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Input-Output Scenario Analysis – Using constrained optimisation to integrate dynamic model outputs

Thomas Wiedmann[a)], Arne Geschke[b)] and Manfred Lenzen[b)]

a) CSIRO Ecosystem Sciences, Canberra ACT 2601, Australia

b) ISA - Integrated Sustainability Analysis, School of Physics, The University of Sydney, NSW 2006, Australia

*) Corresponding author. Postal address: CSIRO Ecosystem Sciences, Clunies Ross St, Black Mountain, Canberra, ACT 2601, Australia. Tel.: +61 2 6246 4360. Email: tommy.wiedmann@csiro.au

Abstract

Australia faces significant sustainability challenges in the context of climate change, economic growth, population pressures, and increasing resource scarcity. To provide a systematic and integrated analysis of Australia's future development CSIRO is building up and integrating analytical capacity across different science domains. Environmentally extended input-output analysis is one of the techniques to be used for assessing scenarios of future economic and urban development in Australia and to be integrated with other integrated assessment models (IAM) such as a climate/economic systems model, a stocks-and-flows model, a land-use model and an energy sector model.

In this paper we describe the process of generating historic and future time series of environmentally extended multi-state input-output tables of the Australia economy (AUS-MRIO). We use the software tool AISHA which was created for the purpose of building series of contingency tables (for example input-output matrices with environmental extensions). The software operates a matrix balancing algorithm and solves a constrained optimisation problem. Creating a time series of input-output tables involves preparing initial estimates, defining and scripting constraints, and setting appropriate boundary conditions. AISHA will not only be used to update an existing AUS-MRIO from 1999 to 2008, but also to implement scenario variables derived from other IAM models as exogenous constraints. Effectively, this creates a dynamically extended version of AUS-MRIO linked to defined scenario pathways.

The novelty of our work lies in the cross-model integration of scenario variables by implementing a mechanism to use these variables as data constraints in future time series of IO tables. Application of the dynamically extended IO tool in (urban) sustainability analyses adds the perspective of consumption-based environmental accounting to integrated assessment modelling.

Keywords

environmentally extended input-output analysis, future scenarios, integrated assessment modelling, dynamic analysis

1 Introduction

Australia faces significant sustainability challenges in the context of climate change, economic growth, population pressures, and increasing resource scarcity. Research is needed to address national environmental and development issues, such as urban development, water restrictions, land disturbance, resource use, loss of biodiversity, etc. in an integrated way. Scenario modelling is needed to indicate ways out of Australia's "race to the bottom", where the Nation's natural endowment is eroded because of an industrial structure that has to expand volumes of primary exports to maintain a trade balance.

In order to understand these interacting challenges and assess the consequences of different policy choices, a flexible and integrated assessment modelling (IAM) approach is needed, drawing on a coupled suite of models that evaluate scenarios across a range of climate, economic, population and development projections. As part of its Integrated Carbon Pathways (ICP) project, CSIRO is building up new analytical capacity with the aim to provide a systematic and integrated analysis of Australia's economic, environmental and social development pathways. Work on the sustainability assessment of urban systems and infrastructure is being undertaken as a sub-component of the IAM capacity. Environmentally extended input-output analysis is one of the techniques to be used for assessing scenarios of future urban development and to be integrated with a climate/economic systems model, a stocks-and-flows model, a land-use model and an energy sector model.

In this paper we describe the process of generating historic and future time series of environmentally extended multi-state input-output tables of the Australia economy (AUS-MRIO). We use the software tool AISHA which was created for the purpose of building series of contingency tables (Geschke et al., 2011; Yu et al., 2009). One main application of AISHA is the balancing of input-output matrices with physical-unit extensions (e.g. environmental flows) (Kanemoto et al., 2011; Wood, 2011). The software operates a matrix balancing algorithm based on KRAS (Lenzen et al., 2009) and uses externally defined constraints to solve a constrained optimisation problem. Creating a time series of tables involves preparing initial estimates, defining and scripting constraints, and setting appropriate boundary conditions. AISHA has not only been used to update an existing AUS-MRIO from 1999 to 2008, but also to implement scenario variables derived from other IAM models as exogenous constraints. Effectively, this creates a 'dynamic' version of AUS-MRIO linked to defined scenario pathways.

