The Australian Stocks and Flows Framework – a tool for strategic biophysical assessment of a national economy

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1 Abstract
The Australian Stocks and Flows Framework (ASFF) was developed to assess the biophysical longevity of the Australian economy, with top-down coverage of the whole physical economy based on bottom-up process-based detail. The ASFF employs mass-balance identities associated with stock and flow dynamics throughout the national economy and associated interaction with the environment. We show that the ASFF shares common features with complementary approaches, including Mass Flow Analysis, Physical Input-Output Tables, and Life Cycle Analysis, but is distinctly different from these because the biophysical processes throughout the economy and environment are represented explicitly. The detailed physical processes modelled have a strong empirical basis, being calibrated with six or more decades of historical data. Given the coverage of the entire economy in physical terms, it provides for many subject specific analyses such as water, energy, climate change, etc, which can also be assessed in integrated analysis of scenarios to 2100 in order to highlight conflicts, trade-offs, and synergies. The ASFF can be applied and adapted to represent specific interests in more detail and context, as demonstrated by multiple applications of the ASFF. Overall, it is designed to explore the possible trajectories of the national economic system over the long term within irredefutable biophysical constraints, and thereby inform development of appropriate policy. The open biophysical nature of the ASFF is intended for exploration and learning, rather than being normative or policy prescriptive.

Keywords: sustainability, stocks and flows, integrated assessment, physical economy, scenarios, tensions

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2 Introduction

The need to address issues surrounding natural resource use, and the wastes and emissions associated with economic activity is increasingly recognised by decision-makers at the international level; two prominent examples are the Copenhagen Conference on Climate Change in 2009 and the Group of Eight (G8) summit of 2000. Despite the growing awareness of strategic environmental issues, there remains an apparent desire for better information systems and indicators to help guide policy development (Weisz and Schandl, 2008). For instance, the OECD was commissioned by the G8 to provide guidance on information systems and indicators, and France created the Commission on the Measurement of Economic and Social Progress to address concerns about current statistical measures (Stiglitz et al., 2009).

Such requests for more information contrast somewhat with the large range of indicators, approaches and models now available to portray the impact of economic activity on the environment and subsequent implications for sustainability. Various contributions have been developed over several decades, and some better known examples include: indicators such as, the Ecological Footprint, Human Development Index, and Genuine Progress Indicator; approaches such as, Life Cycle Assessment/Analysis, Mass/material Flow Analysis, Physical Input-Output Tables, and System for Integrated Environmental and Economic Accounting; and models such as, IMAGE, TARGET, GUMBO, Threshold-21. Reviews of these tools (e.g., (Bartelmus, 2003; Costanza et al., 2007; Lotze-Campen, 2008; Lutz et al., 2002; Stiglitz et al., 2009)) make it clear that many aspects are important for assessing sustainability, and few, if any, of the tools encompass all aspects sufficiently to be truly unifying. It seems that tools in this ensemble are best viewed as contributing particular perspectives on sustainability, and individual tools might be used with specific purposes in mind.

In this paper we describe a new tool for assessing strategically the longevity of a national economy. This interest was focused on the Australian economy due to the previous lack of comprehensive analytic capability at this national level. Despite being labelled the “land of plenty” and (with deliberate irony) the “lucky country” (Horne, 1964), Australia is currently facing a number of substantial challenges (see e.g., (DPMC, 2008)). While Australia has a distinctive biophysical character (Schandl et al., 2008), the challenges are of similar to those faced by many other nations, though they may differ in extent and combination. Many of these challenges have a physical nature (biological, environmental or anthropogenic), in particular:

- population aging and labour supply;
- oil depletion and transport fuels;
- agricultural production and land degradation;
- water availability for agriculture and human settlements;
- access/depletion of other mineral resources;
- aging infrastructure;
- greenhouse emissions from energy consumption and impacts of climate change.

Other non-physical issues are also on the contemporary Australian agenda, such as indigenous affairs (DPMC, 2008). These issues may be important for cultural or ethical reasons, but are not seen as directly impacting on the future of the Australian economy. Our interest was in identifying critical aspects underpinning the longevity of a national economy. This is based on the hypothesis that some degree of physical or environmental dependence is necessary for any economy, irrespective of the social and economic systems employed (including culture, institutions, technology, etc.). The development approach was to examine the characteristics of the range of issues potentially facing the Australian economy and develop the modelling capability accordingly.

This paper describes the resulting simulation and analysis capability of the economy of Australia. The Australian government research organisation, CSIRO, developed the Australian Stocks and Flows Framework (ASFF), with the support of whatif Technology and associated software platform (whatif, 2008). This capability is the Australian Stocks and Flows Framework (ASFF), which has undergone substantial development since its original application to the environmental implications of alternative immigration and population futures (Foran and Poldy, 2002). While expressed largely in physical terms, it explicitly recognises the importance (and complexity) of social/economic behaviour that influences the physical domain.

The ASFF is a highly disaggregated simulation of physically significant stocks and flows in the Australian socio-economic system (Poldy et al., 2000). It simulates the physical processes of economic activity explicitly, based on the underlying thermodynamic constraint of conservation of mass and energy. It covers all the physical elements of each sector of the Australian economy that are significant from a thermodynamic perspective, including some service aspects. Natural resources (land, water, air, biomass and mineral resources) are also represented explicitly. The temporal extent of the ASFF is long-term: scenarios over the future are calculated to 2100, and the model is also run over an historical period from 1941. Such a capability could be generalised to other nations with suitable data.

The ASFF was developed to provide a quantitative modelling framework for identifying and exploring current and future environmental/resource challenges facing Australia, and for transparently analysing potential solutions and pathways. When using the ASFF, solutions are constrained to be consistent with underlying physical (thermodynamic) constraints. This includes interactions across economic sectors or environmental compartments due to its comprehensive coverage (aiding integrated assessment).

Following this introduction, we first review the physical issues facing Australia, many of which are listed above, and derive the general characteristics of the model required to analyse such issues. Section three then provides an overview of the ASFF. A more detailed but succinct description of the processes modelled is provided in the Appendix/Online material, which complement the comprehensive detail available in (Poldy et al., 2000). To bed the concepts down, section four discusses how the ASFF is implemented and provides brief illustrations of its application. In section five, we place the ASFF in the context of other related tools and processes also used for sustainability analysis. This shows how the ASFF complements and effectively draws on the strengths of these other approaches. A short description of
recent and ongoing developments of the ASFF is given in section six, before closing with a summary. The sections of this paper collectively address aspects of model development and evaluation as proposed by Jakeman et al. (Jakeman et al., 2006), which is summarised in Table 1.

Table 1. Ten steps for developing and evaluating environmental models suggested by Jakeman et al., (Jakeman et al., 2006) and the sections of this paper that address these steps.

<table>
<thead>
<tr>
<th>Development and Evaluation Step</th>
<th>Related discussion on the ASFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of the purposes for modelling</td>
<td>Introduction (section 1); and Assessing the longevity of the economy (section 2)</td>
</tr>
<tr>
<td>Specification of the modelling context: scope and resources</td>
<td>Assessing the longevity of the economy (section 2); and Scope and content of the ASFF (section 3)</td>
</tr>
<tr>
<td>Conceptualisation of the system, specification of data and other prior knowledge</td>
<td>Scope and content of the ASFF (section 3); and Overview of the modular structure (section 3.1)</td>
</tr>
<tr>
<td>Selection of model features and families</td>
<td>Development of the ASFF (section 2.1)</td>
</tr>
<tr>
<td>Choice of how model structure and parameter values are to be found</td>
<td>Development of the ASFF (section 2.1); and Creating and using the ASFF (section 4)</td>
</tr>
<tr>
<td>Choice of estimation performance criteria and technique</td>
<td>Creating and using the ASFF (section 4)</td>
</tr>
<tr>
<td>Identification of model structure and parameters</td>
<td>Commonality between the ASFF and other methods for system analysis (section 5)</td>
</tr>
<tr>
<td>Conditional verification including diagnostic checking</td>
<td>Development of the ASFF (section 2.1)</td>
</tr>
<tr>
<td>Quantification of uncertainty</td>
<td>Assessing the longevity of the economy (section 2); and Creating and using the ASFF (section 4)</td>
</tr>
<tr>
<td>Model evaluation or testing (other models, algorithms, comparisons with alternatives)</td>
<td>Development of the ASFF (section 2.1)</td>
</tr>
</tbody>
</table>

3 Assessing the longevity of an economy

In this section we propose the general features of an analysis system relevant to assessing the future success and longevity of the Australian economy. We start by grounding this through a summary of major contemporary challenges facing Australia, summarised in Table 1 in terms of their spatial, temporal, biophysical and economic characteristics (and subjectively listed in rough order of increasing challenge down the table). Further subjective elaboration of these challenges is unnecessary here—rather we seek a suitable analytic system to provide quantitative insight on any such challenges. Consequently, general observations about the characteristics are then made from this examination, from which we draw the features of the analysis system.

Most of the challenges are distinctly national in scope i.e., all or many regions of Australia are faced by the challenges, even though there may be some degree of difference from one region to another. A number of the challenges also have an international dimension, in the sense that the underlying resource may move in and out of Australia.

Virtually all the challenges are characterised by dynamics that operate on decade-long time-scales. On the face of it, the arguable exception to these spatial and temporal characteristics is water availability, which can vary considerably by region and on time-scales much less than decades. However, even for water, the natural and anthropogenic movement of water across state borders and the long lifetime of water infrastructure imply the use of similar dynamics and scale to the other challenges (this time-step issue is explored further in Turner et al., 2010a).

The majority of the challenges have a strong physical character, being essential as elements of or inputs to the operation of Australia’s economy. This situation contrasts with the financial relevance of the challenges to the past (and current) economy. In many cases the economic value of the underlying resource has been relatively small. The most obvious exception is labour. Due to contemporary issues though, there are indications that the future financial value of a range of resources are likely to increase, e.g., due to possible carbon reduction strategies or depletion of resource availability.

Lastly, a more subtle but important characteristic to consider is the potential for interactions between the challenges. Table 1 indicates that each challenge has an influence on one or more of the other challenges, since there are many common requirements for land, water, labour and resources.

