load rule_ed.rule_graph_label(a%)
      Next a%
    ElseIf old_ntr > new_ntr Then
      For a% = new_ntr + 1 To old_ntr
        Unload rule_ed.rules_graph(a%)
        Unload rule_ed.rule_graph_label(a%)
      Next a%
    End If
  End If
End If
End Sub
```

SIM_FRAC.BAS

```
Rem variables associated with fractal analysis
Global fs As surface             ' for fractal analyses
Global frac_map() As Variant      'storage map for fractal analysis: dim
s.x,s.y
Global frac_cell() As Variant     '0/1 map outlining fractal shape: dim
s.x,s.y
Global frac_count() As Integer   '0/1 denotes whether land-class counted
for fractal purposes
Global frac_maxr As Integer      ' max sized radius of object
Global frac_ct() As Single       ' cell count array dim 1 to frac_maxr
Global x_centre As Single
Global y_centre As Single
```

```
Sub frac_analyse ()
If filop = 0 Then
  frac_set_frac_map
  frac_find_centre
Else
  frac_find_ovctr (current)
End If

  For a% = 1 To frac_maxr
    Call frac_calc(a%)
  Next a%

End Sub

Sub frac_calc (r As Integer)
Rem computes fractal dimension parameters for radius r
  frac_ct(r) = 0
  ' ensures cells checked are within bounds of map
  If x_centre - r < 1 Then lowa% = 1 Else lowa% = Int(x_centre - r)
  If x_centre + r > fs.x Then higha% = fs.x Else higha% = Int(x_centre
+ r)
  If y_centre - r < 1 Then lowb% = 1 Else lowb% = (y_centre - r)
  If y_centre + r > fs.y Then highb% = fs.y Else highb% = (y_centre +
r)
  For a% = lowa% To higha%
    For b% = lowb% To highb%
      If Sqr(((a% - x_centre) ^ 2) + ((b% - y_centre) ^ 2)) <= r Then
        If frac_cell(a%, b%) = 1 Then frac_ct(r) = frac_ct(r) + 1
      End If
    Next b%
  Next a%
End Sub

Sub frac_draw_map ()
frac.f_map.Cls
If fs.d = 2 Then
  For a% = 1 To fs.x
    For b% = 1 To fs.y
      frac.f_map.Line     (a%,     b%)-Step(1,     1),     RGB(255     -
(frac_count(frac_map(a%,  b%))  *  255),  255  -  (frac_count(frac_map(a%,
b%)) * 255), 255 - (frac_count(frac_map(a%, b%)) * 255)), BF
    Next b%
  Next a%
Else
  For a% = 1 To fs.x
    frac.f_map.Line     (3,     a%)-Step(1,     1),     RGB(255     -
(frac_count(frac_map(a%, 1)) * 255), 255 - (frac_count(frac_map(a%, 1))
* 255), 255 - (frac_count(frac_map(a%, 1)) * 255)), BF
  Next a%
End If
End Sub

Sub frac_draw_over ()

End Sub
```

```
Sub frac_find_centre ()
Rem determines median x and y values
Rem also determines outside edges of rectangle req. to
Rem hold city shape, and => largest radius required
x_count! = 0
y_count! = 0
f_count% = 0
x_min% = fs.x
y_min% = fs.y
x_max% = 1
y_max% = 1
For a% = 1 To fs.x
  For b% = 1 To fs.y
    If frac_cell(a%, b%) = 1 Then
      x_count! = x_count! + a%
      y_count! = y_count! + b%
      f_count% = f_count% + 1
      If a% < x_min% Then x_min% = a%
      If a% > x_max% Then x_max% = a%
      If b% < y_min% Then y_min% = b%
      If b% > y_max% Then y_max% = b%
    End If
  Next b%
Next a%
x_centre = x_min% + (x_max% - x_min%) / 2
y_centre = y_min% + (y_max% - y_min%) / 2
maxr! = x_centre - x_min%
If x_max% - x_centre > maxr! Then maxr! = x_max% - x_centre
If y_max% - y_centre > maxr! Then maxr! = y_max% - y_centre
If y_centre - y_min% > maxr! Then maxr! = y_centre - y_min%
frac_maxr = Int(maxr!) + 1
ReDim frac_ct(1 To frac_maxr)
End Sub

Sub frac_find_ovctr (l As Integer)

x_count! = 0
y_count! = 0
f_count! = 0
x_min% = fs.x
y_min% = fs.y
x_max% = 1
y_max% = 1

For a% = 1 To fs.x
  For b% = 1 To fs.y
    If frac_cell(a%, b%) > 0 Then
      x_count! = x_count! + a% * frac_cell(a%, b%)
      y_count! = y_count! + b% * frac_cell(a%, b%)
      f_count! = f_count! + frac_cell(a%, b%)
      If a% < x_min% Then x_min% = a%
      If a% > x_max% Then x_max% = a%
      If b% < y_min% Then y_min% = b%
      If b% > y_max% Then y_max% = b%
    End If
  Next b%
Next a%
```

```
x_centre = x_min% + (x_max% - x_min%) / 2
y_centre = y_min% + (y_max% - y_min%) / 2
maxr! = x_centre - x_min%
If x_max% - x_centre > maxr! Then maxr! = x_max% - x_centre
If y_max% - y_centre > maxr! Then maxr! = y_max% - y_centre
If y_centre - y_min% > maxr! Then maxr! = y_centre - y_min%
frac_maxr = Int(maxr!) + 1
ReDim frac_ct(1 To frac_maxr)

End Sub

Sub frac_open_map (file As String)
  On Error Resume Next
  Open file For Input As #1
  If Err = 52 Then
    MsgBox "Bad File Name.", 48
  End If

  ' read new nclass & nt.r value and resize arrays accordingly
  Input #1, fs.d
  Input #1, fs.x
  Input #1, fs.y

  'erase & reinitialise fractal map array
  Erase frac_map
  Erase frac_cell
  ReDim frac_map(1 To fs.x, 1 To fs.y)
  ReDim frac_cell(1 To fs.x, 1 To fs.y)
  If fs.d = 2 Then
    frac.f_map.Scale (0, 0)-(fs.x + 2, fs.y + 2)
  Else
    frac.f_map.Scale (0, 0)-(5, fs.x + 2)
  End If

  ' read in map coordinates
  For a% = 1 To fs.x
    For b% = 1 To fs.y
      Input #1, frac_map(a%, b%)
      If frac_map(a%, b%) < 1 Then frac_map(a%, b%) = 1
      If frac_map(a%, b%) > nclass And modfile = 1 Then frac_map(a%,
b%) = nclass
    Next b%
  Next a%
  Close #1

End Sub

Sub frac_open_over (file As String)
  On Error Resume Next
  Open file For Input As #1
  If Err = 52 Then
    MsgBox "Bad File Name.", 48
  End If

  ' read new nclass & nt.r value and resize arrays accordingly
  Input #1, fs.d
  Input #1, fs.x
```

```
  Input #1, fs.y

  'erase & reinitialise fractal map array
  Erase frac_map
  Erase frac_cell
  ReDim fracc_map(1 To fs.x, 1 To fs.y, 1 To nclass)
  If fs.d = 2 Then
    frac.f_map.Scale (0, 0)-(fs.x + 2, fs.y + 2)
  Else
    frac.f_map.Scale (0, 0)-(255, fs.x + 2)
  End If

  ' read in map coordinates
  For z% = 1 To nclass
    For a% = 1 To fs.x
      For b% = 1 To fs.y
        Input #1, fracc_map(a%, b%, z%)
      Next b%
    Next a%
  Next z%
  Close #1

End Sub

Sub frac_save_data (file$)
  On Error Resume Next
  Open file$ For Output As #1
  If Err = 52 Then
    MsgBox "Bad File Name.", 48
  End If

  Print #1, "Radius ";
  For a% = 1 To frac_maxr
    Print #1, CStr(a%) + " ";
  Next a%
  Print #1, "Cell count ";
  Print #1, " "
  For a% = 1 To frac_maxr
    Print #1, CStr(frac_ct(a%)) + " ";
  Next a%
  Close #1
End Sub

Sub frac_set_frac_map ()
Rem frac_count() is an array of size nclass, set to 0 or 1
Rem 1=cells of that class count as filled for fractal shape
For a% = 1 To fs.x
  For b% = 1 To fs.y
    If frac_count(frac_map(a%, b%)) = 1 Then
      frac_cell(a%, b%) = 1
    Else
      frac_cell(a%, b%) = 0
    End If
  Next b%
Next a%
End Sub
```

SENSOVER.BAS

```
Rem functions for sensitivity analysis and overlay maps

Global ov() As Single  ' overlay function storage, dim s.x, s.y, nclass
                       ' ov stored as value between 0 and 255, for
graphical convenience
Global c_over As Integer
Global maxrad%         ' max radius for D plots

' counters for storing frequency distribs and radial analyses
Global histct%()
Global histradct()
Global radct%()

Sub advance_current_over ()
  ' differs from advance_current in that active & passive land-use
classes can be shown
  c_over = c_over + 1
  If c_over > nclass Then c_over = 1
  tp_see.tpv_pict.BackColor = land_use_col(c_over)
  tp_see.tpv_text.Caption = land_use_type(c_over)
  Call draw_overlay(c_over)
End Sub

Sub check_var (a_fr, a_to, a_st, s_fr, s_to, s_st)
'check from, to and step parameters for correctness
If a_st = 0 Then 'if no variation, set from,to accordingly
  a_fr = alpha
  a_to = alpha
  a_st = 1
ElseIf a_fr > a_to And a_st > 0 Then 'reverse sign of step size if
needed
  a_st = -a_st
ElseIf a_fr < a_to And a_st < 0 Then
  a_st = -a_st
End If
'round term off to next full step size
If (a_fr - a_to) Mod a_st <> 0 Then
  a_to = (a_fr - a_to) - (a_fr - a_to) Mod a_st + a_st
  MsgBox "Rounding final value of alpha to " + CStr(a_to), 64
End If

If s_st = 0 Then 'if no variation, set from,to accordingly
  s_fr = seed
  s_to = seed
  s_st = 1
ElseIf s_fr > s_to And s_st > 0 Then 'reverse sign of step size if
needed
  s_st = -s_st
ElseIf s_fr < s_to And s_st < 0 Then
  s_st = -s_st
End If
'round term off to next full step size
If (s_fr - s_to) Mod s_st <> 0 Then
  s_to = (s_fr - s_to) - (s_fr - s_to) Mod s_st + s_st
  MsgBox "Rounding final value of seed to " + CStr(s_to), 64
```

```
End If

End Sub

Sub draw_hist_over ()
Rem do graphic output for hist_over for current class

maxval% = 1
For a% = 1 To 256
  If maxval% < histct%(a%, c_over) Then maxval% = histct%(a%, c_over)
Next a%

an_view.Show
an_view.angraph.Cls
an_view.yhi.Caption = CStr(maxval% + 1)
an_view.ylo.Caption = CStr(0)
an_view.xlo = CStr(1)
an_view.xhi = CStr(255)
an_view.Caption = "Analyser: Frequency Histogram"
an_view.angraph.Scale (0, maxval% + 1)-(256, 0)
For a% = 1 To 256
  an_view.angraph.Line (a% - 1, 0)-Step(1, histct%(a%, c_over)), RGB(0,
0, 0), BF
Next a%
End Sub

Sub draw_hist_rad_over ()
Rem do graphic output for hist_over for current class

maxval% = 1
maxval2% = 1
For a% = 1 To maxrad%
  If  maxval%  <  histradct(a%,  c_over)  Then  maxval%  =  histradct(a%,
c_over)
  If maxval2% < radct%(a%) Then maxval2% = radct%(a%)
Next a%


an_view.Show
an_view.angraph.Cls
an_view.yhi.Caption = CStr(maxval% + 1)
an_view.ylo.Caption = CStr(0)
an_view.xlo = CStr(1)
an_view.xhi = CStr(maxrad% + 1)
an_view.Caption = "Analyser: Radial Distribution"
an_view.angraph.Scale (0, maxval% + 1)-(maxrad% + 1, 0)
' draw area chart of radial average coverage
For a% = 1 To maxrad%
  an_view.angraph.Line  (a%  -  1,  0)-Step(1,  histradct(a%,  c_over)),
RGB(0, 0, 0), BF
Next a%
' draw line chart of cell count for 2d maps
'If s.d = 2 Then
  scf% = maxval% / maxval2%' scaling factor
  an_view.angraph.Line (.5, radct%(1) * scf%)-(1.5, radct%(1) * scf%),
RGB(255, 0, 0)
  For a% = 2 To maxrad%
```

```
    an_view.angraph.Line (a% - .5, radct%(a% - 1) * scf%)-(a% + .5,
radct%(a%) * scf%), RGB(255, 0, 0)
  Next a%
'End If
End Sub

Sub draw_overlay (l As Integer)
  ' draw overlay map
  If s.d = 2 Then
    For a% = 1 To s.x
      For b% = 1 To s.y
        If stp_bw = 1 Then tone = (255 - ov(a%, b%, l)) Else tone =
ov(a%, b%, l)
        tp_see.tpv_map.Line (a%, b%)-Step(1, 1), RGB(tone, tone, tone),
BF
      Next b%
    Next a%
  Else
    tp_see.tpv_map.Cls
    For a% = 1 To s.x
      If stp_bw = 1 Then tone = RGB(0, 0, 0) Else tone =
land_use_col(l)
      tp_see.tpv_map.Line (0, a%)-Step(ov(a%, 1, l) / 2.55, 1), tone,
BF
    Next a%
  End If
End Sub