The novelty of our work lies in the cross-model integration of scenario variables by implementing a mechanism to use these variables as data constraints in future time series of IO tables. Application of the dynamic IO tool in (urban) sustainability analyses adds the perspective of consumption-based environmental accounting to integrated assessment modelling.

2 Data

2.1 Data framework

The AUS-MRIO is a multi-state input-output data framework, extended by physical-unit satellite accounts on environmental flows such as greenhouse gas emissions, water use, land use, material flows, etc. The basic setup of tables is depicted in Figure 1.

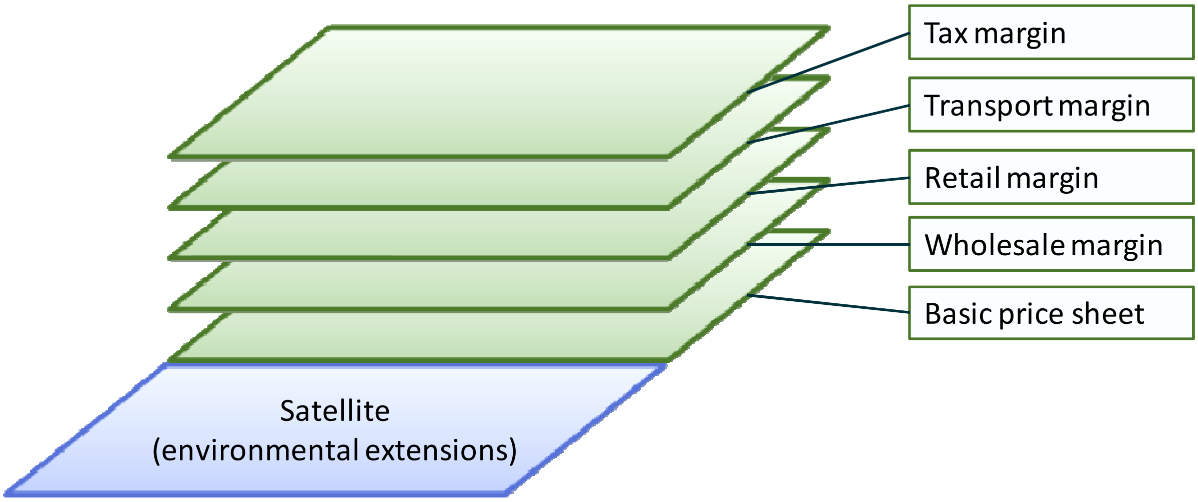

Figure 1: Basic layout of the stack of input-output valuation tables in AUS-MRIO. The satellite block is an extensions only to the basic price table.

The bottom table in Figure 1 is a basic-price industry-by-industry flow table, extended by the satellite table. Tables stacked on top of the basic-price table represent valuation tables, including trade and transport margins as well as taxes. Cell-wise addition of basic-price and valuation tables result in purchasers prices for all transactions.

Figure 2 shows the layout and 'topography' of the basic-price layer in the AUS-MRIO dataset one year. The AUS-MRIO tables have the following characteristics (for each year):

- balanced eight-region (states) input-output table at basic (current) prices
- four valuation sheets (margins and taxes)
- sector-resolution of 344 for all states and territories
- five rows of primary inputs, including compensation of employees, profits and value added
- six columns of final demand, including households, government and capital investment
- detailed environmental extensions ('Q block', 1273 rows), including material flows, energy consumption, land use & disturbance, greenhouse gas emissions and pollutants, and others.