The general characteristics identified above imply that quantitative analysis or modelling requires a wide range of the features summarised in Error! Reference source not found. to address questions of the longevity of a national economy. The national and whole-of-economy coverage recognises that activities in a different area may alleviate environmental issues, but may also transfer pressures from one area to another (geographic substitution).
<table>
<thead>
<tr>
<th>Strategic challenge</th>
<th>Geographic scale</th>
<th>Temporal scale</th>
<th>Biophysical relevance to the economy</th>
<th>Financial relevance to the economy</th>
<th>Interdependence – other challenges (directly) affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>trade balance</td>
<td>national issue, with imports of high value goods commonly exceeding exports of low value commodities</td>
<td>effects accrue annually</td>
<td>relevance is indirect</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>population aging and labour supply</td>
<td>national issue, with some regional distinctions; international connection via immigration</td>
<td>dynamics evident over several decades</td>
<td>labour necessary for the economy; demand for goods and services</td>
<td>high – highly skilled labour force</td>
<td>high</td>
</tr>
<tr>
<td>aging infrastructure</td>
<td>national issue, with regional differences</td>
<td>decades for depreciation and sub-decade development</td>
<td>essential for production of goods and services from utilities</td>
<td>moderate (through depreciation)</td>
<td>moderate (through depreciation)</td>
</tr>
<tr>
<td>access/depletion of mineral resources</td>
<td>spatially specific production, widely dispersed nationally; international connection via trade</td>
<td>decades for new sources to be developed; many decades for depletion</td>
<td>relatively small contribution to domestic industrial processes</td>
<td>high – significant exports</td>
<td>increasing</td>
</tr>
<tr>
<td>agricultural production and land degradation</td>
<td>national issue, with spatially specific production; international connection via trade</td>
<td>annual to decades</td>
<td>essential for supply of food and fibre</td>
<td>low to moderate – historically significant exports</td>
<td>uncertain</td>
</tr>
<tr>
<td>water availability for agriculture and human settlements</td>
<td>spatially specific issue, with inter-state implications</td>
<td>annual and sub-annual management (allocations); multi-year natural and anthropogenic storage</td>
<td>essential for drinking, sanitation, industrial processes, irrigation</td>
<td>low – virtually no price for water</td>
<td>increasing</td>
</tr>
<tr>
<td>oil depletion and transport fuels</td>
<td>national issue, with spatially specific production; national use of fuels; international connection via trade</td>
<td>decades for new sources of oil (or other fuels) to be developed; many decades for depletion</td>
<td>freight is a large component of the economy; private and public mobility of labour</td>
<td>low energy prices – contributed to exports</td>
<td>increasing</td>
</tr>
<tr>
<td>greenhouse emissions and impacts of climate change</td>
<td>national issue, with regional differences; potential international implications</td>
<td>annual issue for potential national and international accounting schemes; decades and longer for impacts</td>
<td>potential damage from climate change to infrastructure and environmental resources</td>
<td>nil</td>
<td>increasing</td>
</tr>
</tbody>
</table>
The degree of spatial and temporal resolution, and other levels of detail, is determined by the physically significant differences that can be represented and the potential for substitution. A physical process may be represented explicitly if the process has a unique output or has different intensity of inputs (energy, materials, water or labour). The decision about what resolution of level of sufficient detail is ultimately one of experience and pragmatism. Extra detail is only worth adding if insights gained are more accurate (and not just more precise); increasing precision without commensurate accuracy may not be worth the modelling and analysis effort.

Importantly, a focus on physical processes implies inclusion of several fundamental and related concepts: mass, energy; time; and technology. At the very least we must observe conservation of mass and energy i.e., the 1st law of thermodynamics. This is relevant to situations for example when material inputs are converted to another material, such as iron ore, coke, etc forming steel though one of several technological processes.

Conservation of mass also enters through the concepts of stocks and flows. A stock of cars for example may grow or diminish in combination with flows of new or discarded cars respectively, where the total mass balances. Typically large changes to stocks associated with the national economy occur over many years and sometimes decades. Consequently, this aspect of conservation of mass requires us to include such dynamics (Ruth and Davidsdottir, 2009), and employ timeframes that are at least one and ideally three times the characteristic lifetime of the stock. The dynamics and lifetimes of stocks are influenced by behaviour (i.e., choosing a new car and discarding the old) and technology.

Technology and technological progress must also be represented since this allows for decreased resource intensity i.e., the amount of energy or mass required per unit service (or good) delivered. This may be part of an evolutionary process, such as increasing efficiency of coal-based thermal power stations, or part of a substitution process, as in a switch from non-renewable to renewable electricity generation. The 2nd law of thermodynamics also implies that efficiencies cannot increase without constraint.

Focusing on biophysical processes also offers the potential for the analysis capability to avoid normative positions. Such a capability can explore the question of where the socio-economic system can go within bio-physical constraints, and which physical pathways lead to desirable outcomes. It does not, of itself, suggest what those desirable outcomes are or provide policy prescriptions about how technological and socio-economic behaviour should be changed to achieve the outcome via the feasible physical pathway. Common-sense suggests that policy prescriptions be informed by an examination of what is physically possible and the implications. This approach fulfils the role of identifying the envelope of possible futures (see Fig 2 of (Schellnhuber, 1999), and answers Schellnhuber’s 1st question “what kind of world do we have?” and the physical part of his 3rd question “what must we do to get there?”, but not the 2nd “what do we want?”).

A framework with the features above (and general features described by (Lutz et al., 2002)) therefore recognises the influence of human behaviour, technological innovation and the potential for substitution, while observing irrefutable and fundamental physical laws. It recognises that national planning requires a strategic approach to develop alternative pathways that deal with multiple interacting issues, while acknowledging that national policy development is often dynamic and driven by short-term pressures. It aims to provide the means for identifying the plausible pathways to desirable futures for the economy, and so to encourage political consensus.

### 3.1 Development of the ASFF

The initial development and application of the ASFF according to the principles above was undertaken jointly by researchers at the Australian government research organisation, CSIRO² (Barney Foran and Franzi Poldy), and whatIf Technologies Inc (whatIf, 2008) (then Robert Hoffman and Bert MeInnes). In the late 1990’s CSIRO were seeking national scale simulations to deal with the issues identified.

#### Table 3. Summarised features for modelling longevity of national economies.

<table>
<thead>
<tr>
<th>Features required</th>
<th>Level of detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covers the whole nation with connection to other nations via trade</td>
<td>spatial detail to allow for significant geographical differences</td>
</tr>
<tr>
<td>Spans a century long timeframe</td>
<td>1–5 year time-steps sufficient to capture significant changes and stock dynamics</td>
</tr>
<tr>
<td>Includes all environmental compartments—land, water, air</td>
<td>sufficient spatial or other detail to differentiate between key biophysical processes</td>
</tr>
<tr>
<td>Identifies physical goods and services delivered to the population</td>
<td>what materials and processes to include (and what to group together) is determined by similarities in terms of energy, material, water, labour intensities, as well as the possibility for substitution</td>
</tr>
<tr>
<td>Incorporates physical transformation processes that convert resources to goods and services</td>
<td></td>
</tr>
<tr>
<td>Incorporates the wide physical interdependence of sectors across the whole economy</td>
<td></td>
</tr>
<tr>
<td>Open to the influence of different sets of values, i.e., not normative or prescriptive, but more descriptive</td>
<td></td>
</tr>
</tbody>
</table>

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² Commonwealth Scientific and Industrial Research Organisation

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above. Independently, whatIf Technologies had developed a prototype national simulation of the Canadian economy (SERF) (Gault et al., 1987), testing concepts of stocks and flows modelling and, in parallel, developing a software environment (whatIf®) to undertake model design and coding, to incorporate historical data and to manage the creation and analysis of quantitative scenarios.

Several features were established by whatIf Technologies regarding the structure of national biophysical modelling. They employed a hierarchical structure for dealing with feedbacks, introduced transparency to dealing with the major input-output relationships, and created the Design Approach to implement these features. These aspects are explored below.

Using difference equations for stock-flow balances encouraged a systematic and hierarchical way of dealing with feedbacks that differs somewhat from common System Dynamics applications. At the level of dealing with individual stocks, software tools (e.g., cohort-based population models) incorporate feedback, with the result that scenario data is available over the complete time series, rather than the calculations having to step forward through time. Above this level, within a software module (called ‘calculators’), feedback can also be used explicitly using the diagrammatic interface of the software (e.g., determining density of dwellings in expanding urban areas). At the highest level, feedback between modules is restricted to either that provided by people responding to tensions displayed in the ASFF, to complementary code written specifically for the feedback task, or coupling with other models or analysis. This approach to high level feedbacks emphasises the importance of human decisions and behaviour (individual, social or economic) in response to the biophysical system. This aspect is explored further in the Overview of the modular structure of the ASFF.

A second feature introduced by whatIf Technologies, which relates to the first, was the desire to make comprehensive physical input-output (I-O) models of economies more transparent and interactive without the need for mathematical skills or I-O knowledge. This feature is related to the concept of “tensions” and is described more fully in the sections 3.1 and 3.2, and section 5.2 comparing I-O with the ASFF. Briefly, the approach was to:

- expand the final demand vector to reflect services provided from different stocks;
- treat finished goods as an explicit bundle of materials, and allow for substitution between materials and goods;
- employ an advanced physical I-O model of the basic industry operations for transformation of materials and energy, which allows more than one process to produce the same product (among other innovations in the I-O calculations); and
- treat activity in primary industries separately so that flows (including those with zero monetary value) from the environment are made explicit.

The experience of developing the Canadian model, and subsequently the ASFF, demonstrates an early application of the “Design Approach” (Gault et al., 1987). The Design Approach refers to both the development of frameworks or simulations, and how the frameworks are implemented. The development stage emphasizes the involvement of key stakeholders and users of the framework in the design of the framework. The visual design interface of the whatIf software is utilised by the modelling team with the stakeholders/users to create diagrams of the relationships between stocks, flows and parameters for the topics/components of interest, as well as a modular or hierarchical structure of the major components of the framework. The diagrams aim to provide sufficient information for knowledgeable people to recognise and verify the logical relationships, and for the model developers to write the code using the proprietary language designed for mathematically manipulating multi-dimensional data objects.

In creating the ASFF, the first aspect of the Design Approach was implemented in two stages. First, a preliminary version of the ASFF was developed between CSIRO and whatIf Technology, using the Canadian SERF as a guide for key concepts (such as what elements of the physical economy to represent as vintage stocks and how to manipulate them). This preliminary version was populated with historical data covering many decades of the 20th century in a large calibration exercise (see Implementation). Then the second phase involved a series of 16 separate workshops (Conroy et al., 2000) where industry, government and other experts in specific areas, such as demography, transport, etc., reviewed the framework components and data, and modifications were made as appropriate.

The application of the ASFF as functional prototype framework illustrates the second aspect of the Design Approach. Quantitative scenarios are designed and created in the ASFF by the user (operating in “decision space”), and then re-designed until physically realistic (in the “machine space” occupied by the ASFF) and desirable outcomes are created. This relies on the “open” nature of the ASFF, where feedbacks based on human reactions (e.g., social, economic, technological) to the physical situation depicted in the ASFF are deliberately not built into the core of the ASFF, but are developed as complementary macros, implemented through integration with other models, or performed by people operating the ASFF. In this latter option, physically unfeasible or problematic outcomes (“tensions”) must be resolved by people interacting with the ASFF, similar to the flight simulator concept. We discuss feedbacks and the ASFF in more depth in several subsequent sections of this paper.

The first application of the ASFF was for the Australian government’s Immigration department to explore the environmental implications of potential alternative immigration scenarios (Foran and Poldy, 2002). Together with the Immigration department, a base case scenario was established in the earlier workshops, and two other scenarios based on higher and zero net immigration rates, after resolving several physical tensions.