Sub hist_over ()
Rem make frequency histogram of overlay map
ReDim histct%(1 To 256, 1 To nclass)
For a% = 1 To s.x
  For b% = 1 To s.y
    For c% = 1 To nclass
      histct%(Int(ov(a%, b%, c%)) + 1, c%) = histct%(Int(ov(a%, b%,
c%)) + 1, c%) + 1
    Next c%
  Next b%
Next a%

draw_hist_over
End Sub

Sub hist_rad_over (xctr%, yctr%)
Rem make average distrib vs. radius profile from omp for calculating D

'determine maximum radius from given centre
If xctr% > s.x / 2 Then maxx% = xctr% Else maxx% = s.x - xctr%
If yctr% > s.y / 2 Then maxy% = yctr% Else maxy% = s.y - yctr%
If s.d = 2 Then
  maxrad% = Int(Sqr(maxx% ^ 2 + maxy% ^ 2)) + 2
Else
  maxrad% = maxx%
End If

' scan map and add up ov terms plus counters
ReDim histradct(1 To maxrad%, 1 To nclass)
```

```
ReDim hradct%(1 To maxrad%, 1 To nclass)
ReDim radct%(1 To maxrad%)
For a% = 1 To s.x
  For b% = 1 To s.y
    If s.d = 2 Then
      dis% = Int(Sqr((a% - xctr%) ^ 2 + (b% - yctr%) ^ 2)) + 1
    Else
      dis% = Int(Abs(a% - xctr%)) + 1
    End If
    radct%(dis%) = radct%(dis%) + 1
    For c% = 1 To nclass
      histradct(dis%, c%) = histradct(dis%, c%) + ov(a%, b%, c%)
      hradct%(dis%, c%) = hradct%(dis%, c%) + 1
    Next c%
  Next b%
Next a%

' compute average as total/count
For a% = 1 To maxrad%
  For b% = 1 To nclass
    If hradct%(a%, b%) > 0 Then
      histradct(a%, b%) = histradct(a%, b%) / hradct%(a%, b%)
    Else
      histradct(a%, b%) = 0
    End If
  Next b%
Next a%

draw_hist_rad_over

End Sub

Sub open_seed (s_dir$, s_file$)
  ' reopen seed files *.map and *.dtp
  Open s_dir$ + "\" + s_file$ For Input As #1
  Call open_map_head(1)
  Call open_map_body(1)
  Close #1
  draw_map
  Open s_dir$ + "\" + Left$(s_file$, Len(s_file$) - 4) + ".dtp" For
Input As #1
  Call open_transp_head(0, 0, 1, Left$(s_file$, Len(s_file$) - 4))
  Call open_transp_body(0, 1)
  Close #1
  Call draw_tpmap(current)
End Sub

Sub reset_over ()
  overlay.dir_name.Text = cdir$
  overlay.dir_list.Path = overlay.dir_name.Text
  overlay.file_name.Text = "*.map"
  overlay.file_list.Pattern = overlay.file_name.Text
  overlay.select_list.Clear
  overlay.x_dim.Caption = "1"
  overlay.y_dim.Caption = "1"
End Sub
```

```
Sub reset_sens ()
  sens_frm.cdirname.Text = cdir$
  sens_frm.rootname.Text = Left$(root$, 2)
  sens_frm.first.Text = CStr(first)
  sens_frm.map_save.Text = CStr(map_save)
  sens_frm.dtp_save.Text = CStr(dtp_save)
  sens_frm.stp_save.Text = CStr(stp_save)
  sens_frm.stop_time.Text = CStr(stop_time)
  sens_frm.alph_from.Text = "0"
  sens_frm.alph_to.Text = "0"
  sens_frm.alph_step.Text = "0"
  sens_frm.seed_from.Text = "0"
  sens_frm.seed_to.Text = "0"
  sens_frm.seed_step.Text = "0"
  sens_frm.seed_dir.Text = cdir$
  If mapname$ = "" Then
    sens_frm.seed_file.Text = "*.map"
  Else
    sens_frm.seed_file.Text = mapname$ + ".map"
  End If
End Sub

Sub save_hist (fileno%)
  Print #fileno%, cdir$ + "\" + mapname$
  Print #fileno%, "Value",
  For a% = 1 To 255
    Print #fileno%, Format$(a%, "###"),
  Next a%
  Print #fileno%, " "
  For b% = 1 To nclass
    Print #fileno%, land_use_type(b%),
    For a% = 1 To 255
      Print #fileno%, Format$(histct%(a%, b%), "######.##"),
    Next a%
    Print #fileno%, " "
  Next b%
  Print #fileno%,
End Sub

Sub save_rad_hist (fileno%)
  Print #fileno%, cdir$ + "\" + mapname$
  Print #fileno%, "Value",
  For a% = 1 To maxrad%
    Print #fileno%, Format$(a%, "####"),
  Next a%
  Print #fileno%, " "
  Print #fileno%, "Cell count",
  For a% = 1 To maxrad%
    Print #fileno%, Format$(radct(a%), "#####.##"),
  Next a%
  Print #fileno%, " "
  For b% = 1 To nclass
    Print #fileno%, land_use_type(b%),
    For a% = 1 To maxrad%
      Print #fileno%, Format$(histradct(a%, b%), "#####.##"),
    Next a%
    Print #fileno%, " "
```

```
  Next b%
  Print #fileno%,
End Sub

Sub sensitivity_run (s_dir$, s_file$, a_fr, a_to, a_st, s_fr, s_to,
s_st)

' open text file for central record output from sensitivity runs
Open cdir$ + "\" + root$ + "_sens.txt" For Output As #3
Write #3, "Sensitivity Analysis File Directory"

' make series of time-stamped sub-directories
On Error Resume Next
For di% = first To stop_time Step map_save
  MkDir cdir$ + "\" + root$ + Format$(di%, "0000")
Next di%
On Error GoTo 0

' iterate through values of alpha and seed
aa% = 0
For a = a_fr To a_to Step a_st
  alpha = a
  aa% = aa% + 1
  bb% = 0
  For b = s_fr To s_to Step s_st
    seed = b
    bb% = bb% + 1
    ' send progress report to screen
    sens_frm.alph_count.Caption = CStr(a)
    sens_frm.seed_count.Caption = CStr(b)
    ' write progress to text file
    sens_ct$ = root$ + Format$(aa%, "000") + Format$(bb%, "000")
    Write #3, "alpha = " + CStr(a) + ", seed = " + CStr(b) + "; " +
sens_ct$
    Call open_seed(s_dir$, s_file$)
    ' calculate *.stp values from seed and alpha parameter
    Randomize b
    For l% = 1 To nclass
      If replacell(l%) >= 0 Then Call init_stp_from_dtp(l%)
    Next l%
    ' reset simulation clock to zero and simulate
    t = 0
    running = 1
    Do
      Call sim_step(s, newcell())
    Loop While running = 1 And t < stop_time
  Next b
Next a
Close #3
sens_run% = 0

Call open_seed(s_dir$, s_file$)   ' re-open seed file to be returned to
when sensitivity run finished


End Sub
```

```
Sub set_overlay (d$, flist$(), x%, y%)
  If c_over < 1 Or c_over > nclass Then c_over = 1
  ' reset size of overlay storage files
  ReDim ov(x%, y%, nclass)
  ' determine total number of maps being overlaid
  ' and hence increment per map for overlaying
  nmaps% = UBound(flist$) - LBound(flist$) + 1
  ovinc = 255 / nmaps%
  ' open each map in turn and do calculations
  For a% = LBound(flist$) To UBound(flist$)
    Call say("Overlaying Map " + CStr(a%) + " of " + CStr(nmaps%))
    ' read map data
    Open d$ + "\" + flist$(a%) For Input As #1
    Call open_map_head(1)
    Call open_map_body(1)
    Close #1
    ' add map data to ov as relevant
    For b% = 1 To s.x
      For c% = 1 To s.y
        ov(b%, c%, cell(b%, c%)) = ov(b%, c%, cell(b%, c%)) + ovinc
      Next c%
    Next b%
  Next a%
  set_overlay_map
  Call draw_overlay(c_over)
  Call say("Idle")
End Sub

Sub set_overlay_map ()
  'open and retitle tp viewer, close map viewer
  tp_see.Caption = "Overlay Viewer"
  viewmap = 2
  tp_see.WindowState = 0
  redraw_tpv
  map_see.WindowState = 1
  ' rescale picture map accordingly
  If s.d = 2 Then
    tp_see.tpv_map.Scale (1, 1)-(s.x + 1, s.y + 1)
  Else
    tp_see.tpv_map.Scale (1, 1)-(100, s.x + 1)
  End If
End Sub

Sub set_sens (stor_dir$, r$, a_fr, a_to, a_st, s_fr, s_to, s_st,
s_dir$, s_file$, sav_first%, sav_map%, sav_dtp%, sav_stp%, sim_l%)

sens_run% = 1

' lots of parameters passed here: they are
' stor_dir$ = storage directory for results, r$ = rootname for results
files
'  a_fr%,a_to%,a_st% define pattern of variation of alpha, none if
a_st%=0
' s_fr% etc. similarly for seed number
' sav_etc. denote pattern of saving data in given simulation run
' sim_l is length of each simulation
```

```
' assign to global variables
root$ = r$
cdir$ = stor_dir$
first = sav_first%
map_save = sav_map%
dtp_save = sav_dtp%
stp_save = sav_stp%
stop_time = sim_l

'Call check_var(a_fr, a_to, a_st, s_fr, s_to, s_st)
Call sensitivity_run(s_dir$, s_file$, a_fr, a_to, a_st, s_fr, s_to,
s_st)
End Sub
```

Appendix 4 Source Code Listings for IPSO Model

The IPSO Model was implemented as a series of Java (1.0) classes capable of running as an Applet from a web page, or as a desktop application. A batch-mode utility was developed for automating multiple runs and parameter variation in the latter case, and saving output files (both full data and summary reports) as comma-separated value (.CSV) files which could be subsequently analysed by a spreadsheet program.

Owing to the inherently modular nature of java, the complete project included 40 files of source code. 19 of these were explicitly concerned with displaying output via a GUI (graphical user interface), and a further 6 solely with file input-output. The main model file *IPSOModel.java* and the remaining 14 non-GUI files are listed below.

Package ipso

IPSOModel.java

```
package ipso;

import java.util.*;
import java.awt.*;

//
//
// IPSOModel
//
//
class IPSOModel extends Observable
{
  //// instance variables ////

  //system constraints
  IPSOParameterSet ip;  //set of parameter constraints

  //system components
  Vector tech;  //list of Technology objects
  Vector proc;  //list of HMCProcess Objects
  Vector prod;  //list of Product objects (resource=false)
          //if (ip.autogrow) getProd(0) refers to special case of
          //human-made capital, the stuff of which all HMCProcesses
          //are themselves composed (units of prod.siz field)
  Vector res;    //list of Product objects (resource=true)

  //simulation time handling variables
  float tim;
  float dt;

  //miscellaneous
  int Nnewtechs;      //counter of new technologies to be added either
            //through automated invention or user intervention
  Vector newtech;      //temp. storage vector for holding any new techs
```

```
  //supply of HMC available to reinvest in new processes
  float availHMC;

  //// constructor methods ////

  //default constructor passing instance variables including arrays of
existing techs, procs, prods
  IPSOModel(IPSOParameterSet i, Technology[] vt, HMCProcess[] vpc,
Product[] vpr, float t, float d)
  {
    ip=i;
    tim=t;
    dt=d;

    tech=new Vector(vt.length*2);
    proc=new Vector(vpc.length*2);
    prod=new Vector(vpr.length);
    res=new Vector(vpr.length);

    Nnewtechs=0;
    newtech=new Vector(5);

    int x;
    for(x=0;x<vt.length;x++)
    {
      addTech(vt[x]);
    }

    for(x=0;x<vpc.length;x++)
    {
      addProc(vpc[x]);
    }

    for(x=0;x<vpr.length;x++)
    {
      addPR(vpr[x]);
    }
  }

  //alternative constructor passes sys constraints plus req. number
  //of techs, procs, PR's to start with; they are randomly gen'd
  //from the sys constraints data
  IPSOModel(IPSOParameterSet i, int vt, int vpc, int vpr, float t,
float d)
  {
    ip=i;
    tim=t;
    dt=d;

    tech=new Vector(vt*2);
    proc=new Vector(vpc*2);
    prod=new Vector(vpr);
    res=new Vector(vpr);

    Nnewtechs=0;
    newtech=new Vector(5);
```

```
    int x;
    int np=1;
    int nr=0;
    //first product is always set as HMC, entered into prod rather than
res vector
    Product thisProd=new Product("HMC",new PresParameterSet(0,0,1,

ip.pr.initResStk,ip.pr.initRenStk,ip.pr.initProdStk,
                                ip.pr.renCoeff));
    addPR(thisProd);
    for(x=1;x<vpr;x++)
    {
      thisProd=new Product("_"+new Integer(x).toString(),ip.pr);
      if (thisProd.resource)
      {
        nr++;
        if (thisProd.renewable)
thisProd.name="Renewable"+thisProd.name;
        else thisProd.name="Depletable"+thisProd.name;
      }
      else
      {
        np++;
        if (thisProd.stockable)
thisProd.name="Stockable"+thisProd.name;
        else thisProd.name="Non-stockable"+thisProd.name;      }
      addPR(thisProd);
    }

    for(x=0;x<vt;x++)
    {
      addTech(new Technology("Technology_"+new
Integer(x).toString(),ip.t,writeProdArray(),writeResArray()));
    }

    int y;
    for(x=0;x<vpc;x++)
    {
      y=new Float(Math.random()*tech.size()).intValue();
      addProc(new HMCProcess("Process_"+new
Integer(x).toString(),tim,getTech(y),ip.pc));
    }