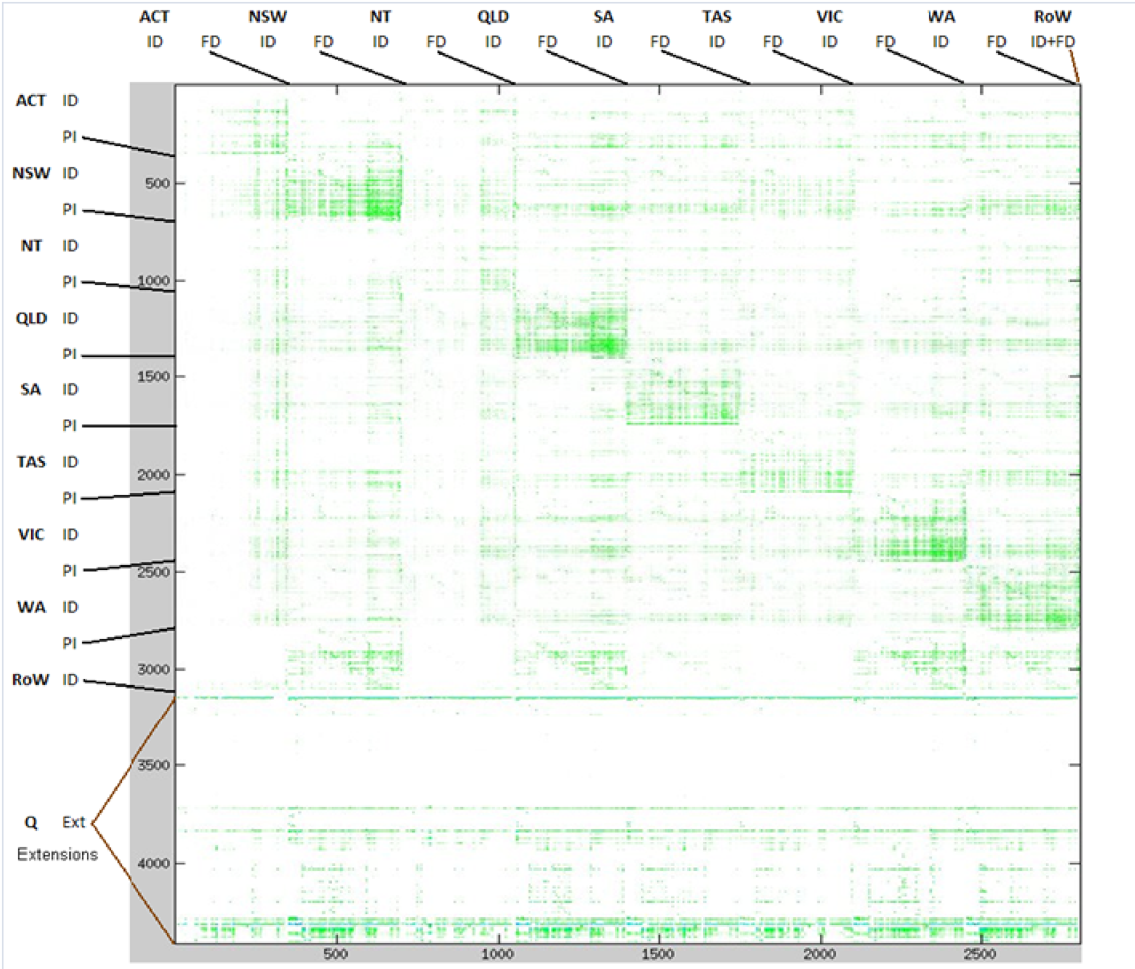

Figure 2: Topographical representation of the eight-region EE-IO framework created in milestone M1a (generated using Aisha software developed at the University of Sydney)

2.2 Data sources

The main data sources used for constructing a time series of tables for the years 2000 to 2008 included:

- A previous version of AUS-MRIO for the financial year 1999/2000 as the basis for an initial estimate (Gallego and Lenzen, 2009)
- Australian National Accounts: Input-Output Tables - Electronic Publication, 2007-08 Final, ABS Catalogue Number 5209.0.55.001 (ABS, 2011a)
- Australian National Accounts, State Accounts, 2010-11, ABS Catalogue Number 5220.0 (ABS, 2011b)

3 Methodology

3.1 Constructing the raw data initial estimate

As an initial estimate for the AUS-MRIO time series we constructed a raw data table as follows.

The Australian Bureau of Statistics publishes the Australian national data in supply and use table format (SUT). There are no state-based input-output data published for Australia. Hence, the state-specific input-output data as well as transactions between states (interstate trade flows) needed to be imputed.