Substantial public commentary and controversy followed the release of the “Future Dilemmas” report (Foran and Poldy, 2002), partly driven by the alarm of conventional economists at the “lack of prices” in the ASFF (documented by a leading investigative journalist program “Four Corners” (Dempster, 2002), and partly by the environmental issues raised. In subsequent years, the ASFF has been applied and refined in a number of areas, including: agricultural land (Dunlop et al., 2002) and cropping systems (Dunlop and Turner, 2003), fisheries (Kearney and Foran, 2002; Lowe et al., 2003), state of the environment reporting (Lennox and Turner, 2005), rail transport (Turner et al., 2002), resource use trajectories (Schandl et al., 2008), “green collar” jobs (Hatfield-Dodds et al., 6 of 25
4 Scope and content of the ASFF

The ASFF is a highly disaggregate simulation of all physically significant stocks and flows in the Australian socio-economic system. Stocks are the quantities of physical items at a point in time, such as land, livestock, people, buildings, etc., and are expressed in numbers or SI units. Flows represent the rates of change resulting from physical processes over a time period, such as the (net) additions of agricultural land, immigration and birth rates, etc. In the first version of the ASFF there were over 800 multi-dimensional variables (about 300 that are exogenous).

The ASFF is a simulation that covers the thermodynamically significant physical processes of each sector of the Australian economy as depicted schematically in Figure 1. Natural resources (land, water, air, biomass and mineral resources) are represented explicitly, and flows of raw materials are harvested or extracted from the domestic environment (bottom of Figure 1). Materials are generally progressively transformed to become goods and to provide the basis for services for the population (following flows upward in Figure 1). Part of the framework incorporates a physical input-output model for the transformation of basic materials and energy types (Lennox et al., 2005). Some transformations involve the creation of secondary energy flows (to the left in Figure 1), which are used throughout the economy. Allowance is also made for recycling of waste flows, and for improvements or additions made to the environmental resources (e.g., forests). Otherwise, wastes and emissions return to the environment. Materials at various stages of transformations and energy may enter or exit the national economy as imports or exports (to the left and right of Figure 1 respectively). Likewise, immigration and international travellers add to the permanent and temporary population dynamics. Finally, the population provides a labour force for the various sectors of the economy (top of Figure 1).

Figure 1. Schematic summary of physical flow connections of a modern economy like Australia’s. Flows of people, energy and materials may enter and exit the economy, principally as imports and exports on the left and right respectively. Within the domestic economy, natural resources are extracted or harvested from the environment (shown at the centre bottom of the diagram). Materials are transformed progressively (going upward in the diagram), with the use of suitable energy, to eventually provide goods and services for the population. The population provides a labour force (at the top) for all the economic sectors. Wastes and emissions are generated by the economic activity, and may be recycled, exported or returned to the environment. Other flows occur between economic sectors.
Throughout the framework there are physical accounting relationships that represent the key processes, such as converting the requirement for transport of goods into the size of the freight transport fleet and the fuel requirement. A detailed explanation of the relationships throughout the ASFF is available in Poldy et al. (Poldy et al., 2000). Variables representing physical stocks and flows obey the thermodynamic constraints of conservation of mass and energy.

Geographically, the ASFF covers continental Australia, including the marine area within Australia’s economic exclusion zone (for fishing and fuels). Within specific sectors of the framework different geographic resolutions are used, e.g., agriculture is resolved at the 58 statistical divisions across Australia. The temporal extent of the ASFF is long-term: scenarios over the future are calculated to 2100, and the model runs over the historical period to reproduce the observed data. (In the first version of the ASFF the historical period covered 1941–1991, while a new version allows for repeated updates of the historical period.) In some sectors such as agriculture it is necessary to provide data substantially prior to 1940 due to the lengthy life-time of important agricultural land stocks, e.g., of different quality (Dunlop et al., 2002). The time step used is 5 years, coinciding with Australian Bureau of Statistics census years and providing sufficient resolution for the dealing with challenges that have multi-decadal lifetimes. (A new version of the ASFF is being developed with a 1-year time step to increase engagement with stakeholders.)

### 4.1 Overview of the modular structure

To achieve the modelling features described earlier in Section 2.1, the actual relationship among data variables and modules within the ASFF is somewhat different to that depicted in Figure 1. In broad terms, relationships represent either ‘requirements’ or ‘provisions’ as shown schematically in Figure 2. The high level structure of the ASFF depicts information flows among the major modules of the ASFF (shown as boxes), which may contain other modules (such as household formation, within demography). Arrows indicate data flows from one component to another within the ASFF; solid lines represent information on physical things produced or provided from one component to another; dashed lines represent physical things required by one component from another. This concept of representing requirements as the reverse of a flow of physical items provided, is analogous to the concept of an electrical current being the reverse of the flow of electrons. As a central feature of the Design Approach, these information flows eventually lead to the creation of tensions between requirements and provisions (collected in the components at the bottom and right of Figure 2). Based on the concepts just described, this section outlines the overall logic of the links shown in Figure 2; while further details on the specific calculations in each of the modules can be found in the Appendix/Online material.

Two of the major modules in Figure 2 (the boxes with round corners), representing demography and the primary industries, are driven exogenously and have only data flows exiting them. For example, the Australian population provides a labour force (blue solid line), which is subsequently compared with the requirement for labour created by activity in all industries (red dashed line exiting the box around all industries). A population consumes food and other non-durables, and needs dwellings and other buildings (for offices, education, health services, etc.), and personal and public transport. Consequently, the requirements of the Demography component drive the Consumables, Buildings and Transport components. The latter is also driven by requirements for transport services that are related to the building stock, such as urban freight.
The requirement for manufactured goods and infrastructure drives the modules in the Secondary Light Industry component. Additionally, discards of goods, durables and decommissioned infrastructure are potentially recycled in Secondary Light Industry. Manufactured goods can be sourced from overseas, so the Secondary Light Industry generates a requirement for imported goods (dealt with in the International Trade component). Likewise, manufactured goods may also be exported from Australia (also informing International Trade calculations).

The functioning of Buildings, Transport and Secondary Light Industry collectively create (with the Primary Industries) a requirement for materials, fuel and electricity from Secondary Heavy Industry ("Basic Materials and Energy"). Allowance is also made for secondary materials/energy that are imported (to satisfy domestic demand of the other industry sectors), or exported from Australia after domestic production. This module employs a physical Input-Output process (that also incorporates evolution of productive capacity) to calculate the primary materials required.

Separately, the exogenous Primary Industry component produces primary materials from agriculture, forestry, fisheries and mining. This information is compared in International Trade with the requirement from Secondary Heavy Industry for primary materials. Conservation of mass implies that if there is insufficient domestic production of primary materials in a scenario, then primary materials are imported to satisfy the domestic demand as calculated from above; alternatively if there is excess domestic production of primary materials, they are exported. Along with the imports and exports of secondary materials and goods, and international travel (driven from the Demography component) and invisibles, the International Trade component consolidates the trade balance (in financial units, using prices in combination with the physical flows). The trade balance is one of a collection of “tensions”; an excessively large positive or negative trade balance flags an unlikely international trade situation (which can be solved in a feedback, as described in the following section).

Other tensions may occur, located in the Natural Resources and Labour components, where requirements are compared with provisions (the comparison is represented by opposing left and right arrow heads). The requirement for land, water and labour is gathered from the individual requirements in each of the economic activities represented in the prior components. Unemployment is an obvious tension between
higher labour availability and lower requirements, while the opposite i.e., more workers required in the economy than is available in the labour force is also a tension, though one that is not physically feasible. Similarly, it is possible to produce a preliminary scenario where water required is greater than available resources, or more land required than land mass.

In addition to tensions, other indicators report the emissions of greenhouse and other gases to the atmosphere, and waste to landfill, resulting from all economic activity. These indicators could also be interpreted as tensions if they are compared with target emissions and wastes. Other information in the ASFF can be used to form further indicators and tensions, such as the level of education and health of the population.

Utilising the Design Approach philosophy in the ASFF, we recognise that the national economy operates primarily to supply the domestic population with food, consumables, goods and services, buildings and transport—either through domestic production or international trade. Consequently, the underlying biophysical processes are largely driven by the demographic information, making allowance for imports and exports. Primary industry, however, is driven exogenously for several reasons: first, this permits requirements by primary industries for secondary materials and energy to be specified as an input to Secondary Heavy Industry; so that the input-output function of basic material and energy transformations can be calculated; second, it emphasises the strong dependence of activity in primary industries on natural resources; and third, it recognises the large role of the extractive industries in Australia’s international trade (Schandl et al., 2008).

The choice of what factors of the economy are represented as tensions, and hence which information flows are represented as provisions and which as requirements, is related to our objective of simulating only the irrefutable biophysical relationships or accounting identities of the biophysical processes operating in the economy. These processes are influenced in the ASFF by behavioural and technological parameters, such as the modal share of transport or the efficiency of vehicle engines, respectively. Values for these parameters are exogenous to the core of the ASFF. Potential feedback loops that involve choice are not built or hardwired into the ASFF but instead left open, to be resolved by inspection or automatically through the use of complementary code, or linking with other models or analysis.

4.2 Completing feedbacks to resolve tensions

Therefore, in contrast with many other approaches, such as Computable General Equilibrium (CGE), and System Dynamics, the tensions first expressed in the ASFF scenarios are not automatically resolved. The ASFF core does not employ any endogenous optimization or model closure. Therefore, resolving the tensions provides the opportunity for people interacting with the ASFF to intervene in the future trajectories.

This application of the Design Approach achieves several important characteristics. Firstly, it is intended to stimulate learning about the biophysical basis of the Australian economy and the resulting environmental and social implications, by emphasising potential conflicts. It aids discovery of the key drivers by tracing back through the linear structure of the information flows. Secondly, it does not internalize past social or economic behaviour, and consequently it is open to the search for innovative solutions that resolve the economic, environmental and social tensions. It does this without incorporating any value judgements between these dimensions, and therefore is not ideologically bound or normative. These characteristics are similar to the objectives of Structural Economics, “which is more about constructing solutions than deducing proofs” (Duchin, 1998).

Alternatively, tensions can be resolved in more automated ways, using feedback code written to alter values of exogenous variables so that tensions are eliminated or other goals achieved. These feedback macros effectively form a layer around the core of the ASFF and are the highest level of feedbacks in the hierarchy employed with the ASFF. The feedbacks can be involved and nested. For example, recent research involved the use of two feedbacks that achieve desired levels of both employment and stable international trade surplus (or debt). One feedback macro primarily adjusts a suite of consumption rates (e.g., food and consumables per capita, vehicles per household, size of dwellings, dwelling energy intensity, domestic and international travel rates, etc.) so that any excess unemployment that would otherwise be created by gains in labour productivity and resource efficiency (Schandl and Turner, 2009) is eliminated by the increased demand for goods and services (Turner and Baynes, 2010). This feedback not only adjusts consumption rates, but also scales the service workforce in proportion with the changes to physical capital throughout the economy. This unemployment feedback is essentially a driver of the ‘rebound effect’ or economic growth at the macro level. A second feedback macro maintains the international trade surplus (or debt) at a nominated level relative to GDP3 by adjusting, inter alia, activity across the industrial sectors in concert with import and export rates. For example, increased production of primary material beyond the domestic requirements facilitates higher exports (while also affecting GDP). Some iteration of these feedbacks is necessary since one affects the other. Other dynamics also occur, due to the influence of turnover of infrastructure and other stocks.