  }


  //// main simulation methods ////

  //main simulation step
  void simStep()
  {
    if (ip.autogrow) cullDeadHMCProcesses();
    resetLoadFactors();
    resetIORates();
    calculateLoadFactors();
    applyLoadFactors();
```

```
    addNewTechs();
    if (ip.autogrow) addNewHMCProcesses();
    tim+=dt;
    setChanged();
    notifyObservers();
  }

  //removes any expired HMCProcesses:the loop is done back-to-front
because when
  //an element isremoved from a vector, all subsequent entries shifted
up one index
  //number; if vector were read from 0 up, the entry straight after a
deleted value
  //would escape for one time step from being checked
  void cullDeadHMCProcesses()
  {
    for(int x=proc.size()-1;x>=0;x--)
    {
      if (tim>getProc(x).birth+getProc(x).lt)
      {
        proc.removeElementAt(x);
      }
    }
  }

  //resets all load factors to unity for start of new simstep
  void resetLoadFactors()
  {
    for(int x=0;x<proc.size();x++)
    {
      getProc(x).lf=1;
    }
  }

  //resets all in & out rates to unity for start of new simstep
  //also calculates output rates of renewable resources, which aren't
  //affected by changes in LF
  void resetIORates()
  {
    for(int x=0;x<prod.size();x++)
    {
      getProd(x).inrate=0;
      getProd(x).outrate=0;
    }
    for(int x=0;x<res.size();x++)
    {
      if (getRes(x).renewable)
        getRes(x).inrate=getRes(x).stock*getRes(x).renewcoeff;
      else
        getRes(x).inrate=0;
      getRes(x).outrate=0;
    }
  }

  //iterates to find highest load factor values at which all
  //required products can be sourced
  //then reduces lf for activities which are otherwise over-producing
```

```
  void calculateLoadFactors()
  {
    boolean lfchange=true;
    boolean scarce=true;
    int[] taggedProc;  //lookup table listing processes by their
relationship to
               //scarce products
    int count=0;
    while (scarce)
    {
      //calc supply, demand and d/s ratio initially w. all lf=1
      calcSupplyAndDemandRates();
      //reduce lf if a process is over-producing
      checkForOverSupply();
      //tag all processes by relationship to scarce products
      taggedProc=tagProcsByScarcity();
      if (isScarcity())
      {
        //reduce lf incrementally by tagged process groups
        lfchange=reduceLoadFactors(taggedProc);
      }
      else
      {
        scarce=false;
      }
      count++;
      if (count>20)
      {
        break;
      }
    }
  }

  //determines overall projected supply and demand rates for every
  //product, for current load factors
  void calcSupplyAndDemandRates()
  {
    //resets all rates to base values first
    resetIORates();
    int x;
    int inpx;
    int oupx;
    HMCProcess p;
    Product pd;
    //iterate through each process
    for(x=0;x<proc.size();x++)
    {
      //identify this process by shorthand
      p=getProc(x);
      //check all inputs to process
      //note an INPUT is consumed, so contributes to OUTrate of stock
      for(inpx=0;inpx<p.inp.length;inpx++)
      {
        pd=getInput(p,inpx);
        if (pd!=null) pd.outrate+=p.siz*p.inc[inpx]*p.lf;
      }
      //check all inputs to process
```

```
      //note an OUTPUT is produced, so contributes to INrate of stock
      for(oupx=0;oupx<p.oup.length;oupx++)
      {
        pd=getOutput(p,oupx);
        if (pd!=null) pd.inrate+=p.siz*p.ouc[oupx]*p.lf;
      }
    }
    //iterate through every resource, determining scarcity
    for(x=0;x<res.size();x++)
    {
      pd=getRes(x);
      pd.scarce2=calcScarcity(pd.inrate+pd.stock,pd.outrate);
    }
    //iterate through every product, determining scarcity
    for(x=0;x<prod.size();x++)
    {
      pd=getProd(x);
      pd.scarce2=calcScarcity(pd.inrate+pd.stock,pd.outrate);
    }
  }

  //determines scarcity based on supply and demand
  //scarcity index between 1 and -1
  //negative if surplus
  //positive if shortage
  float calcScarcity(float sup, float dem)
  {
    if (sup<=0) return 1;          //firstly, note absolute scarcity
    else if (dem<=0) return -1;        //unused but available
    else if (sup>dem) return (dem/sup)-1;  //used and available
    else return 1-(sup/dem);         //used, and limited availability
  }

  //reduces lf of any process that is over-supplying
  void checkForOverSupply()
  {
    int x;
    int y;
    boolean changed;
    float minsurp; //value of minimum surplus of any output of this
process
    HMCProcess thisproc;
    Product thisprod;
    for(x=0;x<proc.size();x++)
    {
      changed=false;
      thisproc=getProc(x);
      minsurp=-1;
      for(y=0;y<thisproc.oup.length;y++)
      {
        thisprod=thisproc.oup[y];
        if (ip.autogrow)
        {
          if(!(thisprod.name.equalsIgnoreCase("HMC")))
          {
            if (thisprod.scarce2>minsurp)
            {
```

```
            minsurp=thisprod.scarce2;
            changed=true;
          }
        }
      }
    }
    if (changed && minsurp<0)
    {
      minsurp/=1.05;  //give a 5% safety margin before applying
      if (thisproc.lf>1+minsurp) thisproc.lf=1+minsurp;
    }
  }
}

//sorts processes into three categories
//index 0 = users only of scarce resources
//index 1 = users and producers of scarce resources
//index 2 = neither use nor produce
//index 3 = producers only of scarce resources
//index indicates decreasing preference for reduction of lf in
//order to reduce resource scarcity
int[] tagProcsByScarcity()
{
  HMCProcess p;
  boolean uses;
  boolean makes;
  int[] sproc=new int[proc.size()];
  int inpx;
  int oupx;
  for(int x=0;x<proc.size();x++)
  {
    //identify this process by shorthand
    p=getProc(x);
    uses=false;
    makes=false;
    //check all inputs to process
    for(inpx=0;inpx<p.inp.length;inpx++)
    {
      if (getInput(p,inpx)!=null)
        if (getInput(p,inpx).scarce2>0) uses=true;
    }
    //check all inputs to process
    for(oupx=0;oupx<p.oup.length;oupx++)
    {
      if (getOutput(p,oupx)!=null)
        if (getOutput(p,oupx).scarce2>0) makes=true;
    }
    //assign tag
    if (uses & !makes) sproc[x]=0;
    else if(uses & makes) sproc[x]=1;
    else if (!uses & !makes) sproc[x]=2;
    else if (!uses & makes) sproc[x]=3;
  }
  return sproc;
}
```

```
//returns true if any product or resource has a scarcity value
//greater than unity
boolean isScarcity()
{
  boolean s=false;
  //read in scarcity values to all products and resources
  for(int q=0;q<res.size();q++)
  {
    if (getRes(q).scarce2>0) s=true;
  }
  for(int r=0;r<prod.size();r++)
  {
    if (getProd(r).scarce2>0) s=true;
  }
  return s;
}

//reduces load factors in order starting with the processes putting
//heaviest demands on scarce resources
//attempts a reduction of lf first of only group[i] processes
//(as defined by tagged index sproc), then increases through
//indices as necessary up to [3]
//returns true if change has been made somewhere
boolean reduceLoadFactors(int[] sproc)
{
  boolean changed=false;
  if (reduceLoadFactorsOfTaggedGroup(sproc,0)) changed=true;
  if (reduceLoadFactorsOfTaggedGroup(sproc,1)) changed=true;
  if (reduceLoadFactorsOfTaggedGroup(sproc,2)) changed=true;
  if (reduceLoadFactorsOfTaggedGroup(sproc,3)) changed=true;
  return changed;
}


//reduces load factors of targetted groups of processes as indicated
//by sorted process array 'sproc'  tag values
//returns true if some changes have been made
//after reducing lf for a tagged group, all rates re-calculated,
//but tagging by scarcity not recomputed at this stage (this ensures
//that every process is checked out once)
boolean reduceLoadFactorsOfTaggedGroup(int[] sproc, int tag)
{
  boolean changed=false;
  boolean thischanged=false;  //true if lf of this process changed
  float maxscarce=0;
  HMCProcess p;
  int inpx;
  for(int x=0;x<proc.size();x++)
  {
    if(sproc[x]<=tag)
    {
      p=getProc(x);
      thischanged=false;
      //check all inputs to process
      maxscarce=0;
      for(inpx=0;inpx<p.getParent(this).inp.length;inpx++)
      {
```

```
        if (p.getInput(inpx).scarce2>maxscarce)
        {
          changed=true;
          thischanged=true;
          maxscarce=p.getInput(inpx).scarce2;
        }
      }
      if (thischanged)
      {
        if (maxscarce == 1) p.lf=0;     //no supply, so lf=0
        else if (p.lf>1-maxscarce)
          p.lf=1-maxscarce; //reduced supply, so lf decreases
      }
    }
  }
  return changed;
}

//applies calculated load factors by writing scarce2 to scarce for
//each product/resource, and updating stocks, rates, etc.
void applyLoadFactors()
{
  //a final run of rate calculations
  calcSupplyAndDemandRates();

  //iteration through res and prod updating scarcity record
  //and stock values
  int x;
  Product p;
  for (x=0;x<res.size();x++)
  {
    p=getRes(x);
    p.updateStock(p.inrate,p.outrate,dt);
    p.scarce=p.scarce2;
  }
  for (x=0;x<prod.size();x++)
  {
    p=getProd(x);
    p.updateStock(p.inrate,p.outrate,dt);
    p.scarce=p.scarce2;
  }
}


//invent any new technologies to be introduced
void addNewTechs()
{
  if (Math.random()<ip.t.probInvent)
  {
    String ns="Technology_"+new Integer(tech.size()).toString();
    tech.addElement(new
Technology(ip.t,writeTechArray(),writeProdArray(),writeResArray()));
  }
}

//uses all available HMC to create new HMCProcesses, favouring those
//generating scarce resources and dis-favouring those that use them
```

```
void addNewHMCProcesses()
{
  //method 3 involves random allocation of investment based on
  //investment weights

  int x;

  //assign weight to all HMCProcesses based on the scarcity of their
  //feedstocks and products
  assignInvWeights(ip.iwt);

  //add them all up, and keep a score of total so far at each
addition
  //weighting function biased against large procs to reflect
  //existing stock of HMC in system
  float cumivwt=0;
  float cumval[]=new float[tech.size()];
  for(x=0;x<tech.size();x++)
  {
    cumivwt+=getTech(x).investWeight;
    cumval[x]=cumivwt;
  }

  //stock of available HMC
  Product HMC=getProd(0);
  //availHMC+=((HMC.inrate-HMC.outrate)*dt);
  availHMC+=HMC.stock;
  boolean moreInvesting=true;
  if (availHMC<=0) return;

  //pick random tech and make a new one based on it
  float randinv;
  int thistech;
  Technology thisTech;
  HMCProcess newproc;
  while(moreInvesting)
  {
    randinv=(float)(Math.random()*cumivwt);
    thistech=0;
    for(x=0;x<tech.size();x++)
    {
      if (randinv>cumval[x]) thistech++;
    }
    thisTech=getTech(thistech);
    newproc=new HMCProcess("New_"+thisTech.name,tim,thisTech,ip.pc);
    if (availHMC>newproc.siz)
    {
      addProc(newproc);
      availHMC-=newproc.siz;
    }
    else
    {
      moreInvesting=false;
      HMC.stock=availHMC;
    }
  }
```

```
/*
//method 1 & 2 puts residual into industry
//method 1 treated HMC as non-stockable - at small timestep never
//accumulated enough to built a single unit IND, so no growth
//method 2 allowed stocking of HMC; led to wild exponential growth
//with no investments into other sectors -

int x;
int y;
int z;

Product thisProd;     //pointers to current product
int thisPindex;
Technology thisTech;  //pointers to current Tech
int thisTindex;
int thisOindex;       //pointer to current output of Tech
float maxInvWt;       //lowest investWeight chosen where competing
techs

float shortfall;     //shortfall in prod p req. investment
float ratePerProc;     //rate of supply per ave. process
int newprocs;        //no. new procs to meet shortfall
float reqHMC;        //HMC required to build newproc new procs

//determine available HMC
Product HMC=getProd(0);
float availHMC=HMC.stock+HMC.inrate-HMC.outrate;
if (availHMC<=0) return;

//assign weight to all HMCProcesses based on the scarcity of their
//feedstocks and products
assignInvWeights(iwt);

//boolean array indicating whether a product's investment needs met
yet
boolean[] done=new boolean[prod.size()];
float maxscarce;

//set up array; set done=false if resource is scarce
int ct=0;
for(x=1;x<prod.size();x++)
{
  if (getProd(x).scarce>0)
  {
    done[x]=false;
    ct++;
  }
  else done[x]=true;
}

//visit each prod in order of scarcity
maxscarce=0;
for(x=0;x<ct;x++)
{
  //find scarcest remaining product
  thisPindex=0;
  for(y=1;y<prod.size();y++)
```

