Compiling and using input–output frameworks through collaborative virtual laboratories

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HIGHLIGHTS

- A novel method for producing multi-regional input output tables is developed.
- We describe the Australian Industrial Ecology Virtual Laboratory (IELab) approach.
- A highly automated collaborative research platform has been established.
- The project advances analytical capacity of sustainability science in Australia.

ARTICLE INFO

ABSTRACT

Compiling, deploying and utilising large-scale databases that integrate environmental and economic data have traditionally been labour- and cost-intensive processes, hindered by the large amount of disparate and misaligned data that must be collected and harmonised. The Australian Industrial Ecology Virtual Laboratory (IELab) is a novel, collaborative approach to compiling large-scale environmentally extended multi-region input–output (MRIO) models.

The utility of the IELab product is greatly enhanced by avoiding the need to lock in an MRIO structure at the time the MRIO system is developed. The IELab advances the idea of the "mother–daughter" construction principle, whereby a regionally and sectorally very detailed "mother" table is set up, from which "daughter" tables are derived to suit specific research questions. By introducing a third tier – the "root classification" – IELab users are able to define their own mother-MRIO configuration, at no additional cost in terms of data handling. Customised mother-MRIOs can then be built, which maximise disaggregation in aspects that are useful to a family of research questions.

The second innovation in the IELab system is to provide a highly automated collaborative research platform in a cloud-computing environment, greatly expediting workflows and making these computational benefits accessible to all users.

Combining these two aspects realises many benefits. The collaborative nature of the IELab development project allows significant savings in resources. Timely deployment is possible by coupling automation procedures with the comprehensive input from multiple teams. User-defined MRIO tables, coupled with high performance computing, mean that MRIO analysis will be useful and accessible for a great many more research applications than would otherwise be possible. By ensuring that a common set of analytical tools such as for hybrid life-cycle

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assessment is adopted, the IELab will facilitate the harmonisation of fragmented, dispersed and misaligned raw data for the benefit of all interested parties.

1. Introduction and overview

A meaningful and close integration of data from the natural environment and the economy is essential for multidisciplinary studies on the total environment. Environmentally extended input–output (EEIO) analysis is widely used to provide insight on the linkages between environmental impacts and economic activity. EEIO is applied at scales ranging from individual consumption to world trade, and in a variety of contexts including consumption-based accounting, life cycle assessments (LCA) and supply chain analysis of resource use and pollution (Suh, 2009). A number of multi-region input–output (MRIO) databases have been constructed at global[1] and national[2] scales.

Each MRIO database construction typically focuses on specific research questions, requiring a good sectoral and regional resolution in those parts of the MRIO table that are most relevant to addressing those particular questions. For example, land use impact studies require high detail in agricultural sectors; water management studies might also require high detail in water-stressed regions; employment analysis might require high detail in service sectors; whilst studies on biodiversity might require high regional detail specifically for developing countries.

More generalised use of MRIO tables for meaningful environmental footprint and LCA applications would require a more consistent approach to sectoral and regional disaggregation; however, this remains a substantial challenge for the EEIO research community. The conventional approach to compiling high-resolution MRIO tables is usually arduous and expensive because regional economic and environmental data is usually scant and rarely aligned. These data limitations, along with other resource and computational issues, usually compromise the number of sectors and regions that can be analysed.

Because of these difficulties, only a handful of research groups around the world have taken on the task of compiling high-resolution international or sub-national multi-region input–output (MRIO) databases. Even fewer have done so in a way that can directly take information about individual products and/or processes into account (Ewing et al., 2012; Schoer et al., 2012; Steen-Olsen et al., 2012; Tukker and Dietzenbacher, 2013). More widespread MRIO development has been impeded by limitations in the financial and human resources that can be committed to the task. As a result, only a subset of all potentially suitable raw data is typically located and collected during MRIO table construction. The MRIO layout and resolution are also commonly constrained to match readily available data. Different MRIO construction teams have mostly worked in isolation from each other, thus missing out on opportunities to gain leverage from each other's efforts.

Existing global MRIO databases are highly sophisticated, and have supported high-quality analysis on specific questions (Andrew and Peters, 2013; Ewing et al., 2012; Lenzen et al., 2012b, 2013; Tukker and Dietzenbacher, 2013; Wiedmann and Barrett, 2012). However, they can fall short of the detail needed to address a wider spectrum of research questions. Furthermore, the resource-intensive approach to data compilation means that many MRIO frameworks are difficult to update as the global economy changes over time. MRIO constructions can therefore be at risk of losing relevance over time, as their data currency wanes and/or research priorities change.

In this paper we describe a new approach that overcomes some of the limitations listed above. Both accessibility and utility of the MRIO product are improved by building an MRIO framework that can address a wide range of research questions posed by a wide range of researchers.

Section 2 introduces a new MRIO construction concept that avoids the need to impose aggregation on the input data and allows multiple versions of MRIO tables to be constructed. The philosophy here is to minimise the effect of data and resource limitations on the utility of the final product. This is achieved using a three-tiered root–mother–daughter structure that allows for maximum flexibility in the provision and use of disaggregated data, without compromising the transparency and utility of the overall MRIO analysis.

The base tier is a fixed *root* classification — this represents the maximum sectoral and spatial detail that might be attainable if highly disaggregated data were universally available. This root classification is so detailed that no actual MRIO system could be built from it because it would exceed current computer storage limits (as also described by Wittwer and Horridge, 2008). Instead, its role is to provide a consistent structure against which all input data can be mapped. Imposing this fixed reference point means that any number of *mother* MRIO tables – the second tier – can be derived, without requiring any manual rehandling of data. *Mother* tables aggregate the *root* classification to a point that the MRIO can actually be constructed with available computing resources. The sectoral and regional classification of any particular *mother* MRIO would be tailored to a particular family of research questions. The third tier is the *daughter* table, which has two roles. Firstly, it allows simplification of any mother table components that are unnecessary for analysing a particular research problem. Secondly, it provides a mechanism for including any problem-specific information that is not already captured in the root.[3]

Section 3 describes a computational infrastructure – known as a *Virtual Laboratory* – that makes MRIO analysis more accessible to a greater number of users, and will encourage participation in collaborative research. The *Virtual Laboratory* allows users to operate a highly automated process to build MRIO tables to suit their own research purposes. It also facilitates timely, transparent, cost-effective updating of MRIO tables as new data are released, and allows sharing of resources and tools across multiple research teams.