In addition to people or macros resolving tensions, the ASFF can also be used in conjunction with other simulations, such as economic models. For example, preliminary research has involved the soft-coupling of the ASFF with a Monetary Circuit Theory (MCT) model, which is a dynamic simulation of financial flows in the economy (Keen, 1995, 2009). The ASFF and MCT models were linked through each models representation of unemployment and consumption, with the MCT driving the changes in the ASFF (Turner and Baynes, 2010), (and similarly an Asia-Pacific Stocks and Flows Framework was linked with a multi-sectoral MCT model (Turner et al., 2010b)). The potential exists for the ASFF to feedback natural resource constraints to the MCT, creating an iterative process.

A similar interaction could be implemented, in principle, between the ASFF and standard economic models, e.g., CGE for instance. In theory, this would introduce prices to the integrated modelling and the subsequent reaction of the market to resource constraints and other challenges. This

3 The ratio of international trade balance to GDP is a common measure of economic stability, since it indicates how well an economy can service its debt or maintain a surplus on the internal market.
would be most appropriate where future trajectories involve marginal adjustments to production and consumption patterns over time (allowing coupling of the models with minimal changes to the economic model). Analysis and modelling of scenarios involving non-marginal changes would require parameter changes within the economic model (informed by ASFF or other analysis), such as to shift in or out the demand or supply curves for specific goods or services. The case of potential oil constraints may be a prime example, where the future price of oil and alternative transport fuels/systems, and associated societal or market responses, cannot be extrapolated with any confidence from historical trends. Long run modelling of urban metabolism and associated energy and resource use is another example, as over decadal time scales changes in non-price variables (such as planning standards or public sector infrastructure investment) are likely to play a very significant role in shaping urban resource use but these factors are not well represented in price-driven economic models. A primary function of the ASFF is to identify and assess such challenges and potential interactions, and then facilitate the quantitative exploration of potential futures and potential, possibly innovative, solutions.

5 Creating, validating and using the ASFF

Two front-end components of the whatIf software (whatIf, 2008) have been used to create and operate the ASFF, namely the “Documenter”, and “Scenario And Model Manager” (SAMM) respectively. SAMM is used as the interface between the operational model and the user, allowing control parameters to be changed, scenarios to be defined and stored (as the collective settings of all control parameters), and rapid evaluation and display of the resulting model outputs. At the beginning of the process, Documenter is primarily used to design the model using a graphical depiction of model structure, the model variables and the relationships between them. Both SAMM and Documenter employ the Tool Object Oriented Language (TOOL) to provide the programming construct for handling the large multi-dimensional variables. Therefore all observed and constructed data can be represented and simulated in all its complexity. Display of these variables is provided through propriety Graph, Table (spreadsheet), and Geomap applications, with options to export to common spreadsheet and GIS packages.

There are three key stages to the process of developing a decision support model, such as ASFF, using the whatIf applications:

- designing models or frameworks;
- data integration (calibration); and
- scenario creation and comparison.

The first step involves designing the model using the Documenter application, resulting in a graphical representation of the model. This conceptual step consists of identifying the processes to be represented in the framework, and defining the variables and the relationships among them. An important element of design is the designation of the critical uncertainties or tensions that will be the subject of exploratory simulation. It is important that the design not be constrained by the unavailability of data, although model development should be cognisant of the data sources identified. The model design step is best accomplished by the interaction between policy analysts, planners, interest groups and science/technology experts in workshops with the model developer. The programming of TOOL code to capture the variable relationships in terms of mathematical statements completes the design step.

The next step involves the calibration of the model over historical time to ensure that the model outputs are entirely consistent with the observed data. Calibration involves assembly and formatting of all relevant data sets, estimation of missing data, correction of erroneous data, and estimation of parameters and variables that do not have any observed data (see e.g., (Baynes et al., 2010)). The estimation of values for some variables may be comparatively free or in other cases completely constrained depending on the relationships described in the model and the observed data that is available. Either way, the result is a complete and consistent database in the sense that all variables have data over all their dimensions (completeness), and the observed data is reproduced when the model is run over the historical period (consistency).

This is a necessary but not sufficient requirement for validation of the model, where the model reproduces the entire collection of historical data. While the simulated historical reproduction is not independent of the historical input data, the reproduction is a demanding test of the model due to the interactions between the many components of the economy and environment that are included in the ASFF. In a sense these interactions provide additional information due to the structural constraints they impose. Another major component of validation was provided by an extensive review of both the model and the historical data simulation (and base case scenario). This review was undertaken by industry, government and sector level experts through a series of 16 workshops, which have been fully documented (Conroy et al., 2000). The diagrammatic interface of the model, where all variables are shown as inputs and outputs of code boxes (with stocks as barrels, flows as pipes and other parameters as hexagons), facilitates model interpretation. The interface also permits mouse-click access to all data in all variables, as well as each segment of code. Further validation of the ASFF derives from the comparison of scenario outputs, as noted in the following section.

The third step to the Design Approach involves the creation and comparison of scenarios. Scenarios are plausible pathways into the future, plausible in that they are internally consistent (within the framework) and anchored in the present (values of variables at the start of the scenario period are derived from the values at the end of the historical period). Changes to the values of any number of the independent (control) variables are made in the SAMM application. Changes can be made through several interfaces: graphically, tabular, in a geographic display, using Excel, or with the use of individual macros written specifically. Earlier instances of control variables can also be selected from any extant scenario. The resulting model outputs and the control variables can be saved as a scenario, compared with earlier scenarios and used as the basis for subsequent scenarios.

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4 Further development of the whatIf software is planned to integrate the Documenter and SAMM into one model development and operational environment.
5.1 Scenario outcomes

The ASFF has been applied to a wide variety of issues related to the biophysical activity of the Australian economy, as outlined in Section 2. Here we summarise the scenario outcomes of these studies to illustrate the breadth of analysis that can be accomplished, as well as the physical magnitude of the issues facing Australia. A more detailed description of the collection of issues is available in (Turner and Foran, 2008), and substantial detail provided in the studies referenced above (section 2.1). These references also provide descriptions of the many input settings for the scenarios. In general, the scenario settings summarised here are consistent with a “business as usual” continuation of trends, though a key feature of our analysis is the creation of multiple scenarios which are used to explore alternatives and sensitivity. Scenarios, therefore, are not predictions. Error! Reference source not found. provides a summary of the main features of the scenarios in terms of the outcomes and some key input settings.

From a perspective of analytic lessons, we note that fisheries and agriculture have been studied in greater detail and disaggregation (Dunlop et al., 2002; Lowe et al., 2003) following their exploration at more aggregate levels (Foran and Poldy, 2002). Comparison of results from these studies shows a great degree of commonality in the overall outcomes of scenarios. This suggests that high levels of details are not necessary for strategic analysis. The agreement also contributes to the validation of the ASFF.

From the analysis of issues summarised in Table 4 it is not clear that the Australian economy can function adequately in 2050 (or earlier). Serious issues are evident in food supply (both cropping and seafood), water supply, provision of transport fuels, and labour availability, among other issues. These tensions have not been fully resolved, and casual observation suggests that attempting to solve them in conventional ways (with technology and in isolation) leads to increasing pressure on other issues (Turner and Foran, 2008).

Table 4. Summary of scenario outcomes of selected analysis using the ASFF.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Key settings</th>
<th>Issue</th>
<th>Quantitative extent of the issue…by 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Population increases due to net immigration (0.67% pa of population) and fertility rates stabilise at 1.65; n/a</td>
<td>insufficient labour force to support the aging population</td>
<td>dependency ratio (number of young + old people relative to those of working age) about 20% greater than contemporary level, and nearly at historic high</td>
</tr>
<tr>
<td>Technology</td>
<td>efficiency in energy, material, water, etc. use increases towards saturation levels n/a</td>
<td>diminishing domestic production of oil, while demand continues to grow</td>
<td>less than 10% of demand provided through domestic oil production</td>
</tr>
<tr>
<td>Consumption</td>
<td>consumption rates (e.g., consumables per capita, cars per household, dwelling size) increase at historic rates towards saturation levels n/a</td>
<td>reduced water availability due to climate change</td>
<td>30% decrease in river flow in SE Australia, decreasing further if metropolitan water supplies are provided by catchment supply</td>
</tr>
<tr>
<td>Labour force</td>
<td>further increases in productivity that diminish over time</td>
<td>growing proportion of land degraded</td>
<td>40% of agricultural land degraded with 20% lost productivity</td>
</tr>
<tr>
<td>Transport fuels</td>
<td>continued reliance on private cars and road-based freight (diminished by slow increase in rail share); medium probability of discovery rate</td>
<td>lock-in to dirty technological processes due to longevity of plant such as electricity generation</td>
<td>all electricity generation plant built after 2012-2016 must be 100% carbon neutral to achieve 60-90% reductions relative to 1990</td>
</tr>
<tr>
<td>Water resources</td>
<td>global average temperature increase of 2.2 °C by 2050</td>
<td>steady or declining rates of wild catch</td>
<td>wild catch remains 20% below peak rate of the 1990’s</td>
</tr>
<tr>
<td>Agricultural food production</td>
<td>no additions of new agricultural land</td>
<td>increasing greenhouse gas emissions above Kyoto reference levels</td>
<td>CO₂ emissions from electricity generation and transport increase to 250% of 1990 levels</td>
</tr>
<tr>
<td>Fisheries</td>
<td>deliberate management of fisheries to avoid biomass depletion (fishing curtailed when biomass drops below maximum sustainable yield)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>continued growth in per capita energy and material consumption of ~2% pa pc; and average plant lifetimes of 40 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissions</td>
<td>electricity generated by thermal coal-based power stations, with efficiencies increasing at historical rates towards 50% in 2050; likewise for automobile internal combustion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It is also evident from recent and ongoing research into the potential to ameliorate these national environmental challenges, that considerable change in multiple aspects of society and the economy are required to achieve sustainable economies (Foran and Poldy, 2002; Schandl and Turner, 2009; Turner, 2011 (in press); Turner et al., 2011, to be published). Some of these studies are based on scenario analysis while others vary (sets of like) parameters across a range of values akin to sensitivity analysis. It is evident from the size of the changes required that typical uncertainties present in the model parameters do not substantially influence the strategic outcomes of the simulations. We understand this to be due to a combination of effects, in particular: national outcomes are an aggregate over many spatial and sectoral contributions, which dilutes individual uncertainties; cancelling out of uncorrelated error terms, which is more likely in a multi-variable model; and the inertia associated with the dynamics of vintage stocks, which causes the system to be less sensitive to variations in parameters.