```
    {
      if (getProd(y).scarce>maxscarce & !done[y])
      {
        maxscarce=getProd(y).scarce;
        thisPindex=y;
      }
    }
    done[thisPindex]=true;
    thisProd=getProd(thisPindex);

    //determine cheapest investment in it (highest maxInvWt)
    thisTech=null;
    thisOindex=-1;
    thisTindex=0;
    maxInvWt=0;
    for(y=0;y<tech.size();y++)
    {
      thisTech=getTech(y);
      for(z=0;z<thisTech.oup.length;z++)
      {
        if (thisTech.oup[z]==thisProd)
        {
          if (maxInvWt<thisTech.investWeight)
          {
            maxInvWt=thisTech.investWeight;
            thisTindex=y;
            thisOindex=z;
          }
        }
      }
    }
    if (thisOindex>=0) thisTech=getTech(thisTindex);

    //if a technology exists, invest in it
    if (thisTech!=null)
    {
      ratePerProc=thisTech.ouc[thisOindex]*thisTech.siz;
      shortfall=thisProd.outrate-thisProd.inrate;
      newprocs=(int)(shortfall/ratePerProc);
      for(z=0;z<newprocs;z++)
      {
        addProc(new HMCProcess(
          "New_"+thisTech.name,tim,thisTech,ip.pc));
      }
      availHMC-=thisTech.siz*newprocs;
      getProd(0).stock-=thisTech.siz*newprocs;
      if (availHMC<=0) return; //pull out if no HMC left
    }
  }
  //if any surplus HMC, put it in industry
  if (availHMC>0)
  {
    //select HMC
    thisProd=getProd(0);

    //determine cheapest investment in it (lowest minInvWt)
    thisTech=null;
```

```
      thisOindex=-1;
      thisTindex=0;
      maxInvWt=0;
      for(y=0;y<tech.size();y++)
      {
        thisTech=getTech(y);
        for(z=0;z<thisTech.oup.length;z++)
        {
          if (thisTech.oup[z]==thisProd)
          {
            if (maxInvWt<thisTech.investWeight)
            {
              maxInvWt=thisTech.investWeight;
              thisTindex=y;
              thisOindex=z;
            }
          }
        }
      }
      if (thisOindex>=0) thisTech=getTech(thisTindex);

      //if a technology exists, invest in it
      if (thisTech!=null)
      {
        ratePerProc=thisTech.ouc[thisOindex]*thisTech.siz;
        newprocs=(int)(availHMC/ratePerProc);
        for(z=0;z<newprocs;z++)
        {
          addProc(new HMCProcess(
            "New_"+thisTech.name,tim,thisTech,ip.pc));
        }
      }
    }
    */
  }


  //assigns investment desirability weights to all Technology types
  //scarcity of input decreases weight; scarcity of output increases
it, both taking
  //capital intensity of production into account (i.e. inc[] and ouc[]
terms)
  //the parameter i is the initial value of the weight to which the
  //weighting scheme is added - a large value minimises diversity,
whereas
  //a high value maximises it (and therefore weights have more
importance
  //in determining investment allocation)
  void assignInvWeights(float i)
  {
    Technology thisTech;
    Product thisProd;
    for(int x=0;x<tech.size();x++)
    {
      thisTech=getTech(x);
      thisTech.investWeight=i;
      for(int p=0;p<thisTech.inp.length;p++)
```

```
      {
        //read scarcity of each input and adjust invWt by capital
productivity for that input
        //no reward for use of resource, but penalty if scarce
        thisProd=thisTech.inp[p];
        if (!thisProd.resource) thisTech.investWeight-=thisProd.scarce;
        else if (thisProd.scarce>0) thisTech.investWeight-
=thisProd.scarce;
      }
      for(int q=0;q<thisTech.oup.length;q++)
      {
        //read scarcity of each output and adjust invWt
        thisProd=thisTech.oup[q];
        thisTech.investWeight+=thisProd.scarce;
      }
      if (thisTech.investWeight<0) thisTech.investWeight=0;
    }
  }


  //// helper methods and sundries ////

  //adds a Technology object to tech vector
  void addTech(Technology t)
  {
    tech.addElement((Object)t);
  }

  //adds a HMCProcess object to proc vector
  void addProc(HMCProcess p)
  {
    proc.addElement((Object)p);
  }

  //adds a Prod/Resource object to tech vector
  void addPR(Product pr)
  {
    if (pr.resource)
    {
      res.addElement((Object)pr);
    }
    else
    {
      prod.addElement((Object)pr);
    }
  }

  //helper methods to access storage Vectors
  Technology getTech(int i)
  {
    if (i>=0 & i <tech.size())
    {
      Object o=tech.elementAt(i);
      if (o instanceof Technology)
      {
        return (Technology)o;
      }
```

```
    else return null;
  }
  else return null;
}

//helper methods to access storage Vectors
HMCProcess getProc(int i)
{
  if (i>=0 & i <proc.size())
  {
    Object o=proc.elementAt(i);
    if (o instanceof HMCProcess)
    {
      return (HMCProcess)o;
    }
    else return null;
  }
  else return null;
}

//helper methods to access storage Vectors
Product getProd(int i)
{
  if (i>=0 & i <prod.size())
  {
    Object o=prod.elementAt(i);
    if (o instanceof Product)
    {
      return (Product)o;
    }
    else return null;
  }
  else return null;
}

//helper methods to access storage Vectors
Product getRes(int i)
{
  if (i>=0 & i <res.size())
  {
    Object o=res.elementAt(i);
    if (o instanceof Product)
    {
      return (Product)o;
    }
    else return null;
  }
  else return null;
}

//writes Tech vector to an array of Techs
Technology[] writeTechArray()
{
  Object[] o=new Object[tech.size()];
  tech.copyInto(o);
  Technology[] t=new Technology[tech.size()];
  for(int x=0;x<t.length;x++)
```

```
  {
    if (o[x] instanceof Technology) t[x]=(Technology)o[x];
  }
  return t;
}

//writes Proc vector to an array of Procs
HMCProcess[] writeProcArray()
{
  Object[] o=new Object[proc.size()];
  proc.copyInto(o);
  HMCProcess[] p=new HMCProcess[proc.size()];
  for(int x=0;x<p.length;x++)
  {
    if (o[x] instanceof HMCProcess) p[x]=(HMCProcess)o[x];
  }
  return p;
}

//writes Prod vector to an array of Prods
Product[] writeProdArray()
{
  Object[] o=new Object[prod.size()];
  prod.copyInto(o);
  Product[] p=new Product[prod.size()];
  for(int x=0;x<p.length;x++)
  {
    if (o[x] instanceof Product) p[x]=(Product)o[x];
  }
  return p;
}

//writes Res vector to an array of Prods
Product[] writeResArray()
{
  Object[] o=new Object[res.size()];
  res.copyInto(o);
  Product[] p=new Product[res.size()];
  for(int x=0;x<p.length;x++)
  {
    if (o[x] instanceof Product) p[x]=(Product)o[x];
  }
  return p;
}


//conversion methods between separate Res and Prod vectors in which
//permanent references stored, and temporary arrays in which res and
//prods are lumped together
int PRToRes(int i)
{
  if (i>0 & i<res.size()) return i;
  else return -1;
}

int PRToProd(int i)
{
```

```
  if (i>=res.size() & i <res.size()+prod.size())
    return i-res.size();
  else return -1;
}

int ResToPR(int i)
{
  if (i>0 & i<res.size()) return i;
  else return -1;
}

int ProdToPR(int i)
{
  if (i>0 & i<prod.size()) return i+res.size();
  else return -1;
}

//helper methods for accessing technologies' inputs
Product getInput(Technology t, int i)
{
  return t.getInput(i);
}

//helper methods for accessing technologies' outputs
Product getOutput(Technology t, int i)
{
  return t.getOutput(i);
}

//helper methods for accessing processes' inputs
Product getInput(HMCProcess p, int i)
{
  return p.getInput(i);
}

//helper methods for accessing processes' outputs
Product getOutput(HMCProcess p, int i)
{
  return p.getOutput(i);
}

//helper method to initially alert display devices
//does some basic calculations beforehand
void initNotifyObservers()
{
  resetLoadFactors();
  resetIORates();
  calcSupplyAndDemandRates();

  setChanged();
  notifyObservers();
}

//helper method to tell observers that simulation is finished
void notifyObserversToStop()
{
  setChanged();
```

```
    notifyObservers("stop");
  }

}
```

ClusterAnalyser.java

```
package ipso;

//
//
// ClusterAnalyser performs static network analyses
//
//
class ClusterAnalyser
{
  IPSOModel ip;

  //array of users and makers of each product
  //third array is union of two others
  boolean[] hasUsers;
  boolean[] hasMakers;
  boolean[][] users;
  boolean[][] makers;

  //arrays for storing clustering data
  int[] proccl;
  int[] prodcl;
  int[] procsz;
  int[] prodsz;

  //constructor automatically assigns model and analyses it for product
  //and process clusters
  ClusterAnalyser(IPSOModel i)
  {
    assignModel(i);
    analyse();
  }


  void assignModel(IPSOModel i)
  {
    ip=i;
  }

  //fills default data arrays when first used
  void fillUsersMakers()
  {
    int npr=ip.res.size()+ip.prod.size();
    hasUsers=new boolean[npr];
    hasMakers=new boolean[npr];
    users=new boolean[npr][ip.proc.size()];
    makers=new boolean[npr][ip.proc.size()];
    int n;
    int index;
    HMCProcess p;
    Product pr;
    for(int x=0;x<ip.proc.size();x++)
```

```
  {
    p=ip.getProc(x);
    for(n=0;n<p.inp.length;n++)
    {
      pr=p.inp[n];
      if (pr.resource)
      {
        index=ip.res.indexOf(pr);
        if (index>=0 & index <ip.res.size())
        {
          hasUsers[index]=true;
          users[index][x]=true;
        }
      }
      else
      {
        index=ip.prod.indexOf(pr);
        if (index>=0 & index <ip.prod.size())
        {
          hasUsers[index+ip.res.size()]=true;
          users[index+ip.res.size()][x]=true;
        }
      }
    }
    for(n=0;n<p.oup.length;n++)
    {
      pr=p.oup[n];
      index=ip.prod.indexOf(pr);
      if (index>=0 & index <ip.prod.size())
      {
        hasMakers[index+ip.res.size()]=true;
        makers[index+ip.res.size()][x]=true;
      }
    }
  }
}

//generic analysis 'batch instruction' method
synchronized void analyse()
{
  fillUsersMakers();
  proccl=findProcClusters();
  prodcl=findProdClusters();
  procsz=analyseClusters(proccl);
  prodsz=analyseClusters(prodcl);
}

//determines process clustering pattern
//returns array of integers clusterID, with dimensions proc.size()
int[] findProcClusters()
{
  int nclusters=0;
  //clusterID contains cluster no. to which this process belongs
  int[] clusterID=new int[ip.proc.size()];
  //look up all processes to see if assigned to a cluster yet
  //if not, create a new one
  int thisCluster;
```

```
    int y;
    int z;
    for(int x=0;x<ip.proc.size();x++)
    {
      if (clusterID[x]==0)
      {
        //if not yet assigned, start new cluster
        nclusters++;
        thisCluster=nclusters;
        clusterID[x]=thisCluster;
      }
      else
      {
        //otherwise append to existing cluster
        thisCluster=clusterID[x];
      }
      //assign same ID to all users in same row
      for(y=0;y<ip.res.size()+ip.prod.size();y++)
      {
        if (users[y][x])
        {
          //if true, add all entries in same column to this cluster
          for(z=0;z<ip.proc.size();z++)
          {
            if (users[y][z]) clusterID[z]=thisCluster;
            if (makers[y][z]) clusterID[z]=thisCluster;
          }
        }
        if (makers[y][x])
        {
          //if true, add all entries in same column to this cluster
          for(z=0;z<ip.proc.size();z++)
          {
            if (users[y][z]) clusterID[z]=thisCluster;
            if (makers[y][z] & hasUsers[y]) clusterID[z]=thisCluster;
            //nb extra condition above: don't treat two procs as same
cluster
            //if they simply produce same waste!
          }
        }
      }
    }
    return clusterID;
  }

  //determines product clustering pattern
  //returns array of integers clusterID, with dimensions
res.size()+prod.size()
  int[] findProdClusters()
  {
    int nclusters=0;
    int npr=ip.res.size()+ip.prod.size();
    //clusterID contains cluster no. to which this process belongs
    int[] clusterID=new int[npr];
    //look up all processes to see if assigned to a cluster yet
    //if not, create a new one
    int thisCluster;
```