Section 3 also presents the workings of a real Virtual Laboratory – the Industrial Ecology Lab (IELab) – set up in Australia to provide sub-national MRIO analysis of that country's highly heterogeneous regional economic structures, climates, natural environments, and resource endowments.[4]

Section 4 presents outcomes from the IELab collaboration to date. Achievements include the harmonisation of a wide variety of fragmented, dispersed and misaligned economic and environmental data — something long overdue in Australia. At the time of writing, the IELab is providing its users with analytical capabilities for various economic and environmental, single-year or time-series applications. It also meets the requirements for constructing MRIO cores for dynamic

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[1] See Tukker and Dietzenbacher (2013); Wiedmann (2009); Wiedmann et al. (2007); and Wiedmann et al. (2011a).

[2] See Cazcarro et al. (2013); Daniels et al. (2011); Escobedo-Cardeñoso and Oosterhaven (2012); Feng et al. (2013); Guan and Hubacek (2007); Jackson and Schwarm (2011); Lenzen (2009); and Többen and Kronenberg (2011).

[3] The mother–daughter idea goes back to Wittwer and Horridge's (2008) large-scale TERM database that serves as a master for the flexible aggregation into small-scale input–output cores for CGE simulations with high regional and sectoral detail (Horridge M. The TERM model and its data base. Centre of Policy Studies, Monash University, Clayton, Australia, 2011, Wittwer G, Horridge M. Bringing Regional Detail to a CGE Model using Census Data. Spatial Economic Analysis 2010; 5: 229–255).

[4] The construction and publication of sub-national MRIO tables are not part of the mandate of the Australian Bureau of Statistics.

economic forecasting models that are frequently used in Australia to support government decision-making.

Section 5 provides some reflections on the process of developing and implementing this novel approach to constructing MRIO tables.

2. The root–mother–daughter approach to compiling large-scale MRIO databases

The innovation proposed in this work is to move beyond Wittwer and Horridge's fixed master table idea, and allow many *mother* tables to be derived from an "impossibly large" (Wittwer and Horridge, 2008) detailed, regional and sectoral *root* classification. In a Virtual Laboratory setting this is achieved through a flexible, automated MRIO construction pipeline that includes data pooling, constraint writing, and reconciliation steps. An example of this is provided in Section 4.

The flexibility is made possible by allowing users to build their own mother MRIO table, whose specific regional and sectoral table structure is defined as a subset of a fixed root classification. The root classification itself is too large to ever be used for a fully populated mother table (see Appendix 1). Instead, its role is to provide a consistent structure against which all input data is mapped. This means that existing data streams can be used as is, even when a new mother-MRIO classification is chosen. All that is required to make use of the existing data is to define a set of concordances between the root and mother classifications, specific to that particular mother-MRIO table. For data-to-root mapping to be possible, at least one vector of primary data must be expressed directly in the root classification. This vector can be used as a proxy for generating the data-to-root classification maps for any dataset that lacks better information.

A second innovation is to allow *daughter* tables to be derived, whereby users combine a conventional mother table with their own bottom-up data that is not captured by the root classification. Such bottom-up data could relate to particular specialised technologies, industrial processes, or products, for example. This functionality is useful when users wish to disaggregate specific sectors beyond the limitations imposed by the root classification. In practice, hybrid LCA can be carried out by inserting application-specific data in additional rows and columns into the mother table (augmentation),[5,6] and/or aggregating certain parts of the mother table that are not important for the LCA application. If the row- and column-inserts describe activities that are negligible in turnover compared to the remainder of the economy, a re-balancing of the augmented table is not necessary.

In light of these innovations, we will use the following terms in the remainder of this paper:

- A *root classification* is a very detailed, regional and sectoral classification that is itself too large to serve as the basis of a computable MRIO table, but from which a large variety of present and conceivable future user classifications can be derived by aggregation.
- A *mother table* is a fully populated and memory-storable MRIO table, generated by an MRIO construction pipeline, derived flexibly from the root classification for a certain family of research questions, but not necessarily meant to be used in concrete applications and analytical procedures.
- A *daughter table* is not generated by an MRIO construction pipeline, but derived from a mother table by aggregation and/or hybridisation,

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[5] For example by hybridisation and augmentation with process- or product-specific data, as described in the hybrid-LCA literature (Heijungs and Suh, 2002; Suh, 2004; Suh and Huppes, 2005; Suh et al., 2004, see an overview by Suh and Nakamura, 2007).

[6] The insertion procedures are now standard methodology in hybrid LCA, as attested to by a number of publications (see Heijungs and Suh, 2002; Suh, 2004; Suh and Nakamura, 2007; Wiedmann et al., 2011b).

and is used for specific analytical tasks such as life cycle assessment (LCA) or computable general equilibrium (CGE) modelling.

Implementing a root–mother–daughter approach for large-scale MRIO construction has several challenges. Constructing an MRIO table involves (a) building an initial estimate and a set of constraints; and then (b) combining these in a mathematical optimisation operation to yield a final MRIO table that satisfies the conditions posed by the constraints in an optimal way (Temurshoev et al., 2011). The strategy in Wittwer and Horridge's TERM approach is to generate CGE simulation tables – *post*-optimisation – from a fixed mother (master) table. However, this strategy faces size restrictions because the mother table needs to exist as a fully populated matrix that fits into computer memory. Since we keep mother tables flexible in order to suit the needs of multiple users, we need to introduce a design decision point *pre*-optimisation, during the construction of the initial estimate from the root classification. This means that both the initial estimate construction and the construction of the constraints for the optimisation need to be user-specific and therefore flexible.