6 Commonality between the ASFF and other methods for system analysis

The ASFF has many features in common with other methods and approaches used in system-wide analysis of sustainability, such as Mass Flow Analysis (MFA), Physical Input-Output Table (PIOT) analysis, System Dynamics (SD), and Life Cycle Analysis (LCA). However, despite the complementary nature of the ASFF, it cannot be categorised as any of these well known approaches. It would be possible, for instance, to construct MFA, IO and LCA data from the ASFF, but it is not possible to build the ASFF from any of these alone. In this section we outline the commonalities and differences between the ASFF and other approaches that are generally used in sustainability analysis. The comparison is generally based on the characteristics of the common application of the different approaches since it is beyond the scope of this paper to comprehensively review their extensions and research activities.

6.1 Material Flow Analysis (MFA)

Like MFA accounts (Matthews et al., 2000; Weisz et al., 2007), the ASFF records the flows of materials that enter and exit the economy, either as domestic extraction and output (wastes and emissions) or via imports and exports. Both approaches also identify the accumulation of materials within the economy, as infrastructure and other stocks. This is done explicitly in the ASFF typically by calculating the stock dynamics based on lifetime characteristics and incremental requirements for the stock. Conservation of mass and energy form the basis for both MFA and ASFF, though the aggregate balance is not established in the ASFF.

In contrast, MFA commonly employ a mass balance identity (essentially, inputs equals outputs plus change in stocks) to establish the net addition to stocks, but not the final stock level. In this sense, MFA generally treats the economy as a “black box” (Weisz et al., 2007) i.e., without details of the transformation processes within the economy (though more detailed analysis on processing, recycling, etc. has been undertaken e.g., on the US economy by the WRI (Wernick and Irwin, 2005)). It is therefore necessary to draw a somewhat arbitrary boundary between the environment and the economy, requiring distinctions to be made for example about whether livestock and animals are inside or outside the black box of the economy. It is not necessary to draw a distinction between the environment and the material economy if both are explicitly included in the analytic capability, as in the ASFF. For instance, we may represent land and agricultural practices on that land without having to draw a line between when that land is an asset of the environment or the material economy.

The MFA focus on flows reflects the general difficulty in establishing good data on stocks, so flows to and from the environment are used as indicators of pressure on the environment. In addition to stocks within the economy, and in contrast with MFA, the ASFF also records the environmental stocks, such as water and mineral resources, and wastes accumulated in the environment. The information on stocks within the ASFF relies on the dynamic nature of the simulation and at least one estimate of the stock level at a point in the time frame of the ASFF, while MFA tends to be static. Several advantages result from the dynamic nature of the ASFF, namely:

- identify drivers of change since the factors leading to stock growth or reduction are represented;
- environmental status is properly and explicitly represented via stocks (flows do not of themselves indicate the status); and
- scenarios of the future can be simulated, whereas MFA are used to report current or historical data.

6.2 Physical Input-Output Tables (PIOT)

As a complete account of the Australian physical economy the ASFF is not an IO approach in the traditional sense (i.e., representing the flows between sectors in a matrix, in combination with final demand and input vectors). There are several differences, not least of which is the inclusion of stock dynamics, which are rarely included in IO models (but see e.g., (Duchin and Szylk, 1985)). Also, IO tables are often based on monetary flows, while the ASFF tracks flows of physical quantities. Another difference relates to the use of tensions, as described above.

However, we can draw significant similarities between the ASFF and IO analysis (in addition to the IO process used in the basic industry module described above), as explained in the following. Parameters in individual sectors of the ASFF effectively relate the quantity of inputs required per unit of output of that sector.

In Error! Reference source not found., the physical inputs simulated in the ASFF that are required by a sector in a column of the table are indicated (by ‘x’) against the sectors in rows that directly provide those physically substantive inputs. For example, the demography sector requires consumables, services (e.g., education), buildings (dwellings) and transport. The cascade of requirements continues as depicted in Error! Reference source not found.. The service sector requires buildings (hospitals, schools, etc.) and labour. The labour force is provided by the population (i.e., ‘demographic sector’), but this may not be the same as the aggregate labour required by the economy, so this difference or tension is indicated (by ‘T’) in the upper triangular segment of the IO structure in Error! Reference source not found.. The upper triangular segment of the IO structure contains only flows or

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requirements that are either negligible or have been treated as tensions, or accounted for in other ways, as explained below.

Table 5. Summary of physical IO structure of the ASFF. ‘x’ indicates a (significant) physical requirement modelled in ASFF from the row sector into the column sector. Tensions between requirements and provisions are indicated by ‘T’; negligible flows are indicated by ‘δx’. The IO matrix for basic industry is indicated by ‘B’.

<table>
<thead>
<tr>
<th>Physical flows between sectors</th>
<th>Receiving sectors / modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Providing sectors/ modules</td>
<td>Demography</td>
</tr>
<tr>
<td>Demography</td>
<td>→</td>
</tr>
<tr>
<td>Consumables</td>
<td>→</td>
</tr>
<tr>
<td>Services</td>
<td>→</td>
</tr>
<tr>
<td>Air emissions</td>
<td>→</td>
</tr>
<tr>
<td>Buildings</td>
<td>→</td>
</tr>
<tr>
<td>Transport</td>
<td>→</td>
</tr>
<tr>
<td>Primary industry</td>
<td>→</td>
</tr>
<tr>
<td>Light industry</td>
<td>→</td>
</tr>
<tr>
<td>Basic industry</td>
<td>→</td>
</tr>
<tr>
<td>International trade</td>
<td>→</td>
</tr>
<tr>
<td>Labour</td>
<td>→</td>
</tr>
<tr>
<td>Land</td>
<td>→</td>
</tr>
<tr>
<td>Water</td>
<td>→</td>
</tr>
<tr>
<td>Minerals &amp; biota</td>
<td>→</td>
</tr>
</tbody>
</table>

T
Consequently, the economy-wide physical IO coefficient table is triangular, as illustrated in *Error! Reference source not found.* (Note that the IO table of coefficients for basic industry is an exception and is not triangular; it uses an iterative algorithm to determine production levels.) Also note that basic industry supplies energy and materials for primary industry, which is reflected in the row and column order of Table 5. A similar approach has been developed by Nakamura et al. (Nakamura et al., 2007) where they established a hierarchy of sectors according to the degree of fabrication and hence imply a triangular table.

This contrasts with monetary IO tables, which have many entries throughout the table due to the multitude of monetary flows between industries. An important case is that of services, which may involve relatively large monetary flows from other sectors to services but generally negligible physical flows of materials and energy in the opposite direction other than the availability of service labour (virtually by definition).

Table 5 indicates services dealt with in two ways in the ASFF. First, services to the general population, such as health, education and retail are dealt with explicitly. So too are most transport services, which are physical. Second, other services are effectively supplied to various sectors (shown by δ in the upper triangular section of the IO table) in the sense that these service workers are initially specified exogenously, and therefore we deal with these through the mechanism of tension resolution. This arrangement is made because these services provide predominantly non-physical outputs, such as financial advice for investments made in the various sectors. Consequently, with this service labour (at least initially) specified exogenously a tension may arise between the total labour force required and that available (which is based on the population and participation rates). One way we deal with this tension is using a feedback discussed above (section 3.2), which ensures a specified unemployment rate is achieved. This feedback not only adjusts consumption rates, but also adjusts the service workforce in proportion with the changes to physical capital throughout the economy. Alternatively, monetary IO data could be used in possible future research to establish the service workforce.

Two further examples of physically negligible input flows in the ASFF are: the requirement in the industrial plant of basic industry (after transport, thereby driving the requirement for freight vehicles and subsequently the demand for materials embodied in these vehicles to be produced by the basic industry sector (after allowing for trade of vehicles and materials). The calculated volume of materials (primary and secondary) produced can then be used, in an iterative manner, to inform revisions of the volume of inter-urban freight. In practice, few iterations are required for this calculation to converge.

(In subsequent developments of the ASFF, this approach has been modified, so that freight volumes are driven by the requirements for the movement of goods and commodities of all sectors other than basic industry. This leaves a smaller component of freight movement to be set exogenously and solved by iteration as described above. In terms of the IO structure in *Error! Reference source not found.*, the transport row would be moved down the table, and the transport column moved to the right.)

Key tensions (‘T’) that occur in the international trade, land, water, air emissions and labour are presented. Requirements for flows associated with each module are aggregated within the module, and then compared with the provision of land, water, etc. In the case of international trade, domestic export volumes are aggregated across the light, primary and basic industries and the trade balance (physical and monetary tension) formed with the specified import volume of the same goods and commodities. These tensions are left open for the user to close.

The primary advantage of this approach (i.e., effectively making the IO table triangular) is that the chain of cause-and-effect is made considerably more transparent and tractable because it is linear in the sense that key factors of change can be traced through the structure of the ASFF in a tree-like path. This is obtained at the temporary loss of some accuracy associated with the initial omission of negligible flows, δ—though the adjustments described above are used to ameliorate this. In contrast, the standard IO approach implicitly incorporates all flow on effects in the inverse Leontief matrix, but consequently this complicates the task of untangling the interactions between sectors or industries. This is related to the observation that IO models achieve consistency at the macro-economic and sectoral levels simultaneously (Duchin and Steenge, 2007). Decomposition techniques can be applied to IO matrixes (Lenzen, 2007) to show the indirect contribution of all other sector output to a unit of production in a particular sector. However, they do not show explicitly how those contributions arose—e.g., indirect electricity used will arise from the use by many other sectors. The ASFF in contrast, shows all the processes and dependencies explicitly, without requiring mathematical skills.

Basic IO models also focus on flows, like MFA, while the ASFF makes explicit the dynamics of environmental stocks. Advances in IO modelling have moved beyond early constraints in various ways: incorporating environmental flows; linking consumption to income (“closure for households”); spatial disaggregation; and incorporating dynamic effects including productive capacity. The latter implies that a solution for the IO matrix equation cannot be found using the standard inverse technique (Duchin and Steenge, 2007). The ASFF incorporates such features of advanced IO (except for the linking of income with consumption), while the structure and implementation of the ASFF emphasizes transparency and openness to non-technical users, while maintaining substantial detail and complexity.

### 6.3 Life Cycle Analysis (LCA)

The ASFF is similar to LCA since the ‘cradle to grave’ concept of LCA is dealt with explicitly in the ASFF by the use of stock.
dynamics to track the manufacture, use and disposal/recycling of a variety of artifacts. LCA focuses on particular products (or services) and calculates the direct and indirect material and energy requirements, and wastes and emissions, associated with the complete life cycle of alternative products that can be substituted for each other (Curran, 1996). Like the ASFF, LCA conceptually extends from resource extraction, processing and fabrications, to the disposal /recycling (‘cradle to cradle’) of products.

However, in LCA the indirect physical flows arising from a proportion of the chain of supporting activities, such as transportation and financial services, are attributed to the products being compared; the ASFF does not make such attributions. Therefore the LCA approach is suitable only for marginal comparisons of similar products since it is based on the structure of the economy being largely unchanged (so that the attributions of indirect physical flows remain valid).

Additionally, LCA does not consider the aggregate impacts of the economy-wide adoption of alternative products. This is a role that the ASFF fulfils by allowing different products or technological processes to be substituted for each other in scenarios of the national economy, where the economy may be structurally similar to or distinct from the current economic structure. It seems that this application of the ASFF could be used to generate LCA data. Further, the ASFF incorporates the temporal effects of infrastructure turnover and explicitly identifies the levels of resource and waste stocks, which are not captured in LCA.