```
int x;
int y;
int z;
for(x=0;x<npr;x++)
{
  if (clusterID[x]==0)
  {
    //if not yet assigned, start new cluster
    nclusters++;
    thisCluster=nclusters;
    clusterID[x]=thisCluster;
  }
  else
  {
    //otherwise append to existing cluster
    thisCluster=clusterID[x];
  }
  //assign same ID to all users & makers in same column
  for(y=0;y<ip.proc.size();y++)
  {
    if (users[x][y])
    {
      //if true, add all entries in same row to this cluster
      for(z=0;z<npr;z++)
      {
        if (users[z][y]) clusterID[z]=thisCluster;
        if (makers[z][y]) clusterID[z]=thisCluster;
      }
    }
    if (makers[x][y])
    {
      //if true, add all entries in same column to this cluster
      for(z=0;z<npr;z++)
      {
        if (users[z][y]) clusterID[z]=thisCluster;
        if (makers[z][y] & hasUsers[z]) clusterID[z]=thisCluster;
        //nb extra condition above: don't treat two procs as same
cluster
        //if they simply produce same waste!
      }
    }
  }
}
//clean up operation to remove any zero-sized clusters
//created by renaming an entire subcluster later on
int highest=1;
for(x=0;x<clusterID.length;x++)
{
  if (clusterID[x]>highest) highest=clusterID[x];
}
boolean[] hasMembers=new boolean[highest];
for(x=0;x<clusterID.length;x++)
{
  hasMembers[clusterID[x]-1]=true;
}
int replacements=0;
for(x=0;x<hasMembers.length;x++)
```

```
    {
      if (!hasMembers[x])
      {
        for(y=0;y<clusterID.length;y++)
        {
          if (clusterID[y]==highest-replacements) clusterID[y]=x+1;
        }
        replacements++;
      }
    }
    return clusterID;
  }

  //analyses clusterID array to return number and sizes of clusters as
  //a second array
  int[] analyseClusters(int[] clusterID)
  {
    //find number of clusters
    int nclusters=1;
    int x;
    for(x=0;x<clusterID.length;x++)
    {
      if (clusterID[x]>nclusters) nclusters=clusterID[x];
    }
    //int array for sizes
    int[] sizes=new int[nclusters];
    for(x=0;x<clusterID.length;x++)
    {
      sizes[clusterID[x]-1]++;
    }
    return sizes;
  }

  //procString returns string representation of cluster analysis
  //format is comma separated: no. clusters followed by sizes
  String intToString(int[] i)
  {
    String s=new Integer(i.length).toString();
    for(int x=0;x<i.length;x++)
    {
      s=s+","+new Integer(i[x]).toString();
    }
    return s;
  }


}
```

HMCProcess.java

```
package ipso;

//
//
// HMCProcess
//
```

```
//
class HMCProcess
{
  String name;//text name for displaying
  Technology parent;  //parent Technology
  String pname;    //copy of parent's name field
  float lt;  //lifetime
  float birth;//birth time
  float siz;  //size
  float lf;  //load factor final value passed to display graphs etc.
  Product[] inp;  //array of inputs
  Product[] oup;  //array of outputs
  String[] iname;  //copy of input name fields
  String[] oname;  //copy of output name fields
  float[] inc;//array of input coefficients
  float[] ouc;//array of output coefficients

  //default constructor passing required parameters
  HMCProcess(String n, float tim, Technology t, ProcParameterSet p)
  {
    name=n;
    parent=t;
    pname=t.name;
    lt=t.lt*p.varlt.pickVal();
    birth=tim;
    siz=t.siz*p.varsiz.pickVal();
    inp=new Product[t.inp.length];
    oup=new Product[t.oup.length];
    iname=new String[t.inp.length];
    oname=new String[t.oup.length];
    inc=new float[t.inc.length];
    ouc=new float[t.ouc.length];

    for (int x=0;x<t.inp.length;x++)
    {
      inp[x]=t.inp[x];
      iname[x]=inp[x].name;
      inc[x]=t.inc[x]*p.varcoeff.pickVal();
    }

    for (int y=0;y<t.oup.length;y++)
    {
      oup[y]=t.oup[y];
      oname[y]=oup[y].name;
      ouc[y]=t.ouc[y]*p.varcoeff.pickVal();
    }
  }

  //alternative constructor filling in from scratch
  HMCProcess(String n, Technology par, float l, float tim, float s,
Product ip[], Product op[], float[]ic, float[]oc)
  {
    name=n;
    parent=par;
    pname=par.name;
    lt=l;
    birth=tim;
```

```
    siz=s;

    int ni;
    if (ip.length>ic.length) ni=ic.length; else ni=ip.length;
    inp=new Product[ni];
    iname=new String[ni];
    inc=new float[ni];
    for (int x=0;x<ni;x++)
    {
      inp[x]=ip[x];
      iname[x]=inp[x].name;
      inc[x]=ic[x];
    }

    int no;
    if (op.length>oc.length) no=oc.length; else no=op.length;
    oup=new Product[no];
    oname=new String[no];
    ouc=new float[no];
    for (int y=0;y<no;y++)
    {
      oup[y]=op[y];
      oname[y]=oup[y].name;
      ouc[y]=oc[y];
    }

  }

  //helper methods

  //returns parent for given IPSOModel storage scheme
  Technology getParent(IPSOModel m)
  {
    return parent;
  }

  //returns given Input product type
  Product getInput(int i)
  {
    return inp[i];
  }

  //returns given Output product type
  Product getOutput(int i)
  {
    return oup[i];
  }
}
```

IntParamRange.java

```
package ipso;

//
//
// IntParamRange
//
```

```
//
class IntParamRange
{
  int hival;  //upper value
  int loval;  //lower value

  //default constructor
  IntParamRange(int h, int l)
  {
    hival=h;
    loval=l;
  }

  //picks a radom number in range
  int pickVal()
  {
    return new Float(loval+Math.random()*(hival-loval)).intValue();
  }


}
```

IPSOParameterSet.java

```
package ipso;

//
//
// IPSOParameterSet
//
//
class IPSOParameterSet
{
  boolean autogrow;  //if true, will automatically add new processes
using
            //prod[0] as HMC i.e. substance of which processes are made
            //if false, simply analyses existing processes network
  float iwt;      //additional term to investment weighting for
autogrow models
            //larger values result in more random allocation of HMC

  TechParameterSet t;  //details of allowed range for Technology
objects
  ProcParameterSet pc;//details of allowed range for HMCProcess objects
  PresParameterSet pr;//details of allowed range for Product objects

  //default constructor
  IPSOParameterSet(boolean grow, float i, TechParameterSet tt,
ProcParameterSet ppc, PresParameterSet ppr)
  {
    autogrow=grow;
    iwt=i;
    t=tt;
    pc=ppc;
    pr=ppr;
  }
```

```
}
```

ModelInitialiser.java

```
package ipso;

import java.awt.*;
import java.io.*;
import java.util.*;
import java.applet.*;

//
//
// ModelInitialiser: creates a parameter set and initialises a network
// from it
// allows iteration through 8 variables;
// max. no. inputs & outputs,
// no. techs, processes and products
// prob of product being resource, renwable & stockable
//
class ModelInitialiser extends Frame implements Runnable
{
  //variation parameters
  int ni_lo;
  int ni_hi;
  int ni_s;

  int no_lo;
  int no_hi;
  int no_s;

  int nt_lo;
  int nt_hi;
  int nt_s;

  int npr_lo;
  int npr_hi;
  int npr_s;

  int npd_lo;
  int npd_hi;
  int npd_s;

  float prs_lo;
  float prs_hi;
  float prs_s;

  float prn_lo;
  float prn_hi;
  float prn_s;

  float prstk_lo;
  float prstk_hi;
  float prstk_s;

  int nruns;
```

```
String fnam;

//counters for running through variations
int ct;
int nv;
Label vc;

//thread for running variations
Thread modelrunner;


//initialises with all ranges
ModelInitialiser(int ninp1, int ninp2, int ninpstep,
               int noup1, int noup2, int noupstep,
         int nt1, int nt2, int ntstep,
         int npr1, int npr2, int nprstep,
         int npd1, int npd2, int npdstep,
         float prs1, float prs2, float prss,
         float prn1, float prn2, float prns,
         float prstk1, float prstk2, float prstks,
         int n)
{
  setParameters(ninp1,ninp2,ninpstep,
              noup1,noup2,noupstep,
          nt1,nt2,ntstep,
          npr1,npr2,nprstep,
          npd1,npd2,npdstep,
          prs1,prs2,prss,
          prn1,prn2,prns,
          prstk1,prstk2,prstks);
  nruns=n;
  calcNumVariations();
}

//application version
public static void main(String args[])
{
  ModelInitialiser mi=new ModelInitialiser(2,6,1,
                                        2,6,1,
                      2,42,10,
                      10,100,10,
                      10,100,10,
                      0,1,(float)0.25,
                      0,0,1,
                      0,0,1,
                      1);
  mi.setTitle("IPSO Parameter Variation");
  mi.setLayout(new BorderLayout());
  mi.add("Center",new ModelInitialiserInputPanel(mi));
  mi.vc=new Label("");
  mi.add("South",mi.vc);
  mi.resize(500,360);
  mi.show();
}


//sets parameters
```

```
void setParameters(int ninp1, int ninp2, int ninpstep,
               int noup1, int noup2, int noupstep,
         int nt1, int nt2, int ntstep,
         int npr1, int npr2, int nprstep,
         int npd1, int npd2, int npdstep,
         float prs1, float prs2, float prss,
         float prn1, float prn2, float prns,
         float prstk1, float prstk2, float prstks)
{
  ni_lo=ninp1;
  ni_hi=ninp2;
  ni_s=ninpstep;

  no_lo=noup1;
  no_hi=noup2;
  no_s=noupstep;

  nt_lo=nt1;
  nt_hi=nt2;
  nt_s=ntstep;

  npr_lo=npr1;
  npr_hi=npr2;
  npr_s=nprstep;

  npd_lo=npd1;
  npd_hi=npd2;
  npd_s=npdstep;

  prs_lo=prs1;
  prs_hi=prs2;
  prs_s=prss;

  prn_lo=prn1;
  prn_hi=prn2;
  prn_s=prns;

  prstk_lo=prstk1;
  prstk_hi=prstk2;
  prstk_s=prstks;
}

//determine no. variations
void calcNumVariations()
{
  int n1=1+(ni_hi-ni_lo)/ni_s;
  int n2=1+(no_hi-no_lo)/no_s;
  int n3=1+(nt_hi-nt_lo)/nt_s;
  int n4=1+(npr_hi-npr_lo)/npr_s;
  int n5=1+(npd_hi-npd_lo)/npd_s;
  int n6=1+new Float((prs_hi-prs_lo)/prs_s).intValue();
  int n7=1+new Float((prn_hi-prn_lo)/prn_s).intValue();
  int n8=1+new Float((prstk_hi-prstk_lo)/prstk_s).intValue();
  nv=n1*n2*n3*n4*n5*n6*n7*n8*nruns;

  ct=1;
}
```

```
  IPSOParameterSet makeParameterSet(int ni,int no,
                    float prs, float prn, float prstk)
  {
    //technology w. default lt (irrelevant for statics anyway)
    //standard size 1.0, and I/O coeffs of 1
    ParamRange l=new ParamRange(15,40);
    ParamRange s=new ParamRange(1,1);
    IntParamRange nip=new IntParamRange(1,ni);
    IntParamRange nop=new IntParamRange(1,no);

    TechParameterSet tps=new TechParameterSet(0,l,s,s,s,nip,nop);

    //process allowing no variation here
    ProcParameterSet pps=new ProcParameterSet(s,s,s);

    //products allow input on probres, probren, probstk: other
    //factors irrelevant to static analysis anyway
    ParamRange stk=new ParamRange(100,1000);
    ParamRange rc=new ParamRange(0.01,0.05);
    PresParameterSet pprs=new
PresParameterSet(prs,prn,prstk,stk,stk,stk,rc);

    return new IPSOParameterSet(false,1,tps,pps,pprs);
  }

  //creates number of models and analyses them, throwing results
  //into files
  public void run()
  {
    //local variables
    IPSOParameterSet ip;
    IPSOModel m;
    ClusterAnalyser ca;
    String spr;
    String spd;

    //two output streams for 'compact' data
    File cf_pr;
    File cf_pd;
    FileOutputStream cfos_pr;
    FileOutputStream cfos_pd;
    PrintStream cps_pr;
    PrintStream cps_pd;

    //two output streams for 'verbose data'
    File f_pr;
    File f_pd;
    FileOutputStream fos_pr;
    FileOutputStream fos_pd;
    PrintStream ps_pr;
    PrintStream ps_pd;

    //initialises output streams
    try
    {
      //verbose output streams
      spr=fnam+"_verbose_process.txt";
```

```
        spd=fnam+"_verbose_product.txt";
        f_pr=new File(spr);
        f_pd=new File(spd);
        fos_pr=new FileOutputStream(f_pr);
        fos_pd=new FileOutputStream(f_pd);
        ps_pr=new PrintStream(fos_pr);
        ps_pd=new PrintStream(fos_pd);

        //writes file headers and puts in files

spr="no.inputs,no.outputs,no.techs,no.procs,no.prods,prob_res,prob_ren,
prob_stk,runID,"
          +"no.clusters,cluster sizes...";
        spd=spr;
        ps_pr.println(spr);
        ps_pd.println(spd);

        //compact output streams
        spr=fnam+"_compact_process.txt";
        spd=fnam+"_compact_product.txt";
        cf_pr=new File(spr);
        cf_pd=new File(spd);
        cfos_pr=new FileOutputStream(cf_pr);
        cfos_pd=new FileOutputStream(cf_pd);
        cps_pr=new PrintStream(cfos_pr);
        cps_pd=new PrintStream(cfos_pd);