In our approach we first ask the user to select a subset of the root classification that will be suitable for their specific mother table. Ideally, the user's choice should be informed by the availability of primary data, in order to avoid constructing region or sector groups for which no individual information is available. The selection process results in a concordance matrix between the root classification and the user's specific mother classification. This concordance matrix is then used to aggregate the root-classified proxy vector into a mother-classified proxy vector, which is, in turn, used to set up an initial estimate based on one of many well-known non-survey methods for regional input–output table construction. Thus, initial estimate construction is handled in a flexible way, catering for a wide range of user choices. A further challenge arises with respect to how to express the constraints imposed on the optimisation operation by external data, in a way that works for each possible mother MRIO variant. It is impractical, if not impossible, to write these constraints in terms of every conceivable mother classification, because there are simply too many combinatorial classification subsets contained in the root classification. In our approach, constraints are only ever written once, using the root classification, and then stored. Once a user has selected their mother classification from the root classification, all constraints are automatically adjusted to fit the particular mother MRIO table structure, instead of the (impossible) root MRIO structure. The root-to-mother concordance resulting from the user's selection is again used in this adjustment procedure. Thus, the constraint writing is also handled in a flexible way, catering for a wide range of user choices. Together, flexible initial estimate construction and constraint writing enable flexible, user-specific optimisation and mother table construction. Here, we have kept the description of the procedure for creating flexible mothers brief and qualitative. A more detailed technical description is provided in Appendix 1.

A final challenge is that, in practice, mother tables are likely to be very large-scale, requiring large amounts of input data, processing and storage (Lenzen et al., 2012a). The new approach taken here therefore exploits a) advanced means of computation, b) a high degree of procedural automation (Yu et al., 2009), and c) highly efficient organisational collaboration. For a world MRIO compilation, constructing a mother table would require a) purpose-built, multi-core cluster hardware running parallelised algorithms using in the order of 1 terabyte shared RAM; b) a meta-language for addressing large amounts of raw data and variable spaces (Geschke et al., 2011) as well as constrained optimisation techniques for data reconciliation (Yu et al., 2011). To best take advantage of such computational power requires the Virtual Laboratory architecture, designed to allow a large number of data providers and analysts to work on one platform without costly and inefficient human communication overheads. In Section 3 we first describe general features of a Virtual Laboratory, and explain how it lends itself to MRIO

compilation. We then describe a particular case study — the Australian Industrial Ecology Lab.

3. MRIO compilation in a Virtual Laboratory — the Australian IELab

A Virtual Laboratory (VL) is a novel concept aimed at improving digital connectivity by connecting researchers to existing and new research facilities, data repositories and computational tools. The objective is to streamline research workflows and enable new opportunities for research innovation, research collaboration, and improved research efficiencies. In Australia, VLs are created and administered under the lead of the University of Melbourne's NeCTAR project (www.nectar.org.au), and financed by the Australian Government's Education Investment Fund. NeCTAR Virtual Laboratories seek to support and engage major research communities in Australia by enabling collaboration across multiple research disciplines and problem-oriented research domains.

The aim of a Virtual Laboratory is to provide researchers with desktop or bench-top access to digitally enabled data, analytical and modelling resources, specifically relevant to their research. Each VL integrates existing and new investments in research infrastructure, including data storage, data collections, high performance computing resources, domain-oriented computational analysis and simulation tools, remote access to research facilities and laboratories, online collaborative research environments, real-time communications technologies, and automated research workflow tools. Because of the ability to link a large number of researchers, a NeCTAR VL provides a suitable environment for collaboratively compiling MRIO systems.

The Australian Industrial Ecology Virtual Laboratory (IELab) is a NeCTAR VL that targets a well-described, significant research challenge: in this case, the compilation and use of a time series of Australian sub-national MRIO tables, set up within the University of Melbourne's NeCTAR Research Cloud. The structure and information flows in the IELab are summarised in Fig. 1. For each dataset to be used, the researcher submits to the VL: a) the raw data specific to their research question and b) the information used to align this raw data with the root classification. Automatic data feeds with regularly updated data may also be linked. These automatic data feeds are created by different users, tagged with information on source, contact details, version or other identifying

details, and coordinated using an Application Programming Interface (API) so that changes in data standards and structures, naming conventions and MRIO computation never have to be changed separately by the users.

The three data feed-specific raw ingredients are then gathered in a reconciliation engine (Geschke et al., 2011), which uploads the resultant mother MRIO tables into a designated repository. The reconciliation step can involve any of the procedures commonly applied, such as the construction of an initial estimate and a balancing algorithm.[7] Users can add their own reconciliation engines as long as they communicate seamlessly with the raw data streams and the mother repository.

The IELab is equipped with an analytical toolbox that allows users to calculate derived quantities such as Leontief inverses, multipliers and environmental footprints; and a facility to interrogate outputs and extract them in various formats. Finally, a user interface brings together a) a library of user-defined concordance matrices that can be used to transform the mother MRIO tables into any user-defined daughter format, and b) libraries for storing user and run settings (for example permissions, root-to-mother maps, choice of raw data streams), enabling multiple users to work simultaneously on various individual MRIO projects that may differ by which input data and/or reconciliation method is used.

The entire workflow is handled within a cloud computing setting with nodes all around Australia.[8] Each Virtual Laboratory within the research cloud is allocated resources and software on a so-called *virtual machine*, with the appearance of a stand-alone Linux system. Researchers affiliated with a certain Virtual Laboratory can remotely access this virtual machine using standard protocols such as secure shell. The IELab received the biggest possible allocation within the NeCTAR research cloud, comprised of two computing cores, 64 GB of fully-shared memory and 5 TB of hard disk space.

3.1. Raw data feeds

The raw data streams of the IELab are realised as pieces of computer code – "data feeds" – operating automatically on information stored in standard file formats. The data feeds process, for example, the Australian national input–output tables (ABS, 2012c), state (ABS, 2012a) and regional (OGS, 2004) economic data, census data (ABS, 2012d), and industry-specific reports from government (e.g. ABS, 2008, 2010b) and private-sector (e.g. AAC, 2012; DA, 2012; WFA, 2011; WSAA, 2012) sources.