At the University of Sydney, an advanced RAS-type balancing technique (Lenzen et al., 2009) was used to assemble a detailed multi-regional input-output (MRIO) framework of Australia, making use of a large and diverse amount of survey data available (Gallego and Lenzen, 2009). This Australian MRIO model was used in a case study of virtual water flows of the state of Victoria (Lenzen, 2009). The state-based basic price sheet for Australia for the year 2000 from this study was used as a data source for the initial estimate of AUS-MRIO in this work. For each state, the table contains an IO-table with 344 industry-sectors, 5 value added sectors and 6 final demand sectors. Additionally, the inter-state trade blocks are fully populated.

The four margin tables in AUS-MRIO were estimated using the official Supply and Use Table (SUT) for Australia for the year 2000 that was published by the ABS (ABS, 2011a). The following methodology was employed to generate raw data mark-up tables for the state-based MRIO.

- Disaggregate the Australian Use Table and the 14 published mark-up sheets for the year 2000 from 111 sectors (ABS classification) to 344 sectors (classification chosen for this study), using industry totals ratios from the disaggregated data.
- Aggregate the 14 published mark-up sheets from ABS to the four margin sheets used in AUS-MRIO.
- Calculate the ratios between the basic-price value and the mark-up value in the ABS data for each cell. Perform this for every mark-up sheet separately. The resulting ratio table for the *k*-th mark-up is calculated by
$$r_{i,j}^{k} = \frac{m_{i,j}^{k}}{t_{i,j}}$$
where $t_{i,j}$ is the value of the basic price sheet and $m_{i,j}^{k}$ is the corresponding value of *k*-th mark-up. The same strategy was applied to the value-added block and the final demand block of the Use Table, respectively.
- These ratio tables were then used to estimate the absolute values in the mark-up sheets for each state domestic block and each inter-state trade block of the Australian MRIO for the base year 2000. The same strategy was applied to the final demand and value added blocks.

3.2 Constructing a time series of MRIO tables

In order to construct a time series of MRIO tables we needed to complete three essential steps:

- Collect raw data and assemble an initial raw data table (see section 3.1).

- Define conditions and constraints the MRIO table has to adhere to. These include the balancing condition (total industry outputs need to be equal to total industry inputs) as well as published and other known data points. These conditions are given in the form of mathematical constraints and as boundary conditions.
- Solve the reconciliation problem to obtain an MRIO table that adheres to all conditions within a certain, defined deviation range.

Since the aim of this work was to construct a time series of state-based Australian MRIO tables, these three steps had to be solved for each of the years within the time series.

The collection of raw data is only carried out in detail for one particular year within the time series, called the *base year* of the time series. For this project, the year 2000 was chosen as the base year and the initial estimate for this year was assembled as described in section 3.1 (completing step 1).

Step 2 is carried out as follows. Consider a simple basic price IO table

$$T = \begin{matrix} t_{11} & t_{12} & y_1 \\ t_{21} & t_{22} & y_2 \\ v_1 & v_2 & \end{matrix}$$

with *t* = inter-industry transactions, *y* = final demand and *v* = primary inputs.

Then the balancing condition is given by the mathematical constraints

$$t_{12} + y_1 - t_{21} - v_1 = 0$$
$$t_{21} + y_2 - t_{12} - v_2 = 0$$

Consider further that information is given that the total final demand sum up to a value b. Then the corresponding constraint is $y_1 + y_2 = b$. Let a be a vectorisation of the MRIO table T, then the three constraints introduced can be elegantly summarized in the matrix-by-vector equation

$$\underbrace{\begin{pmatrix} 0 & 1 & 1 & -1 & 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}}_{\mathbf{G}} \underbrace{\begin{pmatrix} t_{11} \\ t_{12} \\ y_1 \\ t_{21} \\ t_{22} \\ y_2 \\ v_1 \\ v_2 \end{pmatrix}}_{a} = \underbrace{\begin{pmatrix} 0 \\ 0 \\ b \end{pmatrix}}_{=:c}$$

Hence, all available data for a particular year can be introduced as mathematical constraints. The mathematical constraints can then be summarised to

$$\mathbf{G}a = c$$

Boundary conditions are typically defined for each element. A classic boundary conditions is the requirement that the transaction values of the basic price sheet have to be non-negative. For the vectorised MRIO table a the boundary conditions are given as lower bounds vector l and upper bounds vector u. The values ∞ and $-\infty$ are feasible elements of l and u and indicate that the corresponding element of the MRIO table is not subject to lower or upper bounds.