        //writes file headers and puts in files

spr="no.inputs,no.outputs,no.techs,no.procs,no.prods,prob_res,prob_ren,
prob_stk,no.runs,"
          +"ave.no.clusters,min cluster size,max cluster size";
        spd=spr;
        cps_pr.println(spr);
        cps_pd.println(spd);

        float avprcl;
        int minprcl;
        int maxprcl;
        float avpdcl;
        int minpdcl;
        int maxpdcl;
        int[] prcl;
        int[] pdcl;

        int x;

        for(int a=ni_lo;a<=ni_hi;a+=ni_s)
        {
          for(int b=no_lo;b<=no_hi;b+=no_s)
          {
            for(int c=nt_lo;c<=nt_hi;c+=nt_s)
            {
              for(int d=npr_lo;d<=npr_hi;d+=npr_s)
              {
                for(int e=npd_lo;e<=npd_hi;e+=npd_s)
                {
```

```
                for(float f=prs_lo;f<=prs_hi;f+=prs_s)
                {
                  for(float g=prn_lo; g<=prn_hi;g+=prn_s)
                  {
                    for(float h=prstk_lo;h<=prstk_hi;h+=prstk_s)
                    {
                      avprcl=0;
                      minprcl=npr_hi;
                      maxprcl=1;
                      avpdcl=0;
                      minpdcl=npd_hi;
                      maxpdcl=1;
                      for(int i=0;i<nruns;i++)
                      {
                        //makes model and it's clusteranalyser
                        ip=makeParameterSet(a,b,f,g,h);
                        m=new IPSOModel(ip,c,d,e,0,1);
                        ca=new ClusterAnalyser(m);
                        prcl=ca.analyseClusters(ca.findProcClusters());
                        pdcl=ca.analyseClusters(ca.findProdClusters());
                        //writes verbose results as strings

spr=makeVarID(a,b,c,d,e,f,g,h,i)+","+ca.intToString(prcl);

spd=makeVarID(a,b,c,d,e,f,g,h,i)+","+ca.intToString(pdcl);
                        //sends strings to output files
                        ps_pr.println(spr);
                        ps_pd.println(spd);

                        //calculates compact results
                        avprcl+=prcl.length;
                        avpdcl+=pdcl.length;
                        for(x=0;x<prcl.length;x++)
                        {
                          if (prcl[x]>maxprcl) maxprcl=prcl[x];
                          if (prcl[x]<minprcl) minprcl=prcl[x];
                        }
                        for(x=0;x<pdcl.length;x++)
                        {
                          if (pdcl[x]>maxpdcl) maxpdcl=pdcl[x];
                          if (pdcl[x]<minpdcl) minpdcl=pdcl[x];
                        }

                        ct++;
                        repaint(100);
                      }
                      avprcl=avprcl/nruns;
                      avpdcl=avpdcl/nruns;
                      spr=makeVarID(a,b,c,d,e,f,g,h,nruns)+","
                        +new Float(avprcl).toString()+","
                        +new Integer(minprcl).toString()+","
                        +new Integer(maxprcl).toString();
                      cps_pr.println(spr);
                      spd=makeVarID(a,b,c,d,e,f,g,h,nruns)+","
                        +new Float(avpdcl).toString()+","
                        +new Integer(minpdcl).toString()+","
                        +new Integer(maxpdcl).toString();
```

```
                    cps_pd.println(spr);
                  }
                }
              }
            }
          }
        }
      }
    }
    ps_pr.close();
    ps_pd.close();
    fos_pr.close();
    fos_pd.close();
    cps_pr.close();
    cps_pd.close();
    cfos_pr.close();
    cfos_pd.close();
  }
  catch (IOException e)
  {
    return;
  }


}

//returns a string identifying this ID
String makeVarID(int a, int b, int c, int d, int e,
         float f, float g, float h, int i)
{
  return new Integer(a).toString() + ","
      +new Integer(b).toString() + ","
      +new Integer(c).toString() + ","
      +new Integer(d).toString() + ","
      +new Integer(e).toString() + ","
      +new Float(f).toString() + ","
      +new Float(g).toString() + ","
      +new Float(h).toString() + ","
      +new Integer(i).toString();
}

//// AWT Interface drawing message
public void update(Graphics g)
{
  String message;
  if (modelrunner!=null)
  {
    if (modelrunner.isAlive())
    {
      message="Calculating "
             +new Integer(ct).toString()
          +" out of "
          +new Integer(nv).toString()
          +" variations";
    }
    else
    {
```

```
        message="finished!";
      }
    }
    else
    {
      message="Not started yet!";
    }
    vc.setText(message);
  }

    //// Event Handling Routines
    public boolean handleEvent(Event e)
    {
      if (e.id == Event.WINDOW_DESTROY)
      {
          dispose();
          return true;
      }
      else
          return super.handleEvent(e);
    }


}
```

ModelRunner.java

```
package ipso;

import java.awt.*;
import java.io.*;
import java.util.*;
import java.applet.*;

//
//
// ModelRunner: creates a parameter set and simulates a network
// from it
// allows iteration through following variables;
// investment weight additional component (determines randomness
// of investment allocation)
class ModelRunner extends Frame implements Runnable
{
  //variation parameters
  float inv_lo;
  float inv_hi;
  float inv_s;

  int nruns;

  IPSOModel im;
  ParameterReader pr;//for building model from inputs

  String fnam;  //for naming output files

  //counters for running through variations
  int ct;
```

```
int nv;
Label vc;

//thread for running variations
Thread modelrunner;

//initialises with all ranges
ModelRunner(String paramf,
         float inv1, float inv2, float invs,
         int n)
{
  pr=new ParameterReader(this,true,paramf);
  setParameters(inv1,inv2,invs);
  nruns=n;
  calcNumVariations();
}

//application version
public static void main(String args[])
{
  ModelRunner mi=new ModelRunner(args[0],1,1,1,1);
  mi.setTitle("IPSO Parameter Variation");
  mi.setLayout(new BorderLayout());
  mi.add("Center",new ModelRunnerInputPanel(mi));
  mi.vc=new Label("");
  mi.add("South",mi.vc);
  mi.resize(500,360);
  mi.show();
}


//sets parameters
void setParameters(float inv1, float inv2, float invs)
{
  inv_lo=inv1;
  inv_hi=inv2;
  inv_s=invs;
}

//determine no. variations
void calcNumVariations()
{
  int n1=1+new Float((inv_hi-inv_lo)/inv_s).intValue();
  nv=n1*nruns;
  ct=1;
}

//initialises output stream using filename string
Printstream initialiseOutputStream(String filename)
{
  try
  {
    f=new File(filename);
    fos=new FileOutputStream(f);
    ps=new PrintStream(fos);
    return ps;
  }
```

```
  catch (IOException e)
  {
    return null;
  }
}


//creates number of models and analyses them, throwing results
//into files
public void run()
{
  //open output files
  PrintStream nproc_ps=initialiseOutputStream("var_nprocs.txt");
  PrintStream lf_ps=initialiseOutputStream("var_nprocs.txt");

  //write file headers

  for(float a=inv_lo;a<=inv_hi;a+=inv_s)
  {
    for(int b=0;b<nruns;b++)
    {
      //makes model and it's clusteranalyser
      im=pr.readModel();
      im.ip.iwt=a;
      //simulate model

      //write data

      ct++;
      repaint(100);
    }
  }
}

//returns a string identifying this ID
String makeVarID(float a, int b)
{
  return new Float(a).toString() + ","
      +new Integer(b).toString();
}

//// AWT Interface drawing message
public void update(Graphics g)
{
  String message;
  if (modelrunner!=null)
  {
    if (modelrunner.isAlive())
    {
      message="Calculating "
             +new Integer(ct).toString()
          +" out of "
          +new Integer(nv).toString()
          +" variations"
          +" time="
          +new Float(im.tim).toString();
    }
```

```
        else
        {
          message="finished!";
        }
      }
      else
      {
        message="Not started yet!";
      }
      vc.setText(message);
    }

      //// Event Handling Routines
      public boolean handleEvent(Event e)
      {
        if (e.id == Event.WINDOW_DESTROY)
        {
            dispose();
            return true;
        }
        else
            return super.handleEvent(e);
      }


}
```

ParameterReader.java

```
package ipso;

import java.util.*;
import java.awt.*;
import java.applet.*;
import java.io.*;

//
// ParameterReader reads parameters for IPSOModel from a file
// and builds a model from them
//

class ParameterReader
{
  boolean StandAlone;  //denotes whether app or applet doing the
calling,
            //(this determines how to retrieve parameters)
  Component parent;  //the AWT component for which the reader operates
  Applet parentApplet;//specific pointer used to applet parents

  String ParamFile;   //denoting name of parameter html file for
standalone
  Vector ParamName;
  Vector ParamValue;

  //default parameter values
  float probinvent=0;
  ParamRange techlt=new ParamRange(15,40);
```

```
ParamRange techsiz=new ParamRange(1,5);
ParamRange techinc=new ParamRange(0.2,2);
ParamRange techouc=new ParamRange(0.2,2);
IntParamRange techinp=new IntParamRange(1,3);
IntParamRange techoup=new IntParamRange(1,3);
ParamRange procvarlt=new ParamRange(1,1);
ParamRange procvarsiz=new ParamRange(1,1);
ParamRange procvarc=new ParamRange(1,1);
float probres=new Float(0.05).floatValue();
float probren=new Float(0.25).floatValue();
float probstk=new Float(0.25).floatValue();
ParamRange resstk=new ParamRange(10,100);
ParamRange renstk=new ParamRange(10,100);
ParamRange prodstk=new ParamRange(10,100);
ParamRange resrenc=new ParamRange(0.01,0.04);
int ntech=10;    //no. technologies at start
int nproc=100;    //no. HMCProcesses
int nprod=20;    //no. products
boolean grow=false;
float iwt=1;
float t=0;
float dt=1;

boolean techRead=false;
boolean procRead=false;
boolean prodRead=false;
Technology[] techArray;
Product[] prodArray;
HMCProcess[] procArray;

//constructor specifies whether an app or an applet
//calling it, gives ref to 'parent' AWT component
//and filename of html parameters (only needed by app)
ParameterReader(Component c, boolean stand, String s)
{
  parent=c;
  if (!stand && c instanceof Applet)
  {
    StandAlone=false;
    parentApplet=(Applet)c;
  }
  else
  {
    StandAlone=true;
  }
  if (StandAlone)
  {
    ParamFile=s;
    openParamFile();
  }
}

//opens the HTML file for reading, and sets up look-up table
void openParamFile()
{
  try
  {
```

```
      ParamName=new Vector();
      ParamValue=new Vector();
      int nextbyte;
      //opens file and reads input through a tokenizer
      FileInputStream fis=new FileInputStream(ParamFile);
      StreamTokenizer st=new StreamTokenizer(fis);
      //configure the streamtokenizer
      st.eolIsSignificant(true);  //end of line character treated as a
token
      st.wordChars('_','_');    //alphanumerics and '_' treated as
parts of words
      st.wordChars('A','Z');
      st.wordChars('a','z');
      st.parseNumbers();      //treat decimal points etc. as whole
numbers
      st.whitespaceChars('<','>');//html tag delimiters treated as
whitespace
      boolean EndOfFile=false;
      boolean EndOfLine=false;
      int next;
      while(!EndOfFile)
      {
        EndOfLine=false;
        next=st.nextToken();
        if (next==StreamTokenizer.TT_WORD)
        {
          if (st.sval.equalsIgnoreCase("param"))
          {
            //reads in the "name=xxx" tokens
            next=st.nextToken();    //reads 'name'
            if (st.sval.equals("name"))
            {
              next=st.nextToken();  //reads the required name
              ParamName.addElement(st.sval);
            }
            //reads in the "value=xxx" tokens
            next=st.nextToken();    //reads 'value'
            if (st.sval.equals("value"))
            {
              next=st.nextToken();  //reads req. value
              //value may be read by streamtokenizer as a number or
              //a word - checks for both
              ParamValue.addElement(st.sval);
            }
          }
        }
        //runs on to end of line
        while (!EndOfLine)
        {
          next=st.nextToken();
          if (next==StreamTokenizer.TT_EOL) EndOfLine=true;
          if (next==StreamTokenizer.TT_EOF)
          {
            EndOfFile=true;
            EndOfLine=true;
          }
        }
```

```
    }
    fis.close();
  }
  catch (IOException e)
  {
    return;
  }
}


//finds parameter from applet context or application's paramfile
String getParam(String s)
{
  if (!StandAlone)
  {
    return parentApplet.getParameter(s);
  }
  else
  {
    Object o;
    String ss;
    for(int x=0;x<ParamName.size();x++)
    {
      o=ParamName.elementAt(x);
      if (o instanceof String)
      {
        ss=(String)o;
        if (ss.equalsIgnoreCase(s))
        {
          o=ParamValue.elementAt(x);
          if (o instanceof String)
          {
            return (String)o;
          }
          else return null;
        }
      }
    }
    return null;
  }
}

//returns an initialised IPSOModel based on the parameters read
IPSOModel readModel()
{
  IPSOModel im;
  TechParameterSet tt=readTechConstraintParameters();
  ProcParameterSet pc=readProcConstraintParameters();
  PresParameterSet pr=readProdConstraintParameters();
  readTimeParameters();

  IPSOParameterSet ip=new IPSOParameterSet(grow,iwt,tt,pc,pr);
  if (getParam("preset")!=null)
  {
    if (readPresetModelParameters(pc))
    {
      im=initModel(ip,true);
```

```
      }
      else
      {
        readModelParameters();
        im=initModel(ip,false);
      }
    }
    else
    {
      readModelParameters();
      im=initModel(ip,false);
    }
    return im;
  }