6.4 **Computable General Equilibrium (CGE)**

Some high-level commonality exists between the ASFF and CGE models, since both are typically concerned with the future of national economies and the dynamics of interactions between sectors. Both are calibrated using historical data, though the ASFF calibration process employs fitting to time-series data while CGE models utilise statistically derived data. CGE models are driven by sets of equations representing relationships between sectors based on relative prices of factors of production (particularly labour and capital) and outputs from various sectors, thus modelling market activity. The ASFF, in contrast, is a process-oriented simulation of the economy in physical and engineering terms and does not make any assumption about the behaviour of economic agents (unless external feedbacks are employed). When applied to resource and environmental issues, CGE models calculate changes in economic activity and resources in the economy, and across sectors and regions, relative to a reference case (with no policy change or other shock). Due to their calibration and structure, CGE models are best suited to analyse marginal changes in rules and resource allocation in each time step, and focus on flow variables (such as GDP, employment, or investment) rather than stocks or asset values. Consequently, CGE models typically do not provide information on the level of resource stocks or environmental status, while this is a key aspect of the ASFF.

Perhaps the largest difference between the ASFF and CGE models relates to the questions and assumptions explored by these different modelling approaches. CGE models are used to develop suites of scenarios involving well defined ‘shocks’ or variations from a reference case, such as the introduction of a carbon price, or a variation in autonomous energy efficiency improvement over time. CGE models explicitly incorporate a significant role for the effect of changing relative prices in resource allocation and avoiding long-term disequilibrium. From this perspective, concerns are sometimes raised by economists at the lack of explicit price signals within the ASFF and associated endogenous changes in economic activity or structure that maintain equilibrium. This criticism neglects that, in practice, CGE modellers give significant attention to ‘sense testing’ and undertaking quality assurance on modelling outputs. It also fails to appreciate that the role of price signals is implicitly included in the historical and projected future relationships (for business-as-usual scenarios) across sectors and physical processes represented in the ASFF. Last, these concerns about price signals fail to recognise the importance of non-price factors in shaping future resource use and patterns of economic activity—particularly step changes in technology (such as the emergence of computing) and the influence of government regulation and public sector investment—which do not arise from the interplay of relative prices in existing economic markets. We thus consider that the ASFF and CGE models have distinctive and complementary contributions to exploring future challenges and potential responses.

6.5 **Other methods and techniques**

The ASFF has common features to other methods used in sustainability and system analysis. The use of stocks and flows is a key feature of system dynamics (Randers, 1980), and these elements are related through differential equations. Incorporating feedbacks is a distinguishing feature of system dynamics and while the ASFF also embodies feedbacks, it does so in a hierarchical manner as described in Section 2.1.

Several advantages follow from this variation. Firstly, ideological bias is removed from the core of the ASFF since the core represents largely irrefutable accounting relationships reflecting mass-balance. Therefore, particular opinions are not built into the core calculations, so that behavioural response or policy choice is exogenous. However, a second strength is that it provides the flexibility to test a wide range of opinions and proposals since there are many inputs to the ASFF that encompass behavioural, engineering and technological change. Thirdly, the linear structure of the ASFF (arising from the Design Approach) substantially enhances learning and understanding since physical cause-and-effect paths are more readily traced. This has proved to be an important feature supporting model transparency, since it allows us to readily explain modelling outcomes. Fourth and finally, it is possible to obtain complex and non-linear outcomes (despite the linear structure), through the use of manual or coded feedbacks that embody past or potentially new socio-economic behaviour.

It is also possible to perform uncertainty and sensitivity analysis on the ASFF variables by constructing macros that repeatedly vary the values of parameters and control variables with systematic increments, and present the results as a family of curves. This requires the probability distributions to entered as input to the macros, and is therefore not as convenient as models, such as FORESCENE (Bringezu et al., 2009), that utilise Bayesian network techniques for dealing with uncertainty. The latter, however, complicate the modelling of dynamic processes. Additionally, the outcome of such uncertainty analysis is very dependent on the estimates (often rather subjective) of the probability distributions.
The use of stocks and flows is also a key feature of more detailed analysis, such as that on metals e.g., (Gerst and Graedel, 2008), which is mostly historical. Other metal stock analysis has been developed in spreadsheet format (Hedbrant, 2001) with evident parallels to the ASFF. These approaches highlight specific detailed issues at elemental levels, while the ASFF aims to make connections with other resource issues, such as energy, land and water.

7 Improvements being implemented

Comparison with complementary approaches in sustainability assessment, as above, can help to guide further improvements of the ASFF. Also, through experience in applying the ASFF in a range of research projects, other constraints of the ASFF have been identified. A summary of these issues and recent and ongoing modifications to improve the ASFF is provided here.

Two common and important issues raised about the ASFF are somewhat conflicting, namely the desire for easy interactions with the ASFF, as well as considerable interest in having more detail (especially spatial). The ASFF described here has a large number of multi-dimensional exogenous inputs (about 300) and even more outputs (about 500), which makes creating scenarios and interpreting the outcomes a complicated task requiring specific skills. Nevertheless, stakeholders often seek greater spatial detail (i.e., at regional or local scales), and desire coverage of more specific materials or commodities (such as provided by many IO analyses).

To enhance the potential for engaging with stakeholders, and other research approaches using standard measures, recent extensions of the ASFF involved the development of a GDP estimate and a Quality of Life (QoL) indicator. The inclusion of these indicators is to allow us to examine how changes to the environmental and physical aspects of the economy are related to changes in the GDP and QoL. They also demonstrate the utility of summary indicators or comparisons, which is a particular advantage of MFA and LCA.

Also as noted, interacting with the ASFF is potentially challenging—the ASFF is more like a flight simulator of a large passenger jet than a single propeller aircraft, in which it takes significant expertise and familiarity to operate the ASFF. Consequently, a recent development has incorporated a mechanism for creating a wide range of alternative scenarios with a small number of settings (of order ten). These settings have been grouped around social behavioural variables (consumption rates), technological options (efficiencies of resource use, pollution control) and economic factors (mode substitution, labour productivity).

The other major issue that has arisen when using the ASFF is resistance to accepting the modelling outcomes by some stakeholders, a common experience for many models. We have described above features of validation and transparency that aimed to address this. We have also outlined above how the concern of standard economists about the “lack of prices” is misplaced in long-term strategic analysis where the focus should be on exploration, and accuracy rather than just precision. To aid engagement with stakeholders seeking greater resolution, the ASFF is in progress, summarised in the following:

access to all calibration data and manipulations through a parallel diagrammatic interface, including updated data on: agriculture; fisheries; industrial processes; and emissions. The restructured hierarchy of modules/components to align with the standard industry code structure (ANZIC) increased and more uniform spatial detail (to more than 1400 Statistical Local Areas (SLA) for households and about 200 Sub-Statistical Divisions (SSD) for most other aspects); time step decreased to 1-year in most components; collected tensions indicators, including those associated with input-output dependencies beyond the basic industries module; introduced several new or expanded components for greater detail on: energy end-use, including combined heat and power; distributed electricity production, including renewable and fuel-based power; service economy represented more explicitly refinements to several modules: basic industry materials and energy processes expanded and better data; agriculture; fisheries; and water accounting e.g., (Baynes et al., 2010; Turner et al., 2010a);

8 Summary

The Australian Stocks and Flows Framework (ASFF) has been developed to assess the biophysical longevity of the Australian economy. This is in keeping with Hall and Klitgaard's principle to "start with the essential process, value it on its own terms and on its contribution to the welfare of all creatures on this planet (including humans) and think about money only much later" (Hall and Klitgaard, 2006).

The ASFF applies top-down coverage of the physical economy, based on bottom-up detail. It shares common features with other popular approaches, including MFA, PIOT, and LCA, but is distinctly different from these. We might summarise the ASFF as a dynamic life cycle stock-extended MFA based on IO or activity analysis principles. It spans, and expands on, all of these separate approaches because the biophysical processes throughout the economy (and environment) are represented explicitly. It is also necessary and advantageous to structure the sectors of the economy in a logical hierarchical manner, making use of the concept of “tensions” that require people to resolve them. The ASFF has a strong empirical basis—the detailed physical account of the national economy is calibrated with six or more decades of historical data, such that this data is reproduced identically (not in a statistical sense).

Given the ASFF’s coverage of the entire economy in physical terms, it provides for many subject specific analyses whether it be water, energy, climate change, etc. Despite the acknowledgement that sub-systems of the economy have
substantial interdependence, single interests or institutions lack the time or resources to put their issue in context or as part of a whole-system. The ASFF provides the capability for undertaking the necessary integrated assessment, and can be easily adapted to represent specific interests in more detail and context, as demonstrated by multiple applications of the ASFF to date.

The open biophysical nature of the ASFF is intended for development of strategy, rather than being normative or policy prescriptive. It is designed to explore the question of where the national economic system can go over the long term within irrefutable biophysical constraints, to inform the development of appropriate policy. No optimisation or ideology is built into the core of the ASFF, though socio-economic feedbacks can be incorporated in several ways. The ASFF employs mass-balance identities associated with stock and flow dynamics throughout the national economy and its interaction with the environment, but does not model behaviour, instead using many exogenous inputs for parameters of social, economic and technological change. In its operation, the ASFF is very analogous to a flight simulator, where the pilot learns from experimenting in the computer environment, to avoid crashing the aircraft in real-life.
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References


9 Appendix (or supplementary on-line material)

9.1 Description of the modular components

The following sub-sections outline the coverage and main calculations of the modules used in the ASFF. Other calculations and considerable detail is available in (Poldy et al., 2000). Not all of the disaggregation in the more than eight hundred ASFF variables can be described in the scope of this paper, and we do not repeat below that nearly all variables are indexed by time-step so that, for example, rates and intensities can change over time.

9.1.1 Demography

The Australian population in the ASFF model evolves from a base population at the start of the simulation according to a standard cohort model and is determined by exogenously specified immigration and emigration, and birth and mortality rates. Many of these factors are detailed by gender, age, simulation year and state location. Internal migration between states is also specified, and state population is split between capital city and the rest of state. The number of households is obtained using age-based formation rates (where age relates to the head of the household) applied to the located population. The calculated population and household stocks are used in many subsequent modules throughout the ASFF.

In addition to the domestic population, the ASFF accounts for the flow of international visitors (on business or for recreation, and from different countries) in terms of their length of stay (person-days).

9.1.2 Consumables

The ASFF calculates the consumption of food and short-lived products (paper, plastic, textile, chemical (organic or non-organic) or pharmaceutical products) using per capita consumption rates. Different rates are applied to the domestic population and international visitors. Since the short-lived products are consumed within the time-step of the simulation they are represented as a flow, and not formed into a vintaged stock.