Defining the set of equations

$$\mathbf{G}a = c \quad \text{with} \quad l \leq a \leq u$$

In addition to the raw data and constraints, reliability data were considered for each element of the MRIO and for each constraint, i.e. the values of the vector c. For this work, each element of the MRIO and of the vector c was considered to be a normally distributed random variable. Hence, the standard deviations of each element of the MRIO and the vector c represent the reliability of the corresponding element. The standard deviations of the elements of the vectorised MRIO a are summarized in the vector σ_a, the standard deviations for c are summarized in the vector σ_c.The vectors σ_a and σ_c have the same size as a and c. Since no data was available on possible covariances between the different MRIO entries, all data were assumed to be independent and normally distributed. This completes step 2.

For the reconciliation problem of step 3 let a_{raw} be the vectorisation of the raw data MRIO table T_{raw}, let $\sigma_{a_{raw}}$ be the corresponding vector of standard deviations, and let a be the vectorisation of the final MRIO table T. The reconciliation problem is given by

$$\min_a f\left(a_{raw}, a, \sigma_{a_{raw}}, \sigma_c\right) \quad \text{subject to} \quad \mathbf{G}a = c \text{ and } l \leq a \leq u$$

A number of different solvers are available to solve the reconciliation problem. In this paper we used the KRAS solver (Lenzen et al., 2009) which is an extension of RAS (Bacharach, 1970) that accounts for conflicting constraints by considering the reliability information of the data given by the standard deviations. Standard deviations σ of table elements were estimated using the method described in (Lenzen et al., 2010).

The reliability data σ_a of the result is calculated as follows. Consider the resulting MRIO fulfils the constraints equation

$$\mathbf{G}a = c$$

Then the standard deviation σ_a of the left hand side of the equation and the standard deviation σ_c of the right hand side must fulfil

$$\sqrt{\mathbf{G}\sigma_a \# \mathbf{G}\sigma_a} = \left\{ \sqrt{\sum_j \left(g_{ij}\sigma_a\right)^2} \right\}_i = \sigma_c$$

This equation represents another underdetermined optimisation problem. The right hand side σ_c of is known. The standard deviations σ_a of the reconciled table are the solution of this optimisation problem. Lenzen et al., 2010 propose the SDRAS algorithm to calculate the solution. KRAS delivers the solution of this problem automatically. This completes the final step 3.

The process described to reconcile an MRIO has to be carried out for each year of the time series. However, the assembly of a complete raw data table as required by step 1 is only necessary for the base year of the time series. For the other years, the following strategy is applied.

Let $T_{raw}^{(2000)}$ be the entire MRIO populated with raw data for the year 2000, i.e. the result of step 1. Now assume that steps 1-3 have been completed for the year 2000, yielding a final MRIO table

$T^{(2000)}$. The final MRIO table $T^{(2000)}$ is then used as the raw data MRIO for the subsequent year of the time series, i.e. $T_{raw}^{(2001)} = T^{(2000)}$. This principle is carried through the entire time series. For example the final MRIO table for 2004 serves as the raw data table for the year 2005, hence $T_{raw}^{(2005)} = T^{(2004)}$.

Reasons for using the final MRIO of the previous year as the raw data table for the subsequent years are

a) The scarcity of data for state-based Australian MRIO tables. Data collection is tedious and time-consuming. Entire data sets are usually not available and parts of the data set have to be estimated.

b) Collection of raw data for an entire MRIO table has to be carried out only for the base year.

c) In the light of data scarcity the final MRIO table of the previous year is the best approximation of the MRIO table of the subsequent year.

The same strategy of time series propagation is being employed in the creation of a global MRIO model at the University of Sydney (Kanemoto et al., 2011).

Since the raw data table for every year except the base year are given by the final MRIO tables of the previous years, the data and information that could potentially be used to assemble a raw data table for any given year within the time series is used otherwise. Hence, all data and information that is available is introduced to the system as additional conditions in step 2.