  //reads technology-related constraints and returns wrapped in object
  TechParameterSet readTechConstraintParameters()
  {
    //read in replacement parameter values
    String param1;
    String param2;

    param1=getParam("probinvent");
    if (param1!=null) probinvent=new Float(param1).floatValue();
    param1=getParam("techlt_hi");
    param2=getParam("techlt_low");
    if (param1!=null & param2!=null)
      techlt=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("techsiz_hi");
    param2=getParam("techsiz_low");
    if (param1!=null & param2!=null)
      techsiz=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("techinc_hi");
    param2=getParam("techinc_low");
    if (param1!=null & param2!=null)
      techinc=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("techouc_hi");
    param2=getParam("techouc_low");
    if (param1!=null & param2!=null)
      techouc=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("techinp_hi");
    param2=getParam("techinp_low");
    if (param1!=null & param2!=null)
      techinp=new IntParamRange(new Float(param1).intValue(), new
Float(param2).intValue());
    param1=getParam("techoup_hi");
    param2=getParam("techoup_low");
    if (param1!=null & param2!=null)
      techoup=new IntParamRange(new Float(param1).intValue(), new
Float(param2).intValue());
```

```
    return new
TechParameterSet(probinvent,techlt,techsiz,techinc,techouc,techinp,tech
oup);
  }

  ProcParameterSet readProcConstraintParameters()
  {
    //read in replacement parameter values
    String param1;
    String param2;

    param1=getParam("procvarlt_hi");
    param2=getParam("procvarlt_low");
    if (param1!=null & param2!=null)
      procvarlt=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("procvarsiz_hi");
    param2=getParam("procvarsiz_low");
    if (param1!=null & param2!=null)
      procvarsiz=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("procvarc_hi");
    param2=getParam("procvarc_low");
    if (param1!=null & param2!=null)
      procvarc=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    return new ProcParameterSet(procvarlt,procvarsiz,procvarc);
  }

  PresParameterSet readProdConstraintParameters()
  {
    //read in replacement parameter values
    String param1;
    String param2;

    param1=getParam("probres");
    if (param1!=null) probres=new Float(param1).floatValue();
    param1=getParam("probren");
    if (param1!=null) probren=new Float(param1).floatValue();
    param1=getParam("probstock");
    if (param1!=null) probstk=new Float(param1).floatValue();
    param1=getParam("resstk_hi");
    param2=getParam("resstk_low");
    if (param1!=null & param2!=null)
      resstk=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("renstk_hi");
    param2=getParam("renstk_low");
    if (param1!=null & param2!=null)
      renstk=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("prodstk_hi");
    param2=getParam("prodstk_low");
    if (param1!=null & param2!=null)
      prodstk=new ParamRange(new Float(param1).floatValue(), new
Float(param2).floatValue());
    param1=getParam("resrenc_hi");
```

```
    param2=getParam("resrenc_low");
    if (param1!=null & param2!=null)
      resrenc=new ParamRange(new Float(param1).intValue(), new
Float(param2).intValue());
    return new
PresParameterSet(probres,probren,probstk,resstk,renstk,prodstk,resrenc)
;
  }

  void readTimeParameters()
  {
    //read in replacement parameter values for time
    String param1;

    param1=getParam("tim");
    if (param1!=null) t=new Float(param1).floatValue();
    param1=getParam("dt");
    if (param1!=null) dt=new Float(param1).floatValue();
    param1=getParam("grow");
    if (param1!=null)
    {
      if (param1.equalsIgnoreCase("true")) grow=true;
    }
    param1=getParam("invweight");
    if (param1!=null) iwt=new Float(param1).floatValue();
  }

  void readModelParameters()
  {
    //read in replacement parameter values
    String param1;

    //for random assignation of new technologies etc.
    //read in number of new technologies, HMCProcesses and products to
generate
    param1=getParam("ntech");
    if (param1!=null) ntech=new Integer(param1).intValue();
    param1=getParam("nproc");
    if (param1!=null) nproc=new Integer(param1).intValue();
    param1=getParam("nprod");
    if (param1!=null) nprod=new Integer(param1).intValue();

  }

  IPSOModel initModel(IPSOParameterSet ips, boolean preset)
  {
    IPSOModel im;
    //initialise model
    if (!preset) im=new IPSOModel(ips,ntech,nproc,nprod,t,dt);
    else im=new IPSOModel(ips,techArray,procArray,prodArray,t,dt);
    return im;
  }

  //reads in preset system of technologies, processes and products
  //to be present in a model, and then chases up the parameter tags
  //for each. The parameter tags and their meanings are:
  //  nptech = no. 'preset' technologies (a single number)
```

```
  //  npproc = no. processes (an array sep. by '%' of no. of each techs
  //           present initially
  //  npprod = no. 'preset' products
  //  tech<n> (e.g. tech1, tech2, etc.)
  //          = individual technology specs.
  //  prod<n> (e.g. prod1, prod2, etc.)
  //          = individual product specs.
  //returns true only if a valid IPSOModel can be constructed from
preset tags
  //(in which case it does so and assigns model to global pointer m
  boolean readPresetModelParameters(ProcParameterSet pc)
  {
    int x;

    //determines whether a preset can be constructed
    int nt=0;
    String param=getParam("nptech");
    if (param!=null)
    {
      try
      {
        nt=new Integer(param).intValue();
      }
      catch(NumberFormatException e)
      {
        return false;  //drops out because nptech not readable
      }
    }
    else return false;    //drops out because nptech not found
    //checks that all tags for techs are present, and stores them in
    //an array if so, else drops out
    String[] techstr=new String[nt];
    for(x=0;x<nt;x++)
    {
      param=getParam("tech"+new Integer(x).toString());
      if (param!=null) techstr[x]=param;
      else return false;  //drops out if can't find a string that it
expects to
    }

    //checks that process size list present
    String procstr;
    param=getParam("npproc");
    if (param!=null) procstr=param;
    else return false;  //drops out if can't find process size list

    //checks all products as for techs
    int np=0;
    param=getParam("npprod");
    if (param!=null)
    {
      try
      {
        np=new Integer(param).intValue();
      }
      catch(NumberFormatException e)
      {
```

```
        return false;  //drops out because npprod not readable
      }
    }
    else return false;    //drops out because npprod not found
    //checks that all tags for prods are present, and stores them in
    //an array if so, else drops out
    String[] prodstr=new String[np];
    for(x=0;x<np;x++)
    {
      param=getParam("prod"+new Integer(x).toString());
      if (param!=null) prodstr[x]=param;
      else return false;  //drops out if can't find a string that it
expects to
    }
    //if it's got this far it has collected all the strings it needs to
    //build the model, so it checks them out here

    //products first...
    Product[] prod=new Product[np];
    Product thisprod=null;
    for(x=0;x<np;x++)
    {
      thisprod=readProdParam(prodstr[x]);
      if (thisprod!=null) prod[x]=thisprod;
      else return false;  //drops out if a product is unreadable
    }
    prodArray=prod;

    //...then techs...
    Technology[] tech=new Technology[nt];
    Technology thistech;
    for(x=0;x<nt;x++)
    {
      thistech=readTechParam(techstr[x]);
      if (thisprod!=null) tech[x]=thistech;
      else return false;  //drops out if a product is unreadable
    }
    techArray=tech;

    //...then generate processes
    int[] nproc=readProcParam(procstr);
    if (nproc!=null & nproc.length==tech.length)
    {
      //generates req. number of processes if nproc readable
      int numproc=0;
      for(x=0;x<nproc.length;x++)
      {
        numproc+=nproc[x];
      }
      HMCProcess[] proc=new HMCProcess[numproc];
      int y;
      int ct=0;
      for(x=0;x<nproc.length;x++)
      {
        for(y=0;y<nproc[x];y++)
        {
```

```
          proc[ct]=new HMCProcess(tech[x].name+new
Integer(y).toString(),
                        t-(float)(Math.random()*tech[x].lt),
                        tech[x],
                        pc);
          ct++;
        }
      }
      procArray=proc;
    }
    else
    {
      return false;//drops out because incompatible string returned by
readProcParam
    }
    return true;
  }


  //reads html tag encoding of product
  Product readProdParam(String thisProd)
  {
    try
    {
      String thisname;
      boolean thisres;
      boolean thisrenstk;
      float thisrc;
      float thisstk;
      String bool;

      StringTokenizer st=new StringTokenizer(thisProd,"/",false);
      thisname=st.nextToken();
      bool=st.nextToken();
      thisres=(bool.equalsIgnoreCase("true"));
      bool=st.nextToken();
      thisrenstk=(bool.equalsIgnoreCase("true"));
      thisrc=new Float(st.nextToken()).floatValue();
      thisstk=new Float(st.nextToken()).floatValue();
      return new Product(thisname,thisres,thisrenstk,thisrc,thisstk);
    }
    catch (Exception e)
    {
      return null;
    }
  }


  //reads Technology-encoding string
  Technology readTechParam(String thisTech)
  {
    try
    {
      String thisname;
      float thislt;
      float thissiz;
      int thisninp;
```

```
      int thisnoup;
      String[] thisinpn;
      Product[] thisinp;
      float[] thisinc;
      String[] thisoupn;
      Product[] thisoup;
      float[] thisouc;

      StringTokenizer st=new StringTokenizer(thisTech,"/",false);

      thisname=st.nextToken();
      thislt=new Float(st.nextToken()).floatValue();
      thissiz=new Float(st.nextToken()).floatValue();
      thisninp=new Integer(st.nextToken()).intValue();
      thisnoup=new Integer(st.nextToken()).intValue();
      thisinpn=new String[thisninp];
      thisinp=new Product[thisninp];
      thisinc=new float[thisninp];
      for(int y=0;y<thisninp;y++)
      {
        thisinpn[y]=st.nextToken();
        thisinp[y]=getProdFromArray(thisinpn[y]);
        thisinc[y]=new Float(st.nextToken()).floatValue();
      }
      thisoupn=new String[thisnoup];
      thisoup=new Product[thisnoup];
      thisouc=new float[thisnoup];
      for(int z=0;z<thisnoup;z++)
      {
        thisoupn[z]=st.nextToken();
        thisoup[z]=getProdFromArray(thisoupn[z]);
        thisouc[z]=new Float(st.nextToken()).floatValue();
      }
      return new
Technology(thisname,thislt,thissiz,thisinp,thisinc,thisoup,thisouc);
    }
    catch (Exception e)
    {
      return null;
    }
  }

  //given a name, this method searches array of products to return
  //first prod with that name
  Product getProdFromArray(String name)
  {
    for(int x=0;x<prodArray.length;x++)
    {
      if (prodArray[x].name.equalsIgnoreCase(name))
      {
        return prodArray[x];
      }
    }
    return null;  //only executed if nothing found
  }

  //returns an array of integers listing no. processes based on each
```

```
  //technology
  int[] readProcParam(String s)
  {
    try
    {
      StringTokenizer st=new StringTokenizer(s,"/",false);
      int[] proc=new int[st.countTokens()];
      for(int x=0;x<proc.length;x++)
      {
        proc[x]=new Integer(st.nextToken()).intValue();
      }
      return proc;
    }
    catch (Exception e)
    {
      return null;
    }
  }


}
```

ParamRange.java

```
package ipso;

//
//
// ParamRange
//
//
class ParamRange
{
  float hival;  //upper value
  float loval;  //lower value

  //default constructor
  ParamRange(float h, float l)
  {
    hival=h;
    loval=l;
  }

  //alternative to deal w. numbers being passed as doubles
  ParamRange(double h, float l)
  {
    hival=new Double(h).floatValue();
    loval=l;
  }

  //alternative to deal w. numbers being passed as doubles
  ParamRange(float h, double l)
  {
    hival=h;
    loval=new Double(l).floatValue();
  }

  //alternative to deal w. numbers being passed as doubles
```

```
  ParamRange(double h, double l)
  {
    hival=new Double(h).floatValue();
    loval=new Double(l).floatValue();
  }

  //picks a radom number in range
  float pickVal()
  {
    return new Double(loval+Math.random()*(hival-loval)).floatValue();
  }


}
```

PresParameterSet.java

```
package ipso;

//
//
// PresParameterSet
//
//
class PresParameterSet
{
  float probRes;  //probability of resource cf. coefficient
  float probRen;  //probability of resource being renewable
  float probStock;//probability of product being storable/stockpilable
(e.g. metal, but not electricity)
  ParamRange initResStk;
          //initial stock range of non-renewable resource
  ParamRange initRenStk;
          //initial stock range of renewable resource
  ParamRange initProdStk;
          //initial stock range of stockable product
  ParamRange renCoeff;

  //default constructor
  PresParameterSet(float prs, float prn, float prst,
           ParamRange iresstk, ParamRange irenstk, ParamRange ipstk,
           ParamRange rc)
  {
    probRes=prs;
    probRen=prn;
    probStock=prst;
    initResStk=iresstk;
    initRenStk=irenstk;
    initProdStk=ipstk;
    renCoeff=rc;
  }

}
```

ProcParameterSet.java

```
package ipso;
```

```
//
//
// ProcParameterSet
//
//
class ProcParameterSet
{
  ParamRange varlt;  //variation in lifetime
  ParamRange varsiz;  //variation in size
  ParamRange varcoeff;//variation in input & output coefficients

  //default constructor
  ProcParameterSet(ParamRange l, ParamRange s, ParamRange c)
  {
    varlt=l;
    varsiz=s;
    varcoeff=c;
  }


}
```

Product.java

```
package ipso;