9.1.3 Dwellings, Other Buildings and Services

To inform the requirement for building space, the ASFF first determines the level of services required by the domestic population and international visitors. Education loads are calculated from the disaggregated population combined with participation rates in primary, secondary and tertiary education. Similarly, the need for health care (expressed in terms of beds) is driven by the population and various morbidity rates and the fraction of the population requiring long-term care.

In addition to international visitors, the ASFF includes travel within Australia by the domestic population (in person-days and by location). In combination with several usage rates, the requirement for accommodation (in beds) and restaurant services (in terms of seats) is generated. These flows of services are converted to a requirement for various building floor spaces via appropriate intensities (e.g., beds per square metre for health care). The space required for retail, wholesale and institutional buildings is derived from the domestic population and per capita area intensities. Similarly, office building floor space is proportional to the number of occupational service workers, which is proportional to domestic population. Buildings associated with manufacturing and processing such as factories are treated elsewhere since the number of people does not directly determine the number of these buildings.

The requirement for dwellings is associated with the number of households, which can have more than one dwelling. Dwelling type is specified by a share parameter and can be single detached units or units that incorporate higher density multiple households. A floor space intensity converts the number of dwellings to total floor space required.

The vintaged stocks for dwellings and all other buildings are evolved from the base stocks at the start of the simulation driven by the floor space required and specified demolition rates, which are differentiated by age of the building. The new floor space required is combined with building mass intensities and material composition parameters to obtain the construction material required. Demolition waste produced is derived from the age-related mass and composition of the buildings demolished in each age cohort.

Materials, water and secondary energy flows for maintenance and operation of buildings are specified on a square metre of floor space basis and vary by building type. In this version of ASFF, end-use detail was not included. The contents required in buildings such as furniture and equipment are specified per unit floor space, and are replaced over time as they are discarded according to a life-table for these contents. This life-table, like others used in the ASFF, is specified in terms of the width and inflection point of a logistic curve describing the fraction of a stock that survives at each time point.

9.1.4 Transport

The transport modules in the ASFF principally determine the (vintaged) stocks of passenger and freight vehicles, as well as road infrastructure, operational inputs required and wastes/emissions produced. Intra-city and inter-city movement of people and of freight is dealt with in separate modules. The general order of calculations is to determine the passenger- or freight- kilometre load first, then evolve the vehicle stock to meet this requirement, and finally calculate the inputs and outputs associated with operating the vehicle stock.

The intercity passenger-kilometre load is determined from the size of the domestic population and international visitors, multiplied by kilometre travel rates. Modal shares are used to split the load between cars, buses, rail and air transport. This approach is suitable for the strategic long-term purposes of the ASFF, compared with more detailed simulations appropriate for operational purposes that might attempt to represent travel over a network. In the case of intra-city travel, the labour

5 (Stock at time $t + dt$, with age $a$) = (Stock at time $t$, with age $a – dt$) – (discarded stock between $t$ & $t + dt$, with age $a – dt$) + (new stock between $t$ & $t + dt$, with age zero; or zero if existing stock is sufficient to meet demand for stock at time $t$); where (discarded stock between $t$ & $t + dt$, with age $a – dt$) = (Stock at time $t$, with age $a – dt$) x (fraction, between 0 & 1, of stock demolished at time $t$, age $a – dt$).
passenger- or tonne-kilometre loads are calculated using such as rail and port facilities, where not incorporated in this new roads constructed. Other transport infrastructure, conversion of road types, and the materials used for these and other parts of the ASFF. This approach enables the overall IO structure of the ASFF to be made triangular (except for the heavy industry IO calculation), enhancing the tractable nature of the chain of cause-and-effect, as discussed further in the section comparing the ASFF with IO approaches.

The calculation of the stock of vehicles other than cars is done separately and in somewhat less detail than for cars. The required stocks of non-auto vehicles that delivers the passenger- or tonne-kilometre loads are calculated using specified load factors and yearly distances travelled (not based on a network model with the ASFF). The calculation of the evolution of the vintaged vehicle stock proceeds in a manner similar to that of the building stock, with an additional share parameter for selecting alternative vehicle types. This parameter enables substitution and operates at the margin i.e., allowing choice among the types of new vehicles (e.g., articulated or non-articulated trucks, or rail, etc.) added to the fleet.

The vintaged stock of cars is essentially composed of personal and fleet autos. The latter are commercial fleet and hire cars, and are determined by the size of the service work-force, the domestic population and the international travellers, with different rates of cars per person. Personal cars are calculated using the number of households and cars per household. The required stock of cars is then evolved as for other vehicles, with choice of new cars based on different fuel/drive-train types (hydrocarbon fuelled, hydrogen based, or electric). Average yearly distance travelled per car is calculated by treating commuting separately from personal/fleet travel, with the former including work year and commuters per car specified exogenously.

For each of the vehicle types generated above, operating materials, energy use, labour required and emissions produced are calculated based on the vintaged stocks, distances travelled, and corresponding intensities which are indexed to the age of the vehicle technology. Additionally, to allow for operational improvements or degradations that are not constrained by turnover of a vintaged stock, there are engine modification parameters that can apply irrespective of vehicle vintage.

The length of roads (rural or urban, and scaled or unscaled) is not related directly to the stock of vehicles, but set exogenously for rural roads and scaled to the city populations for urban roads. Allowance is made for maintenance and conversion of road types, and the materials used for these and the new roads constructed. Other transport infrastructure, such as rail and port facilities, where not incorporated in this version of the ASFF.

9.1.5 Secondary Light Industry

Modules in the secondary light industry section of the ASFF cover construction (of buildings and roads), food processing, manufacturing of goods, and material recycling operations. In general these modules bring together the various material flows of goods and artefacts that have been derived from the elements of the ASFF described above, and determine the processing capacity needed to meet the requirement. The processing generally involves a conversion of basic materials into the goods, etc. required. This demand for basic materials becomes an input to the secondary heavy industry section, described below, which converts raw materials into basic materials and energy. The processing activities of light industry also drive a requirement for energy, materials and labour, and generate emissions.

The module dealing with construction takes as input the previously calculated flows of materials incorporated in new buildings, demolished buildings, new roads and road reconstruction, and uses specified machine and labour intensities to establish the required number of construction machinery and workers. The vintaged stock of machinery is evolved using a life table (for a logistic-curve), as above, and combined with energy intensities to obtain the energy required in construction.

In the food processing module, the foods consumed are first split between that flow produced domestically and an imported flow, specified by as a fraction of the total consumed (and it is possible for more food to be imported than is consumed). The domestically produced food drives the evolution of vintaged plant for food processing, with the location of the plant specified through a share parameter. The plant capacity is expressed in terms of tonnes of food output per time step, and its location is used to inform local water use requirements. The materials incorporated in the plant and those demolished are calculated using a composition share parameter and a throughput ratio (scaling the plant mass to capacity). A set of intensities parameters scale the food produced to energy, labour, materials and water required, and emissions produced.

A light manufacturing (processing and assembly) module consolidates the production of new goods required from final demand goods (associated with building contents), intermediate goods (consolidated from the various operating goods) and vehicles (for all forms of transport), and calculates associated packaging. For each of these goods, the flow of exports is specified exogenously and adds to the domestic requirement, where the latter is reduced by any imports (which are specified as a fraction of the gross domestic requirement). A specified mapping converts each good into its material composition, to become an input to the calculations in the heavy industry module. The flow of goods drives the evolution of manufacturing plant, and the consequent labour, energy, and water required, and emissions produced.

The eventual destination of material wastes is dealt with in a recycling module. This module consolidates the flows of discarded consumables and goods (including vehicles and machinery), and demolished buildings and infrastructure. A fraction of these flows are allocated potentially to be recycled, with the remainder added to the cumulative landfill stock. The flow of potential recycled materials adds to a stockpile, and this is drawn by an independently specified planned amount to be recycled in each time step (or whatever remains).
9.1.6 Secondary Heavy (or Basic) Industry

The module covering basic industry deals with the transformation of raw materials into basic materials (e.g., steel) and secondary energy forms (electricity and fuels), as the foundation of the physical economy. The demand for materials and energy produced by basic industry is driven by upstream sectors that are either linked to population (e.g., building operations), or associated with primary industry (e.g., mining). The basic industry module first consolidates all the material and secondary energy requirements from the entire Australian economy. To these gross domestic requirements are added exogenously specified exports, while imports (specified as a proportion of domestic requirements) and recycled materials are subtracted, to yield the net flow of basic materials and secondary energy that must be produced in Australia to satisfy final demand. These flows are key inputs to a complex Input-Output (IO) application (Lennox et al., 2005), which allows for the output of each industry to be a potential input of other industries i.e., intermediate production. (Inter-industry coefficients in physical IO tables represent the quantity of inputs per unit output in physical units, as opposed to the more common monetary IO tables (Miller and Blair, 1985).) The ASFF IO simulation follows the activity analysis approach (Koopmans, 1953) in allowing multiple processes available for producing identical outputs (allowing for substitution); the use of time-dependent IO coefficients allow the technological coefficients of the production processes to be exogenously changed over time (incorporating efficiency gains for example); and the stock of productive capacity (factories and power plant) evolves dynamically to satisfy demand for secondary materials and energy. Joint production or by-products are not handled in this version of the IO application, though it is possible to incorporate such aspects.

In order to evolve the production plant of basic industry and calculate the material and energy flows needed for their construction (which become part of intermediate production), several exogenous parameters describe the lifetime, throughput and material characteristics of these plant. New plant will be built if the existing productive capacity cannot meet the total material or energy need. The type of transformation process used in the new plant and the location is exogenously prioritised (although the final demand is not disaggregated by location, so that final demand is satisfied by the total plant capacity).

The IO calculation reports the vintage plant capacity, total output of basic industry and the part that is intermediate production. The primary materials required by basic industry are calculated from the reported output, multiplied by an exogenous parameter of the ratio of primary material inputs per unit output. The flow of primary materials required is passed on to the module dealing with International Trade, where it will be compared with primary materials produced in Australia. The total output of basic industry is also used to determine labour and water requirements, and emissions produced by these plant.

9.1.7 Primary Industry

The production of primary materials in the ASFF covers agricultural, forestry, fisheries, and mining. These sectors are driven exogenously, not from the required primary materials that is derived in the secondary heavy industry module, and the calculated production flows are inputs to the International Trade module.

9.1.7.1 Crops and Animals

Production of crops for food and fibre in the ASFF occurs across 58 statistical divisions, on stocks of land vintaged by first year of production. This is determined from specified additions of new land and deletions from the existing stock. The agricultural land stock is apportioned to ten crop types, each of which may be irrigated and/or fertilised, and also allows for fallow or idle land. A relative degradation (or improvement) of land condition (associated with acidity, dryland salinity, irrigation salinity, or soil structure) is specified per unit agricultural activity so that the evolving trophic condition of each vintage is calculated from the cumulative effect of agricultural activity. A change of the base productive yield is derived from this land condition by lookup of a (potentially non-linear) response function. Yields may be increased through fertilisation, irrigation or plant genetics; or affected by a weather-related factor. The contributing factors are combined into a final yield (t/ha), and then multiplied with each area of agricultural land activity and integrated over the vintages to obtain the total gross crop production.