For each raw data stream, three tasks are necessary to create the constraints information required for the MRIO table reconciliation:

a) Convert information obtained from data providers (e.g. Excel files) into .csv files cleaned of strings, blanks, tab stops, line breaks, headers and other peripheral information. The data is saved with standardised file names into the processed data repository.
b) Generate a binary concordance table relating the classification of the raw data source to the root classification; saving these concordance tables as .csv files with standardised file names into the concordance repository. This is usually carried out manually by the data feed provider.
c) Formulate constraints using *ALANG* commands as well as the standardised names of the processed data and concordance files — thus linking the raw data to the MRIO structure (see Geschke et al., 2011). The constraint commands are saved in .txt files into the *ALANG* file repository.
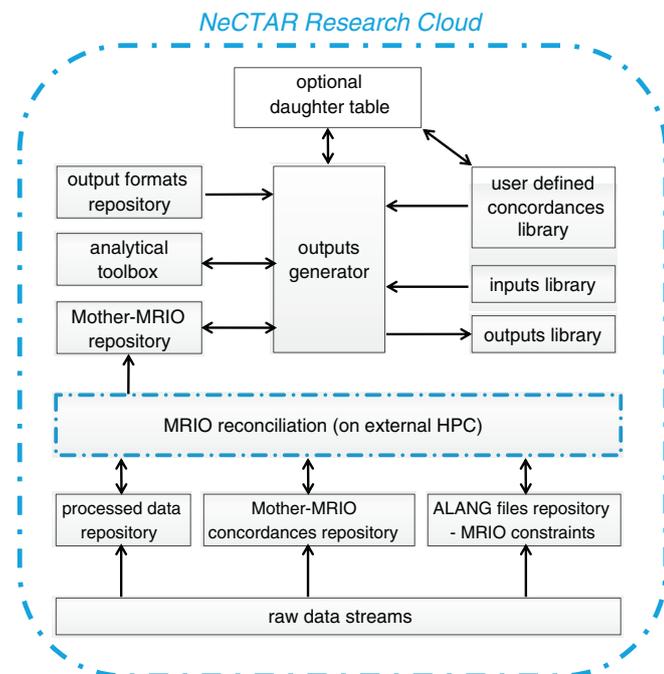

NeCTAR Research Cloud

Fig. 1. Schematic of structure and functionality of the Industrial Ecology Lab.

[7] See Boomsma et al. (1991); Bouwmeester and Oosterhaven (2008); Inomata (2005); Lenzen et al. (2013); Okamoto et al. (2005); Oosterhaven et al. (2008); Rueda-Cantuche et al. (2009); Temurshoev et al. (2011); Timmer (2012); Van der Linden and Oosterhaven (1995); and Yamano and Ahmad (2006).
[8] See http://nectar.org.au/research-cloud.

These tasks include information on standard deviations, which are either obtained from data providers, or if unavailable, estimated within the data feed (see Lenzen et al., 2010). Two additional tasks are involved in creating the initial estimate information required for the MRIO table reconciliation:

d) Using the data-specific source-to-root concordance, and the user-defined root-to-mother concordance, the raw data are converted into *mother-classified* blocks of cleaned, processed data. The transformation of monetary data for the MRIO initial estimate utilises existing non-survey methods to map the data against the root classification (Bonfiglio and Chelli, 2008; Sargento et al., 2012). The transformed data is then saved with standardised file names into the processed data repository.

e) *ALANG* commands are used to identify the file location of the initial estimate data available for each section of the mother MRIO table. The initial estimate *ALANG* commands are saved in .txt files into the *ALANG* file repository.

Note: The information on constraints refers to the root classification, whilst the information on initial estimates refers to the mother classification. A root-classified initial estimate cannot be constructed because it is too large for computer storage (as previously mentioned). Initial estimate construction is therefore dependent on the user's selection of a mother classification. The raw data feeds could also, in principle, refer to the mother classification. However, because of their relatively long runtimes, it is more efficient to run them only once, generating root-classified *ALANG* commands and concordances as fast-readable .txt and .csv files that can then be quickly converted into the mother classification.

3.2. Processed data, concordance and ALANG file pre-processing

To create a mother MRIO table, three sets of information are required (compare with Fig. 1): a) processed, mother-classified initial estimate data and processed constraint data including all matching standard deviation estimates, b) source-to-root concordances matching the processed constraints data as well as a user-defined root-to-mother concordance, and c) *ALANG* command files defining the initial estimate in the mother MRIO classification, and the constraints in the root classification.

When a user activates a Graphical User Interface to create a mother table, these three ingredients are packaged into a standard folder/file structure and deposited into an export repository from which they await being posted as a job into the queue of the reconciliation engine. Before packaging, the *ALANG* command files describing the constraints and their respective source-to-root concordances are converted and re-written so that they refer to the mother classification rather than the root classification. Packaging and root-to-mother conversion are carried out using tailored and automated pre-processing scripts, requiring no manual intervention.

This root-to-mother conversion is the critical innovation that enabled the IELab to move from the fixed mother/master concept in the TERM project to a flexible-mother concept. Root-to-mother conversion is described in detail in Appendix A.

3.3. Table reconciliation

To prepare for table reconciliation, the raw data streams are machine-read, *ALANG* command files are pooled, and a constrained optimisation problem is conditioned. The optimisation problem is subsequently solved and the solution is stored in the mother repository by the MRIO reconciliation engine. Current solvers include tailor-made, large-scale, parallelised Barrier–Penalty (Huang et al., 2008), GRAS (Junius and Oosterhaven, 2003), KRAS (Lenzen et al., 2009) and Cimmino (Censor and Zenios, 1997) algorithms. One of the key constraints imposed during the optimisation procedure is that all MRIO elements must be positive with the exception of changes in inventories and subsidies.

The KRAS and Cimmino optimisation routines are designed to operate in parallel in order to make efficient use of available computing hardware. The basic idea of any parallelised optimisation routine is to split the reconciliation problem into several, ideally independent parts, and distribute the work that is required to solve the different parts onto different computing cores.