//
//
// Product
//
//
class Product
{
  String name;//text name for displaying
  boolean resource;  //true if natural resource cf. product
  boolean renewable;  //true if renewable resource (not used if
!resource)
  boolean stockable;  //true if stock-pilable resource (e.g. steel, but
not electricity)
            //(not used if resource)
  float renewcoeff;  //renewal coefficent
  float stock;    //stock value
  float inrate;    //input rate
  float outrate;    //output rate
  float scarce;    //indicator of scarcity (supply/demand balance)
  float scarce2;      //adjusted indicator of scarcity for iteration
routine

  //default constructor filling in necessary fields
  Product(String n, PresParameterSet p)
  {
    name=n;
    resource=(p.probRes>Math.random());
    if (resource)
    {
      renewable=(p.probRen>Math.random());
```

```
      if (renewable)
      {
        stock=p.initRenStk.pickVal();
        renewcoeff=p.renCoeff.pickVal();
      }
      else
      {
        stock=p.initResStk.pickVal();
      }
    }
    else
    {
      stockable=(p.probStock>Math.random());
      if (stockable)
      {
        stock=p.initProdStk.pickVal();
      }
      else stock=0;
    }
  }


  //alternative constructor specifying absolute values
  Product(String n, boolean res, boolean renstok, float renc, float
stk)
  {
    name=n;
    resource=res;
    if (resource)
    {
      renewable=renstok;
      stockable=true;
    }
    else stockable=renstok;
    renewcoeff=renc;
    stock=stk;
  }

  //updates stock values for given rates
  void updateStock(float inr, float outr, float dt)
  {
    setRates(inr,outr,dt);
    if (stockable)
    {
      stock=stock+(inrate-outrate)*dt;
      //this shouldn't be necessary, but keep it in
      //until problems with simulator are ironed out
      if (stock<0) stock=0;
    }
    else
    {
      stock=0;
    }
  }

  //sets rate terms, taking account of renewable resources own
  //formulation for input rate
```

```
  //renewable always false if !resource (see constructor)
  void setRates(float inr, float outr, float dt)
  {
    if (!renewable)
    {
      inrate=inr;
    }
    else
    {
      inrate=stock*renewcoeff;
    }
    outrate=outr;
  }

  //checks whether proposed rates can be sustained by current
  //stock value: returns a float value equal to ratio of proposed
  //reduction over current stock size
  //scarce represents scarcity when everything is going at full load
  //scarce2 the actual scarcity once lf's adjusted
  void checkRates(float inr, float outr, float dt,int ct)
  {
    setRates(inr,outr,dt);
    scarce2=(outr-inr)/stock;
    if (ct==1) scarce=scarce2;
  }

}
```

Technology.java

```
package ipso;

//
//
// Technology
//
//
class Technology
{
  String name;//text name for displaying
  float lt;  //ave. lifetime
  float siz;  //ave. size
  Product[] inp;  //array of inputs
  Product[] oup;  //array of outputs
  String[] iname;  //copy of input names
  String[] oname;  //copy of output names
  float[] inc;//array of input coefficients
  float[] ouc;//array of output coefficients
  float investWeight; //indicator of desirability of investing
            //in this tech at runtime: based on surplus
            //or scarcity of inputs and outputs

  //default constructor passing required values
  //np is no. manuf. products, nr is no. resources
  Technology(String n, TechParameterSet t, Product[] prod, Product[]
res)
  {
```

```
    makeTechnology(n,t,prod,res);
  }

  void makeTechnology(String n, TechParameterSet t, Product[] prod,
Product[] res)
  {
    //fill in basic parameters
    name=n;
    lt=t.lt.pickVal();
    siz=t.siz.pickVal();

    //inputs
    //set up array of all potential inputs
    Product[] possInputs=new Product[res.length+prod.length];
    int x;
    for (x=0;x<res.length;x++)
    {
      possInputs[x]=res[x];
    }
    for(x=0;x<prod.length;x++)
    {
      possInputs[x+res.length]=prod[x];
    }
    int ni=t.inp.pickVal();
    inp=new Product[ni];
    iname=new String[ni];
    inc=new float[ni];
    int index;
    IntParamRange ninp;
    Product tempp;
    for(x=0;x<ni;x++)
    {
      //pick random entry from poss array and fill in fields
      ninp=new IntParamRange(0, possInputs.length-1-x);
      index=ninp.pickVal();
      inp[x]=possInputs[index];
      iname[x]=inp[x].name;
      inc[x]=t.inc.pickVal();
      //move used entry to end of array, swappping with previous last
entry
      tempp=possInputs[index];
      possInputs[index]=possInputs[possInputs.length-1];
      possInputs[possInputs.length-1]=tempp;
    }

    //outputs
    Product[] possOutputs=new Product[prod.length];
    for(x=0;x<prod.length;x++)
    {
      possOutputs[x]=prod[x];
    }
    int no=t.oup.pickVal();
    oup=new Product[no];
    oname=new String[no];
    ouc=new float[no];
    IntParamRange noup;
    for(x=0;x<no;x++)
```

```
    {
      //pick random entry from poss array and fill in fields
      noup=new IntParamRange(0, possOutputs.length-1-x);
      index=noup.pickVal();
      oup[x]=possOutputs[index];
      oname[x]=oup[x].name;
      ouc[x]=t.ouc.pickVal();
      //move used entry to end of array, swappping with previous last
entry
      tempp=possOutputs[index];
      possOutputs[index]=possOutputs[possOutputs.length-1];
      possOutputs[possOutputs.length-1]=tempp;
    }
  }

  //another constructor that invents 'intelligently', using abundant
  //prods and res as inputs, and scarce prods as outputs: takes an
  //extra boolean argument - if false, defaults to above random mix
  Technology(String n, TechParameterSet t, Product[] prod, Product[]
res, boolean intelligent)
  {
    makeTechnology(n,t,prod,res,intelligent);
  }

  void makeTechnology(String n, TechParameterSet t, Product[] prod,
Product[] res, boolean intelligent)
  {
    if (!intelligent)
    {
      makeTechnology(n,t,prod,res);
      return;
    }

    //otherwise, proceed...
    int x;
    int y;

    //fill in basic parameters
    name=n;
    lt=t.lt.pickVal();
    siz=t.siz.pickVal();

    //inputs
    //set up array of all potential inputs
    Product[] possInputs=new Product[res.length+prod.length];
    for (y=0;y<res.length;y++)
    {
      possInputs[y]=res[y];
    }
    for(y=0;y<prod.length;y++)
    {
      possInputs[y+res.length]=prod[y];
    }

    float cumwt=0;
    float thiswt[]=new float[res.length+prod.length];
    boolean done[]=new boolean[res.length+prod.length];
```

```
int ni=t.inp.pickVal();
inp=new Product[ni];
iname=new String[ni];
inc=new float[ni];
float index;
int ct;
ParamRange ninp;
//reset weighting scheme, eliminating used resources/products
for(x=0;x<ni;x++)
{
  cumwt=0;
  for (y=0;y<res.length;y++)
  {
    if (!done[y])
    {
      if (res[y].scarce2>0) cumwt+=1-res[y].scarce2;
      else cumwt+=1;  //no incentive to use abundant resources
    }
    thiswt[y]=cumwt;
  }
  for(y=0;y<prod.length;y++)
  {
    if (!done[y+res.length])
    {
      cumwt+=1-prod[y].scarce2;
    }
    thiswt[y+res.length]=cumwt;
  }

  //pick random entry from poss array and fill in fields
  //picking weighted by scarcity
  ninp=new ParamRange((float)0, (float)cumwt);
  index=ninp.pickVal();
  ct=0;
  while(thiswt[ct]<index)
  {
    ct++;
  }
  inp[x]=possInputs[ct];
  iname[x]=inp[x].name;
  inc[x]=t.inc.pickVal();
  done[ct]=true;
}

//outputs
Product[] possOutputs=new Product[prod.length];
thiswt=new float[prod.length];
done=new boolean[prod.length];
for(x=0;x<prod.length;x++)
{
  possOutputs[x]=prod[x];
}
int no=t.oup.pickVal();
oup=new Product[no];
oname=new String[no];
ouc=new float[no];
IntParamRange noup;
```

```
    for(x=0;x<no;x++)
    {
      cumwt=0;
      for(y=0;y<prod.length;y++)
      {
        if (!done[y])
        {
          cumwt+=1-prod[y].scarce2;
        }
        thiswt[y]=cumwt;
      }

      //pick random entry from poss array and fill in fields
      //picking weighted by scarcity
      ninp=new ParamRange((float)0, (float)cumwt);
      index=ninp.pickVal();
      ct=0;
      while(thiswt[ct]<index)
      {
        ct++;
      }
      oup[x]=possOutputs[ct];
      oname[x]=oup[x].name;
      ouc[x]=t.ouc.pickVal();
      done[ct]=true;
    }
  }


  //alternative constructor given exact values
  Technology(String n, float l, float s, Product[]ip, float[] ic,
Product[]op, float[] oc)
  {
    name=n;
    lt=l;
    siz=s;

    int ni;
    if (ip.length>ic.length) ni=ic.length; else ni=ip.length;
    inp=new Product[ni];
    iname=new String[ni];
    inc=new float[ni];
    for (int x=0;x<ni;x++)
    {
      inp[x]=ip[x];
      iname[x]=inp[x].name;
      inc[x]=ic[x];
    }

    int no;
    if (op.length>oc.length) no=oc.length; else no=op.length;
    oup=new Product[no];
    oname=new String[no];
    ouc=new float[no];
    for (int y=0;y<no;y++)
    {
      oup[y]=op[y];
```

```
      oname[y]=oup[y].name;
      ouc[y]=oc[y];
    }
  }

  //another constructor that 'mutates' existing technology by either
  //adding a new output, removing an input, or changing a coefficient,
  //(could also make it smaller or more durable?)
  Technology(TechParameterSet tps,Technology[] tech,Product[]
prod,Product[] Res)
  {
    int x;
    int y;

    //fill in basic parameters
    IntParamRange ipr=new IntParamRange(1,tech.length);
    Technology template=tech[ipr.pickVal()];
    name=template.name+" v"+new Integer(tech.length).toString();
    lt=template.lt;
    siz=template.siz;

    double choice=Math.random();
    if (choice<0.5 && template.inp.length>1)
    {
      //knock out an input: only an option if some inputs left
      int ninp=template.inp.length;
      ipr=new IntParamRange(0,ninp-1);
      int knock=ipr.pickVal();
      int ni=template.inp.length-1;
      inp=new Product[ni];
      iname=new String[ni];
      inc=new float[ni];
      for(x=0;x<knock;x++)
      {
        inp[x]=template.inp[x];
        iname[x]=template.iname[x];
        inc[x]=template.inc[x];
      }
      for(x=knock;x<ni;x++)
      {
        inp[x]=template.inp[x+1];
        iname[x]=template.iname[x+1];
        inc[x]=template.inc[x+1];
      }
      oup=new Product[template.oup.length];
      oname=new String[template.oname.length];
      ouc=new float[template.ouc.length];
      for(x=0;x<template.oup.length;x++)
      {
        oup[x]=template.oup[x];
        oname[x]=template.oname[x];
        ouc[x]=template.ouc[x];
      }
    }
    else
    {
      //add new output
```

```
      Product[] possOutputs=new Product[prod.length-
template.oup.length];
      int ct=0;
      boolean gotalready;
      for(x=0;x<prod.length;x++)
      {
        gotalready=false;
        for(y=0;y<template.oup.length;y++)
        {
          if (template.oname[y].equalsIgnoreCase(prod[x].name))
            gotalready=true;
        }
        if (!gotalready)
        {
          possOutputs[ct]=prod[x];
          ct++;
        }
      }
      int no=template.oup.length+1;
      oup=new Product[no];
      oname=new String[no];
      ouc=new float[no];
      for (x=0;x<template.oup.length;x++)
      {
        oup[x]=template.oup[x];
        oname[x]=template.oname[x];
        ouc[x]=template.ouc[x];
      }
      ipr=new IntParamRange(0,possOutputs.length-1);
      Product p=possOutputs[ipr.pickVal()];
      oup[template.oup.length]=p;
      oname[template.oup.length]=p.name;
      ouc[template.oup.length]=tps.ouc.pickVal();

      inp=new Product[template.inp.length];
      iname=new String[template.iname.length];
      inc=new float[template.inc.length];
      for(x=0;x<template.inp.length;x++)
      {
        inp[x]=template.inp[x];
        iname[x]=template.iname[x];
        inc[x]=template.inc[x];
      }
    }
  }


  //returns the product associated with a given input number
  Product getInput(int i)
  {
    return inp[i];
  }

  //returns the product associated with a given output number
  Product getOutput(int i)
  {
```

```
    return oup[i];
  }

}
```

TechParameterSet.java

```
package ipso;

//
//
// TechParameterSet
//
//
class TechParameterSet
{
  float probInvent;  //probability of inventing new technology
  ParamRange lt;    //range for lifetime
  ParamRange siz;    //range for size
  ParamRange inc;    //range for input coeff
  ParamRange ouc;    //range for output coeff
  IntParamRange inp;  //range for number inputs
  IntParamRange oup;  //range for number outputs

  //default constructor
  TechParameterSet(float pi, ParamRange l, ParamRange s, ParamRange i,
ParamRange o, IntParamRange ni, IntParamRange no)
  {
    probInvent=pi;
    lt=l;
    siz=s;
    inc=i;
    ouc=o;
    inp=ni;
    oup=no;
  }
```

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