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ABSTRACT

We describe the creation of the Global Multi-Region Input–Output (MRIO) Lab, which is a cloud-computing platform offering a collaborative research environment through which participants can use each other's resources to assemble their own individual MRIO versions. The Global MRIO Lab's main purpose is to harness and focus previously disparate resources aimed at compiling large-scale MRIO databases that provide comprehensive representations of interregional trade, economic structure, industrial interdependence, as well as environmental and social impact. Based on the operational Australian Industrial Ecology Lab, a particularly important feature of this cloud environment is a highly detailed regional and sectoral taxonomy called the 'root classification'. The purpose of this root is to serve as a feedstock from which researchers can choose any combination of regions and economic sectors to form a model of the economy that is suitable to address their particular research questions. Thus, the Global MRIO Lab concept enables enhanced flexibility in MRIO database construction whilst at the same time saving resources and avoiding duplication, by sharing time- and labour-intensive tasks amongst multiple research teams. We explain the concept, architecture, development and preliminary results of the Global MRIO Lab, and discuss its ability to continuously deliver some of the most prominent world MRIO databases.

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1. Introduction

At the end of 2014, the development of the Australian Industrial Ecology Virtual Laboratory ('IELab', http://ielab.info, Lenzen et al., 2014) was concluded with funding from the National eResearch Collaboration Tools and Resources project (NeCTAR, 2013). The IELab's main purpose is to enable a more automated compilation of large-scale, multi-region input–output (MRIO) tables. These provide comprehensive representations of interregional trade, economic structure, industrial interdependence, as well as environmental and social impact (Duchin, 1992). MRIO databases have underpinned prominently published studies on a wide range of environmental issues, such as the implications of international trade for global carbon emissions (Hertwich and Peters, 2009), water use (Feng et al., 2011), species threats (Lenzen et al., 2012b; Moran and Kanemoto, 2017), mercury emissions (Hui et al., 2017), nitrogen emissions (Oita et al., 2016) and resource efficiency (Wiedmann et al., 2015b; Tukker et al., 2016). They have proven to deliver useful information for policy (Minx et al., 2009; Wiedmann and Barrett, 2013; Wiedmann, 2016), and especially for international negotiations about responsibility for carbon emissions reductions (Peters and Hertwich, 2008; Barrett et al., 2013).

Global MRIOs have also had a major impact on research in important subfields of economics. Johnson and Noguera (2012), Timmer et al. (2013) and Koopman et al. (2014), for example, argued in various ways that conventional indicators based on gross exports of countries do not tell much about the competitiveness of countries and the economic dependencies between pairs of countries anymore. Timmer et al. (2014) focus on trends in the distribution of income in countries between factors of production as a consequence of the emergence of Global Value Chains, while Alsamawi et al. (2014b) investigated the implications for income inequality. Alsamawi et al. (2014a) and Foster-McGregor et al. (2013) studied the consequences of offshoring for employment. Baldwin and Lopez-Gonzalez (2015) and Los et al. (2015) quantified changes in the geographical scope of the international fragmentation of production processes. Using MRIO data, Moran et al. (2015) studied the interaction of scarce natural resources and economic changes in a study related to the emergence of civil wars.

The IELab marks a break with traditional approaches to constructing such databases. This is because rather than tying ownership of an MRIO database to a particular institution or consortium (Murray and Lenzen, 2013; Tukker and Dietzenbacher, 2013), the IELab offers a collaborative research cloud through which participants can use each other's resources to assemble their own individual versions of MRIO databases. A particular central feature of this cloud environment is a highly detailed regional and sectoral taxonomy called the 'root classification'. The function of this root is to serve as a feedstock from which researchers can choose any combination of regions and economic sectors to form a model of the economy that is suitable to address their particular research questions (a so-called base model; compare with Wittwer and Horridge, 2010). Thus, the IELab concept enables enhanced flexibility in MRIO table construction whilst at the same time saving resources and avoiding duplication, by sharing time- and labour-intensive tasks amongst multiple research teams.

At the time of writing, the Australian IELab was the only fully operational virtual laboratory allowing the construction of large-scale MRIO frameworks. It features the following functional components in a fully automated build pipeline: (1) raw[1] and processed data repositories; (2) a graphical user environment for the preparation of construction runs (see Geschke et al., 2011); (3) a constrained-optimisation matrix reconciliation engine (Lenzen et al., 2009); (4) a visual diagnostics suite (Lenzen et al., 2013); and (5) an analytical toolbox including software for undertaking life-cycle assessment (LCA) and various environmental footprints (Foran et al., 2005; Wiedmann et al., 2009). A number of publications have already resulted out of this infrastructure (Wiedmann, 2017), including, for example, carbon footprint analysis of cities (Wiedmann et al., 2015a; Chen et al., 2016a; 2016b) or renewable electricity in Australia (Wolfram et al., 2016), or the simulation of introducing sizeable biofuels industries into Australia (Malik et al., 2014; 2015; 2016). The IELab is aimed at professionals in research institutions, government and the private sector alike, and as such it has a wide range of users. Apart from the five founding universities, several Australian peak bodies and research cooperatives have endorsed the IELab project, including the CSIRO, the Australian Life-Cycle Assessment Society, the Australia New Zealand Society for Ecological Economics and the Co-operative Research Centre for Low Carbon Living. Together these bodies represent thousands of members. In addition, private sector companies and consultancies specialised in regional economic and/or triple-bottom-line/sustainability assessments are especially attracted to the ease of regionalisation of economic and environmental national accounts and the rich ensemble of hybrid-LCA data. Australia's largest water services providers as well as leading global consultancy and asset managements firms have entered into collaboration with IELab, for example, to produce sub-regional input–output (IO) tables for regional governments, or to assess the impact of environmental, economic and social measures on financial markets, business strategies and the sustainability of Australian businesses. Finally, the Australian Bureau of Statistics commits ongoing significant in-kind support to the IELab with the long-term intention of streamlining the compilation of Australia's National Accounts. However, one drawback is that the Australian IELab only offers sub-national MRIO versions for Australia.