Whilst the computational requirements for the raw data feeds can be handled by the resources assigned to the virtual machine of the IELab, the reconciliation requires more RAM and more computing cores than are presently available in the IELab allocation on the research cloud. Additionally, the IE Lab's virtual machine must not be occupied by resource-intensive tasks such as the reconciliation process, as this could impede availability of the virtual machine to the participating researchers. Consequently, the reconciliation of the mother tables is carried out on separate high-performance computers located in different advanced-computation centres. The necessary file transfers and communication across the different computing systems are fully automated and handled by tailored scripts operating on the cloud.

3.4. Analytical toolbox and user interface

The analytical toolbox offers various tools for aggregating or hybridising any mother MRIO table into daughter tables to be used for subsequent analysis,[9] and for generating output data consistent with standard environmental accounting and assessment frameworks.[10] The toolbox is designed with the integration of VL outputs into LCA databases and software packages[11] in mind. The combination of LCA process data and the IELab's MRIO tables will thus enable the implementation of hybrid LCA methodologies that utilise the best aspects of both process-based and input–output methodologies to deliver cutting-edge LCA research (Suh and Nakamura, 2007). This capacity will also facilitate the usage of VL outputs by a large and diverse range of users who are already familiar with existing LCA databases and/or software packages. The toolbox also contains a range of diagnostic[12] and analytical[13] visualisation options. Similar to the raw data feeds, the routines contained in the analysis toolbox are housed and executed within the virtual machine on the research cloud.

The creation of daughter tables is currently a post-optimisation step in the IELab. If the user chooses to insert more specific data than the root classification then the resulting daughter tables will not be balanced. In most cases, process data inserted that way refer to products, processes or companies that are so small that a re-balancing of the entire table is not necessary, because the insertion does not cause a significant economic imbalance. However, a daughter reconciliation capability is planned for the next stages of IELab development.

The user interface for the analytical toolbox has two main purposes: Firstly, it accesses a concordance repository holding user-defined concordance tables that map the mother MRIO classifications into daughter classifications that match users' individual research needs. Users can make their concordance tables available to others, so that particular analytical approaches can be easily shared and replicated. Secondly, the user interface contains a repository for storing analytical outputs, and for sharing those outputs in one workspace with selected users.

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9 For example tools for inserting process data into an input–output table (see Heijungs and Suh, 2002; Suh and Huppes, 2005), for calculating Leontief inverse, multipliers, and for undertaking a production layer decomposition and structural path analysis (see Lenzen, 2002; Peters, 2007; Suh and Heijungs, 2007).
10 ISO (1998) and UNSD (2003).
11 For example ISA (2012), PE International (2012) and PRé (2012).
12 See http://www.worldmrio.com.
13 Wiedmann et al., 2009.

3.5. Collaboration in the Industrial Ecology Lab

The IELab was developed by a consortium of seven Australian research institutions. Each partner provided a set of resources and expertise that maximised the utility of the final product.

3.5.1. Functionality and architecture

The *University of Sydney* (USyd) is primarily responsible for developing the root–mother–daughter approach and the functional architecture used for the MRIO construction and analytical use. This is based largely on its previous experiences in developing a global MRIO (Lenzen et al., 2012a; see also www.worldmrio.com), prototype state level MRIO development (Gallego and Lenzen, 2009; Yu et al., 2009, 2011) and case study applications (Lenzen, 2009; Lenzen and Peters, 2010). USyd contributions also include automation procedures, the *ALANG* meta-language, and the parallelised optimiser suite.

The *University of Ballarat*'s Centre for Informatics and Applied Optimisation (CIAO) is contributing to the IELab functionality by accelerating the constrained optimisation routines and by integrating text mining techniques into data feeds exploring grey literature sources and industry reports, with a focus on environmentally significance sectors and supply chains.

3.5.2. Data feeds

During the initial IELab development, the integration of economic data via data feeds (see Section 2.1) was the domain of USyd (national data), *UNSW Australia* (UNSW — state-level data), and *Griffith University* (GU — substate-level data). The synergies in combining their relative expertise at all three scales enabled rapid progress towards the development of detailed, high quality sub-national MRIO tables for Australia.

Almost all institutions contributed data feeds for the satellite accounts. This component of the initial IELab development is being led by the *Commonwealth Scientific and Industrial Research Organisation* (CSIRO — material flow), the *University of Queensland* (UQ — water use, greenhouse gas emissions, toxic emissions), GU (energy use), UNSW (peripheral pollution data), USyd (waste), and the *University of South Australia* (UniSA — waste). These contributions reflect the data expertise and prior experience of the various contributors,[14] and their interests in applying MRIO analysis to economic and environmental research questions.

The project is run in close collaboration with the Australian Bureau of Statistics (ABS), which has legislated responsibility for the compilation and dissemination of the Australian national input–output tables. The ABS also produces a variety of national environmental accounts that are aligned with the UN's System of National Accounts (SNA, UN, 2009) and the System of Environmental and Economic Accounts (SEEA, UNSD, 2003). The ABS is strongly supportive of the project objectives, given its interest in ensuring that major Australian input–output applications adhere to the SNA and SEEA. The ABS is providing basic and enhanced raw datasets to the IELab development team, along with technical guidance on the development of the IELab framework.

4. Results — the first collaborative Australian MRIO table

At the end of 2013 (the conclusion of the development phase of the IELab), the collaboration of the partner institutions had established a complete Australian MRIO table. In addition, a number of projects had begun using the table for technology and policy applications. The partners involved in the development phase have a variety of research interests for which the IELab will be used, ensuring it will continue to be tested and improved in subsequent years.

4.1. The root and mother classifications

The root classification of the IELab is based on the most detailed regional and sectoral classification for which economic and physical data are available in Australia. For spatial classification we adopt the new Australian Statistical Geography Standard (ASGS) published by the Australian Bureau of Statistics (ABS) which includes a Statistical Area Level 2 (SA2) subdivision of the Australian continent into more than 2200 geographical entities (ABS, 2010a). The spatial root classification is visualised in the map provided in Appendix A4. For sectoral classification we use the Input–Output Product Categories (IOPC) from the ABS which distinguishes 1284 product groups (ABS, 2012b).