3.3 Projection of future time series of MRIO tables

Apart from the construction of a historical time series of AUS-MRIO tables, the project also aims at creating a series of tables that represent possible future economic and environmental flows in the Australia economy. Work is currently being carried out to use outputs from other integrated assessment models as constraints in the balancing of AUS-MRIO tables. Just like published data are being used as constraints in historical tables, specific results from modelling scenarios can be used in a continuation of time series to future years.

Outputs from three different CSIRO models will be used as constraints:

- NIAM – The National Integrated Assessment Model is based on a computable general equilibrium (CGE) model of the Australian economy and provides a regionalized assessment of the impact of climate change on the Australia Economy (Hanslow, 2010). Typical NIAM outputs include projections of GDP, GVA, total industry sector outputs and prices.
- ESM – The The Energy Sector Model is a detailed partial equilibrium model of the Australian energy sector (including transport), co-developed by CSIRO and the Australian Bureau of Agricultural and Resource Economics (ABARE) in 2006. ESM is providing detailed scenario outputs for future energy requirements of electricity generation and transport.
- LUTO – The Land Use model will provide spatial projections of land use area by type of use. These land use types can be allocated to state and territories and to individual sectors in the AUS-MRIO (mostly agricultural sectors).

4 Discussion and Conclusions

We have created a time series from 1999 to 2008 of multi-state environmental input-output tables of the Australian economy (called 'AUS-MRIO'). AISHA, an automated data management system and software tool based on matrix balancing and constrained optimisation, allows for a user-friendly updating mechanism and will be used to create future time series of AUS-MRIO in line with ICP scenarios. Work that remains to be done includes:

- Refining constraints on input-output tables by using more published data such as ABS industry-by-industry flow tables, state accounts, household expenditure surveys and industry-specific data (e.g. detailed mining sector reports etc.).
- Setting and refining constraints on environmental extensions such as greenhouse gas emissions from the national emissions inventory.
- Using outputs from other models as constraints for future time series.

The coupling of outputs from dynamic integrated assessment models effectively creates a dynamically extended version of AUS-MRIO. The input-output model itself is not dynamic as it does not have a time-dependent endogenous feedback mechanisms. However, it expresses the output of other dynamic models as a complete environmentally extended IO system at any point in time.

Using detailed environmental IO tables for future years in scenario analyses adds the perspective of supply-chain and consumption-based environmental accounting to integrated assessment modelling. We identify the following advantages of this dynamic coupling approach:

- High level of compatibility with other models. AUS-MRIO is built around a sectoral representation of the economy; while satellite accounts link to the modelling of specific processes. This is an optimal design for establishing linkages to other sector-based models or to other process-based models
- The AUS-MRIO resource and material flow satellites captures the physical reality of resource constraints. Other models rely on market mechanisms and price modelling to express resource constraints.
- Unprecedented level of sectoral detail. Our existing input-output model has a resolution of 344 sectors, far more than any other Australian of the economy.
- The model will provide a detailed consumption perspective of economy-wide, embodied environmental impacts. 'Footprint' indicators can be generated at a national, regional, local, or individual level. This allows for the exploration of new policy and research questions related to sustainable consumption.
- The model will allow for the specific analysis of sustainability impacts of industrial supply-chains and thus a complete life-cycle assessment (LCA) and triple-bottom-line assessment (TBL) of each economic sector in the Australian economy.
- AUS-MRIO is designed to enable integration with the world's largest and most sophisticated global multi-region input-output models, Eora (Kanemoto et al., 2011; Lenzen et al., 2011), which is at the forefront of analysing and modelling the embodied environmental impacts of international trade – a subject highly relevant to intergovernmental climate and environmental

policy. Through our research and networks we are in a unique position to collaborate with world-leading experts and research teams.

- Increased potential of integrating social sciences with natural, engineering and economic sciences.

We believe that AUS-MRIO will enhance Australia's capability to effectively undertake a transition toward sustainability. One key application of future time series tables will be to provide supply chain links between urban consumption and impacts of production and resource use in non-urban areas, as e.g. demonstrated by Lenzen and Peters, 2010.

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