A proportion of the crop production is reserved as seed for subsequent crops, and another proportion for feed to animals. Separately, the size of (seven types of) livestock is set exogenously for each statistical division and the local animal feed requirement (generated from an intensity variable) is compared with that available from crops (which may be distributed using a share parameter to other statistical divisions). Any excess feed crop production is reported as a tension. If there is insufficient feed from crops, then the remaining feed requirement is delivered by grazing, which drives the requirement for grazing land (via a feed productivity parameter). Animal products (edible commodities, such as beef, poultry and milk, and inedible products, namely wool and skins) are generated from the livestock size and production capacity per animal, and this flow becomes an input to the International Trade module.

9.1.7.2 Forestry

Forestry involves the production of roundwood and pulpwood from plantation and native forests in a range of ecological regions (e.g., tropical rainforest, ash forests of the south-east and native pine). A series of management regimes are used, such as clear cut, selective cut and primary. Several input parameters (mostly specified as a function of tree age) describe the growth dynamics of each forest type, namely the volume of wood per tree, spatial density of trees, tree mortality rates, and frequency of loss due to fires. Without change in these parameters and any other forest intervention the forest volume calculated in the stem growth model used would reach equilibrium over time.

Other input parameters specify forestry management factors, namely planned additions/deletions of forest land, transfers of land between a selection of management regimes, planned wood volume production, minimum age for harvesting trees, and the proportion of forest lands that are replanted (while open forest land will self-seed). The forestry module calculates at each time-step the tree inventory by first accounting for aging and fire losses, then makes the imposed
changes in forest land areas, and finally harvests trees up to the planned wood volume production. The actual volume may be less than planned if there are insufficient suitable trees. Additional “windfall” wood comes from any forest land deletions.

The requirements for different forestry machinery and labour is driven by the number of trees cut, wood volume harvested, and forest area replanted. The evolution of machinery stock is aged as usual, so the flow of discards are passed to the recycling module and the required flow of new machines passed to the processing and assembly module. The machinery stock and appropriate intensity factors determine the energy and operating materials required for forestry operations.

9.1.7.3 Fisheries

Fish for consumption is harvested separately from both wild fisheries (marine and freshwater) and fish farming operations. For the former, exogenous inputs set the desired catch of fish by commercial fishing, both domestic and foreign operations in Australian waters, and by recreational fishing. The fish units are given in combinations of the fish species and the fisheries management jurisdiction (which may be approximately geographically based in many cases). The stock levels of wild fish species are then determined by the consolidated desired catch rates and biological parameters of the species, namely virgin (maximum) biomass, and species recovery rate (time to regenerate in the absence of fishing from 10% to 90% of virgin biomass). These parameters are used in a simple logistic growth (or Schaefer) model to capture the population dynamics of species in response to exploitation—at low biomass levels the growth rate is small to model reproductive limits of a low density population, but the growth rate increases with biomass until at 50% of the maximum (where the maximum sustainable yield occurs); for greater biomass, the growth rate slows and reaches zero at the maximum biomass to model the effects of species competition for resources. The actual catch realised may be less than the desired catch if there is insufficient biomass (i.e., biomass less than the desired catch), in which case the actual catch equals the biomass (from the previous time-step – before the growth dynamics is calculated). In a modified version, the calculation also accounts for fish harvest by mammals i.e., seals.

Additionally, the fishing effort to produce the catch takes account of increasing difficulty as stock levels decrease. The fishing yield per day and boat (for different categories of boats) is scaled by the inverse of the species biomass (relative to the maximum biomass). The adjusted yield is combined with the actual catch produced, and with inputs describing the number of fishing days per year and portfolio of boat types working each species, to calculate the number of boats required. The vintaged stock of boats is evolved with life-table working each species, to calculate the number of boats with the actual catch produced, and with inputs describing the maximum biomass to model the effects of species competition for resources. The actual catch realised may be less than the desired catch if there is insufficient biomass (i.e., biomass less than the desired catch), in which case the actual catch equals the biomass (from the previous time-step – before the growth dynamics is calculated). In a modified version, the calculation also accounts for fish harvest by mammals i.e., seals.

Aquaculture is also included, simply with the production of farmed fish driven directly by specified production volume. Different labour, material and energy intensities apply to the fish produced from aquaculture operations and wild catch fishing.

9.1.7.4 Mining

The mining module covers the discovery and production of (nineteen) material resources, including minerals, energy materials, concentrates, ores and construction materials. The extent of both resources (the ultimate materials available, including inferred and undiscovered materials) and reserves (materials discovered deemed recoverable economically or sub-economically) are established. The cumulative resources are calculated from the specified additions to resources (over time), which allows for discoveries and updated geological inference. Similarly, planned additions to reserves in each time-step account for new material deposits identified (though the actual additions cannot exceed the amount of inferred resources remaining beyond what has been cumulatively extracted). Planned production i.e., extraction of materials is also specified; and the actual extraction volume in a time-step is taken from the amount of reserves remaining (beyond what has been cumulatively extracted), so it is limited to size of the unexploited reserves.

The actual production volumes drive the calculation of the vintaged and located mining capacity stock. This stock, combined with separately intensities and scaling factors, determine the energy, emissions, water, labour, plant material and operating material for mining. To account for higher grade resources being discovered and extracted before lower grade resources, scaling factors are specified for the energy, labour and plant material intensities of mining operations. The scaling factors are indexed by the ratio of cumulative production to resources ever found, allowing increased physical impost as the cumulative production approaches the total resource available.

9.1.8 International Trade

The international trade module of the ASFF, along with the remaining modules to be described below, forms an important indicator of potential tensions in the scenarios created with the ASFF, namely Australia’s trade balance in monetary units. The trade module first consolidates the production of raw materials from the separate primary industries, and consolidates the requirement for raw materials generated from food processing and from the secondary heavy industry module. The proportion of the domestic requirement for raw materials that is (potentially) imported is specified exogenously and then the net requirement to be sourced domestically is calculated. If this net requirement is less than the raw materials produced in Australia, then the excess production becomes exports; if the net requirement is less than that produced, then missing requirement is obtained from imports. The module then draws together all the imports and exports of raw materials, secondary materials and energy, manufactured goods and consumables, and applies to these physical flows exogenous import and export prices (which may be different, and can vary over time) to form the current real goods trade balance.

Three other components of the overall trade balance are calculated. A tourist trade balance is generated from the flows of inbound and outbound travellers determined in earlier
modules of the ASFF, combined here with specified spending rates. There is also an exogenous flow of money in or out of Australia to allow for foreign investment and other “invisibles”. Finally, an interest rate is specified for the interest to be paid or earned on international debt and surplus, respectively. A difference equation is solved to generate the cumulative trade balance, from the real goods balance, tourist balance, invisibles and interest payments in each time period.

9.1.9 Natural Resources

9.1.9.1 Water

In assembling a water balance for the stocks of surface-, soil- and ground (i.e., aquifer)-water bodies, the water module first consolidates the gross water requirements that have been calculated in modules throughout the ASFF. The location of this water use is mapped to 74 water regions (the major river basins) using exogenous share parameters. A separate share variable sets the proportional withdrawal from the three water body types, for each water-using sector within each region. Water discharged after use is calculated by scaling the use with a discharge fraction, including what water body the used water enters. The four other variables for calculating the net water flows entering a water body within a region are: the surface flows from the upstream region; rainfall in the region; and man-made transfers to and from water regions by pipe/channel. The rainwater volume is based on exogenous area-averaged rainfall, and is split between the water body types that first receive the rainwater using a share parameter, which essentially directs rainfall to soil water in practice. Transfers are also exogenously specified between regions, along with shares that split the flows between the water bodies that provide and receive the water. The net region input is obtained from the four inputs (rainfall, river inflow, discharged water, and entering transfers) and two outputs (gross water used, and exiting transfers). However, in this version of the water module it is necessary to adjust the river inflow (i.e., surface flows from the upstream region) since it is an exogenous input, and knowledge of the river network connecting regions (which is mostly only relevant in the Murray-Darling Basin) is used to reset the inflows based on the cumulative net river inputs of all the upstream regions. In a later version of the water module (Turner et al., 2009), the effects of the river network have been fully incorporated, among other changes.

Hydrological parameters specify (in terms of fractions of the water stock) the evaporation rate (from surface water stocks), transpiration rate (from soil water stocks), and the transfers that occur between pairs of the water body types. Using all the hydrological transfer parameters and the calculated net input flow to water body types within a region, the evolution of the three stocks of water in each region is simulated using a set of coupled difference equations.

9.1.9.2 Land

An account of all land-use based on urban activity, intensive agriculture (crop and sown pasture), forestry, extensive grazing and all other uses, is made in the land module of the ASFF. Urban land-use is calculated based on the building stock and length of roads in capital cities. Footprint intensities for buildings, roads and other urban uses convert the stocks to land area (where the intensity for buildings is specified as the marginal rate that applies to new buildings, so that the vintage of demolished buildings is used in calculating urban land deletions). Additions and deletions of forestry and agricultural (intensive use) land are taken directly from the respective sector modules. Exogenous parameters map urban and forest land to statistical divisions, to match the spatial detail of agriculture. The land deletions are consolidated, including an exogenous deletion of grazing/other land use; and land additions for urban, forests, and agriculture are consolidated. Net deletions from the total of urban, forest and agriculture land, become additions to grazing and other land-use (split between these using a share parameter); and consequently, net additions to the more intensive land-uses reduce grazing/other area. The total land area can be aggregated from the components and should equal the land mass of Australia. However, a tension in land use can occur for grazing land, since the requirement for this land was generated in the agriculture module by the feed requirements of livestock, and this may not match the available grazing land calculated here.

9.1.9.3 Air Resources

By and large, the air resources module simply consolidates the various emissions of pollutants to the atmosphere that are calculated as a result of energy use in the sectors of the economy. However, some distinctions are made between emissions from transport activity, direct emissions from processing activities (e.g., fugitive emissions from mining), and emissions associated with energy use for all non-transport activity. The latter requires a separate emission intensity parameter from that used for direct emissions in the relevant modules. This module also locates the source of the emissions so that the flows of city air-shed pollution can be reported. No attempt is made to model the physio-chemical dynamics of air pollutants, or to present a tension (though this could be done by comparison with a specified benchmark for pollution emissions).

9.1.10 Labour

The components of the labour force required by the economy have been calculated in each of the modules dealing with the different sectors of the economy. This gives the labour required by sector of employment, but not occupation. The calculations include services such as health care and education, but in this version of the ASFF many other service jobs are calculated simply with an intensity of occupational services per capita combined with the size of the population. Separately, the labour force available is calculated by first subtracting the defence force personnel numbers from the age-based population, and then applying age and gender specific participation rates to that civilian population (within working age limits). Unemployment results simply if the total labour force available is greater than that required. The alternative tension (“over-employment”) is unphysical, but may occur in a scenario if the available labour force (associated with the population) is less than the labour required (as driven by the economic activity in the ASFF). Either tension, like others in the ASFF, requires intervention to adjust suitable control variables to alleviate them. This can occur manually or with the aid of additional coded scripts.