A fully disaggregated table at root detail would have dimensions of 2.8 million by 2.8 million, therefore requiring ~8 trillion data cells. Reconciliation of such a large matrix is beyond the capacity of existing computer power, and therefore requires the building of a mother table with smaller dimensions. The benefit of using such a detailed root classification is that it enables a high degree of user flexibility in defining a mother table that best meets the needs of any particular analytical application. The SA2 classification, for example, allows the construction of an MRIO for political as well as for physical (watershed/catchment) boundaries (see Appendix 4).

4.2. Table structure and data sources

The first Australian mother MRIO table is a multi-region supply-use table (MR-SUT) distinguishing 19 regions (see Fig. 2). These are six states and territories (Victoria, Australian Capital Territory, Tasmania, South Australia, Northern Territory, and Western Australia), the Illawarra region and the remainder of New South Wales, the state of Queensland broken down into ten regions, and finally a group called 'other territories' (including offshore Christmas and Cocos/Keeling Islands). This disaggregation was largely driven by the availability of state accounts for all eight states and territories (ABS, 2012a) and input–output data for the Illawarra and Queensland sub-state regions (Masouman, 2013; OGS, 2004) and the offshore territory of Norfolk Island (ACIL Tasman, 2012). A visualisation of the transaction values in the MR-SUT is provided in the form of a 'heat map' in Fig. 3.

A 344-industry and -product subset of the IOPC classification called ISAPC (Kanemoto and Moran, 2013) was chosen for the mother MR-SUT sectoral classification, again based on the availability of detailed supply-use data (ABS, 2012b, 2013a). Value added and final demand are included in their 5- and 6-component representations as in the original supply-use tables published by the ABS. Similarly, the mother MR-SUT distinguishes 18 valuations (margins, taxes, subsidies, etc.) as in the published tables. As a result, an MR-SUT for one year contains T transactions, where

$$T = \underbrace{19}_{\text{reg}} \times \underbrace{18}_{\text{valu}} \left(\underbrace{344^2}_{\text{use}} + \underbrace{344^2}_{\text{supply}} + \underbrace{344 \times 6}_{\text{find.dem}} + \underbrace{344 \times 5}_{\text{val.add}} \right) = 82,235,95.$$

The initial estimate for the MR-SUT was constructed based on Flegg's adjusted location quotient (Flegg and Webber, 2000) with a δ parameter of 0.3 (Kowalewski, 2012), and utilising census data (ABS, 2012d, compare Wittwer and Horridge, 2010). In the subsequent reconciliation, the table was constrained by input–output data (ABS, 2012b; ABS, 2012c; ACIL Tasman, 2012; Masouman, 2013; OGS, 2004), the business register (ABS, 2013b), the household expenditure survey (ABS, 2011), state accounts (ABS, 2012a) and by a multitude of detailed industry data (see Appendix 5, and also Gallego and Lenzen, 2009; Lenzen, 2009).
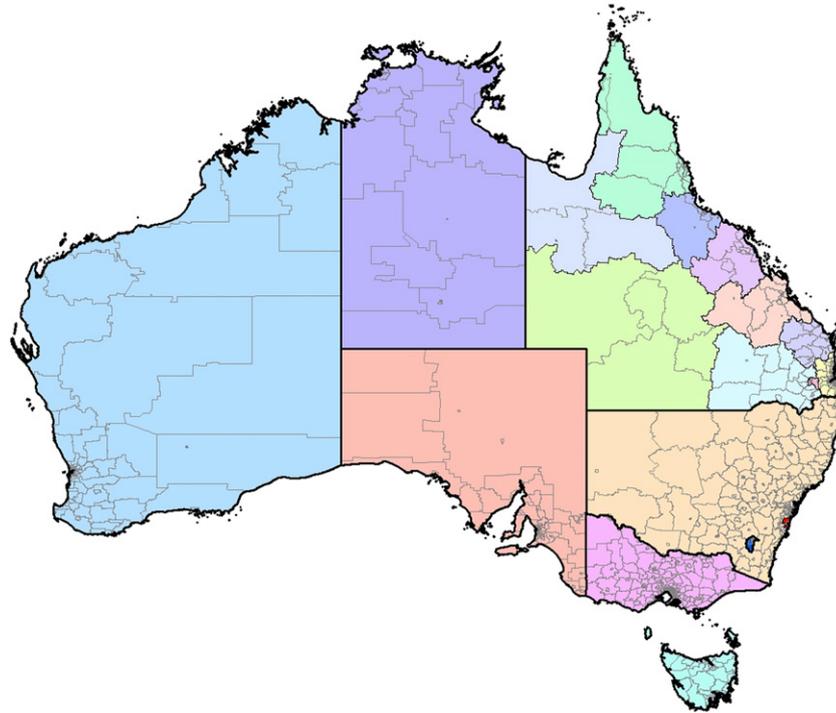
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[14] For example by CSIRO: e.g. Schandl and Capon (2012); Schandl and Turner (2009); Schandl and West (2010); and Schandl and West (2012); by UQ and GU: e.g. Daniels et al. (2011); and Kenway et al. (2011); by UNSW e.g. Lundie and Peters (2005); Lundie et al. (2004); Peters et al. (2010a); Peters and Lundie (2001); Peters et al. (2010b); and Rowley et al. (2009).

Fig. 2. Map of regions in the first Australian mother MRIO table. Each coloured (shaded) region is a separate mother classification, bounded by thin black lines. Heavy black lines are boundaries for state governments. Thin grey lines are boundaries for the SA2 regions.

The Australian MR-SUT is accompanied by matching satellite accounts for greenhouse gas emissions by gas and source (AEGIS, 2013), pollutant emissions by pollutant and receiving medium (NPI, 2013), water by type (ABS, 2012e), energy by fuel (BREE, 2013), material flow by material type (CSIRO and UNEP, 2012) and waste flow by waste type and treatment method (ABS, 2013c).

4.3. Current uses of mother and daughter tables

Given the existence of both energy and water satellite accounts, a major opportunity for using the Australian MR-SUT exists in understanding and harnessing the significant indirect influence of water

management on energy use. Especially in the populous and water-stressed state of Queensland, energy use related to the provision and use of water is estimated at 13% of state electricity use and 18% of state natural gas use (Kenway et al., 2011a,b). Despite its significance, relatively little is understood about the nature of interactions in the water–energy nexus. Thanks to the disaggregation of Queensland into ten regions, the mother MR-SUT will be used by UQ and GU partners for developing strategic tools to help create a water-, energy- and emission-smart region whilst enabling economic growth and regional prosperity. One aspect of this work will be to identify sectors of the Queensland economy that are vulnerable to possible future trends such as higher water and energy costs as well as sectors that produce
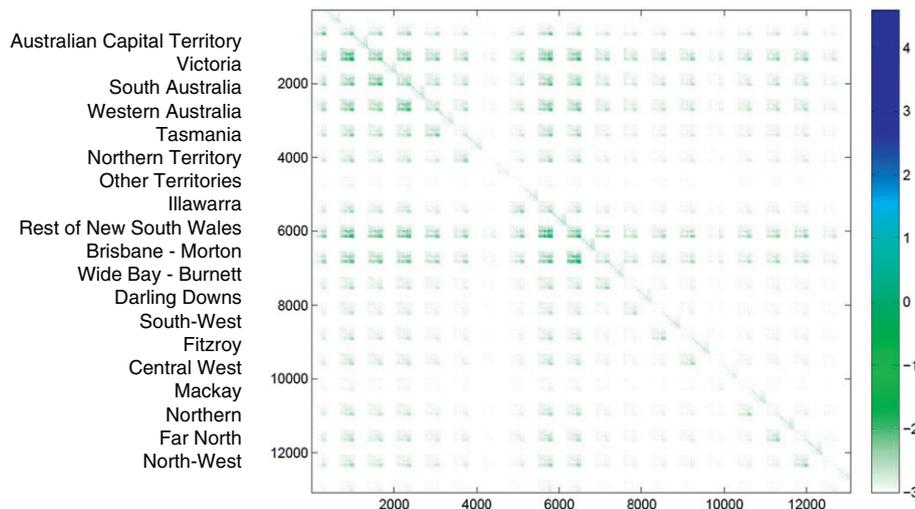

Fig. 3. 'Heat map' of the Australian MR-SUT, depicting transaction values. The shading of cells indicates the log10 of transaction values in millions of AU$, i.e. a value of 0 means AU$1 m, and a value of 3 means AU$1 bn.

higher economic return with efficient and sustainable use of water, energy and other environmental resources (for example food, concrete and other construction materials).

The aforementioned work can be coupled with analysis of impacts on economic activity diversity, estimating intensity in terms of other social impacts in the regions of Queensland, such as additional employment created or wages paid (such as in Foran et al., 2005). For industries such as manufacturing or construction that have been particularly affected from the financial crisis, this could lead to a better understanding and mapping of local economic structure and identifying risk of transmission of negative (or positive) effects. Potential extensions of the work are to estimate the metabolism of a highly urbanized region (Southeast Queensland is comprised of the Greater Capital Area of Brisbane and agricultural areas). Such analysis could help answer questions such as: 'Which sectors or regions are most dependent on "hidden" flows of water and energy (for example as virtual or embodied flows) in addition to their direct water requirements?', 'How does the water, energy or carbon intensity compare across the different industries and regions?', and 'What are the likely effects of relevant potential policy for South East Queensland, Queensland and Australia on water and energy consumption?'

The main objective of UNSW in using the MR-SUT is to conduct state-of-art environmental footprinting and sustainability assessments in applied research projects. This includes the development of tailored decision-support tools for government and industry partners based on a life cycle methodology. One example is UNSW-led research under the Australian Cooperative Research Centre for Low Carbon Living[15] which uses the hybrid LCA functionality of the IELab to evaluate new 'low-carbon' technologies and projects. Economy-wide, comparable and life-cycle-based carbon metrics for the built environment can be derived from the IELab, ranging from individual building materials over buildings and precincts to whole cities. Future work will include the evaluation of different 'low carbon living' scenarios and potential policy intervention points, based on stakeholder consultation (Wiedmann et al., 2013a). Hybrid LCA projects have also been undertaken in environmental engineering projects related water and wastewater treatment technologies (Alvarez-Gaitan et al., 2013).

The CSIRO will use the IELab to provide ongoing support to decision-makers regarding sustainable consumption and production policies, supply-chain initiatives and life cycle assessments. CSIRO has established expertise in direct water, energy and material flows accounting (Baynes et al., 2011; Wiedmann et al., 2013b) and the IELab not only makes good use of this but also permits the production of complementary carbon/energy/water footprinting and social indicators (for example employment) to enable more complete sustainability reporting. The IELab also provides the structure and basis for integrated assessment projects that incorporate other modelling forms: CGE, physical stocks and flows and scenario analysis. Notably, there is a rare opportunity for investigating material stocks and flows in detail using the combination of CSIRO's domestic extraction data and waste flows as they are both available in the IELab.

The University of South Australia is already using the MR-SUT to populate a Waste-Input–Output model (Lenzen and Reynolds, in press). This Waste-Input–Output model includes the highest detail food waste data ever created for Australia (Reynolds et al., 2013). Future research using the MR-SUT is planned to focus upon examining the geographic, social and economic impacts of diet and waste.

Finally, already during its development phase, the IELab supported a number of postgraduate projects, for example studies on the impacts of a potential biofuel industry in Australia, on the changing economy of Norfolk Island, on carbon footprint accounting of cities, on industrial symbiosis and material efficiency, and on waste metal flows in the Australian economy. Another interesting collaboration emerged with the Jolliet Lab at the School of Public Health of the University of Michigan, on modelling the environmental health effects of Australian consumption, by combining an economic MRIO model with a multi-scale fate and exposure model of pollution. Some of these projects use tailored daughter tables that are derived from the mother MR-SUT described above. For example, Malik et al. (submitted for publication) collect detailed process information about potential future production recipes for sugar-cane-based ethanol and gasoalcohol vehicle fuel blends, and simulate their introduction into the Australian economy by augmenting the MR-SUT with new rows and columns representing the new biorefining industries. The augmented table is an example of a tailored daughter table.

4.4. Potential future uses of the IELab

A fundamental objective of the IELab is to provide a system that is accessible and usable by a research community much larger than just those involved in the development phase. The flexible mother–daughter framework has been designed specifically with this in mind, allowing for future implementations of the IELab that might not have been envisaged by the initial project partners. A broader user engagement will be critical to the incorporation of comprehensive high-quality data specific to certain sectors and/or regions within Australia, and to realising the full benefits of the mother–daughter concept.

Corporate sustainability analysis and reporting applications can be addressed by the IELab, building on the experience of the University of Sydney in developing an input–output approach to triple bottom line reporting (Foran et al., 2005). Particularly for calculating corporate and product Scope-3 emissions (see WRI and WBCSD, 2011), the regional detail of the IELab will bring significant enhancements in reporting accuracy.

Policy applications of the IELab are expected to vary widely, providing assessment of issues such as the triple bottom line performance of the Australian economy; regional impacts of the mining boom; effects of region-specific infrastructure projects; effects of alternative regional forestry policies; effects of different policies to reduce CO_2 emissions; or the economic impacts of drought (Foran et al., 2005; Horridge, 2011).

The IELab has already increased the engagement between the input–output and LCA research groups involved. The engagement of a wider and more diverse range of potential users and stakeholders has been formalised through the inclusion of key industry and government representatives in the IELab's User Group, which directly informs the project's Steering Committee. Apart from the IELab developers this group currently comprises about 70 members from the wider research community, government departments and authorities, NGOs as well as private sector consultants and analysts with an according diverse range of applications. As a result of the User Group, we expect that the IELab will enhance and create links amongst and between government agencies and industry groups. Finally, researchers from other countries have expressed an interest in using the IELab technology for the compilation of sub-national MRIO databases and virtual labs in their home country.

5. Conclusions and outlook

The Commonwealth-funded Australian Industrial Ecology Virtual Laboratory (IELab) is being developed by a consortium of seven different research institutions on NeCTAR cloud-computing resources. The IELab will provide widespread research access to a time series of Australian sub-national MRIO tables that can be rapidly updated over time as new data becomes available. It elegantly integrates detailed data from the atmosphere, hydrosphere, biosphere, lithosphere, and anthroposphere. Furthermore, it facilitates harmonisation of previously fragmented, dispersed and misaligned raw data, and a suite of common input–output and LCA analytical tools that allow consistency of research outputs.

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[15] http://www.lowcarbonlivingcrc.com.au.

Unlike MRIO tables constructed using more conventional approaches, the IELab no longer limits all users to the same version of the MRIO table. With the IELab, each user can construct a different mother MRIO, depending on their preferred data sources and MRIO classification structure; their tolerance for data uncertainty; and their need for computational simplicity. Comparisons and trade-offs between different user MRIO versions are facilitated by standard deviation tables that accompany each set of results. Users can reduce the mathematical uncertainty by opting for a high degree of aggregation and conservative data selection, if they feel that coarse analytical results are sufficient. Conversely, the user can increase the resolution of the analysis, if they feel this is sufficiently beneficial to outweigh any increased uncertainty in the results. In addition, users can reduce uncertainty in the areas that matter most to them, by introducing superior data to build tailored daughter tables. This flexibility is made possible by the collaborative and unsupervised Virtual Laboratory approach.

The difference between our approach and the conventional approach may be likened to the difference between a printed, published encyclopaedia and a Wikipedia site. Rather than one organisation being responsible for data, procedures and quality assurance, our approach is driven by multiple users uploading their own data onto a cloud environment, and actively engaging in quality control. The main advantage of the unsupervised approach is that it provides an effective way to share resources for what has traditionally been a quite labour- and time-intensive task, leading to enhanced timeliness of published results. The strategy to minimise downsides of this 'wiki' approach to MRIO construction includes two key components. Firstly, the IELab will encourage the largest possible number of users to test and critique its data quality. To this end, a diverse set of stakeholders participated in the initial development phase, providing them with a motive for ongoing engagement with the product. More generally, the IELab is designed to be as easy as possible to use, by the widest possible set of researchers, for the widest possible range of applications. Secondly, the IELab will be strict in requiring that all data feeds are accompanied by uncertainty information, and a minimum level of documentation. This latter aspect ensures that all users will be able to test and compare the uncertainties associated with any particular customisation of the IELab MRIO tables.

In summary, the IELab in the Virtual Laboratory infrastructure promises: a) significant savings in terms of human and financial resources, thanks to the collaborative nature of the project; b) timely deployment, thanks to the automation procedures; and c) flexibility in future choices about sectoral and spatial representation, thanks to the flexible root–mother–daughter concept.

The IELab development process has been remarkably successful at facilitating collaboration across the large and diverse group of research participants involved. The attraction and power of the IELab concept are that it delivers a product that is more than could be achieved by each individual participant. Enhancing cost-effectiveness, automating data compilation, and providing global stewardship and governance have been identified as key requirements for the advancement of global MRIO compilation and application (Tukker and Dietzenbacher, 2013; Tukker et al., 2009; Wiedmann et al., 2011b). We therefore view the Australian IE Lab project as a test bed for a global application of the Virtual Laboratory and flexible root–mother–daughter approach to MRIO compilation.

Full implementation of the IELab will significantly advance the analytical capacity of environmental and sustainability science in Australia. This will encourage a rapid expansion of national and international research efforts required to address the challenges of economic development, in the face of environmental constraints that are growing in number and in urgency.

Conflict of interest

The authors of the following manuscript declare no conflict of interest.

Supporting Information

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