There has been ample experience with constructing large-scale global MRIO tables within a number of institutions or consortia.[2] However, these undertakings have been impeded by their high financial resource requirements, resulting in infrequent or untimely database updates, or discontinuation of time series. In order to be relevant for international policy, global MRIO databases need to be created and updated in a timely, continuous, consistent and cost-effective way (Wiedmann et al., 2011). These issues can in principle be addressed by instigating a collaboration between the various global MRIO teams (compare with ideas by Pauliuk et al., 2015). This idea was first discussed at a meeting at L'Hermitage-les-Bains on Réunion Island in March 2011, and Project Réunion was formed, with participants[3] from TNO Delft/CML Leiden, the University of Groningen, the OECD, Purdue University, the Japan External Trade Organisation, the Center for International Climate and Environmental Research in Oslo and the University of Sydney. The goal

[1] It should be noted that the Industrial Ecology Laboratory is not meant to be a platform for sharing original data, particularly those copyrighted by statistical agencies. Information disseminated as base tables is usually sufficiently transformed to satisfy confidentiality and copyright requirements.
[2] Andrew and Peters (2013), Dietzenbacher et al. (2013b), Lenzen et al. (2013), Meng et al. (2013) and Tukker et al. (2013).
[3] http://www.isa.org.usyd.edu.au/mrio/mrio.shtml.

of Project Réunion was to coordinate worldwide activities on environmentally extended MRIO database compilation. As a first step, Project Réunion members agreed, in their 2013 meeting at Kurokawa Onsen, to aim at demonstrating the ability to generate, based on unified data pools and construction pipelines, a set of global MRIO databases expressed in the regional and sectoral classifications of the EXIOBASE, WIOD and Eora tables. In 2013, Project Réunion received funding from the Australian Research Council, and work started on realising the collaboration using virtual laboratory technology.

This article deals with the global expansion of the Australian IELab archetype into a global virtual laboratory for Project Réunion participants. In the Methods section, we briefly explain the concept, architecture and development of the *Global MRIO Lab*, with particular focus on a few technical aspects in which the global lab differs from its Australian predecessor, and which had to be solved within the scope of Project Réunion. We then describe some first concrete outcomes in the Results section, with the aim of demonstrating how the virtual laboratory's concept and technical innovations enable researchers to create world MRIO databases in a flexible way. The paper is wrapped up with reflections on Project Réunion's journey, and an outlook for the future.

2. Methods

The concept and architecture of the Global MRIO Lab are identical to those of the Australian IELab (Lenzen et al., 2014). Participating researchers log on to a cloud environment and choose a number of workflows to be executed, such as constructing a new MRIO table, constructing a new time series of MRIO tables (Lenzen et al., 2012c), augmenting an existing MRIO table with process data to undertake a hybrid LCA (Heijungs and Suh, 2002; Suh, 2004; Suh et al., 2004; Suh and Huppes, 2005), and/or using an existing (hybrid) MRIO table for carrying out LCA or footprint analyses (Suh and Nakamura, 2007). Upon entry via a web-based interface, users choose a regional and sectoral classification that is most suitable to their research question and that they want their own tailored MRIO tables to be expressed in. Since users select their own classification from the Lab's root classification, the latter is very detailed to give users the most extensive choice possible.

In order to build a virtual laboratory that is able to generate EXIOBASE-, WIOD- and Eora-classed MRIO databases, four crucial developments are needed: first, a global root classification needs to be defined. Second, a unified MRIO construction workflow needs to be defined that as closely as possible reflects the EXIOBASE, WIOD and Eora construction recipes (raw data, initial estimate and reconciliation method). Third, the global lab needs to be able to deliver MRIO tables with inhomogeneous (i.e. region-specific, as in Eora) sector classifications. Fourth, the global lab should offer a standard deviations database, supporting uncertainty calculus for any user-defined application. These developments are described in the following four subsections.

2.1. *Finding a global root classification*

To construct a new (time series of) MRIO table(s), users first need to define the regional and sectoral classification that they wish their table(s) to be expressed in. In the Australian IELab, this is done via a map and drop-down list shown on a graphical user interface, by selecting and grouping regions and economic sectors from the root classification. Both regional and sectoral roots need to be very detailed representations of the world economy, because their function is to act as a repository from which regions and sectors can be taken to derive many differently classified MRIO tables. Moreover, at least one complete data set expressed in both regional and sectoral root classification has to exist to be able to support the generation of an initial MRIO estimate, which in turn is an essential ingredient for the table reconciliation and balancing (Geschke et al., 2014).

Due to its prohibitive size and a lack of empirical data at this very detailed level, the root itself is unsuitable for serving as a basis for an actual MRIO table (compare with Wittwer and Horridge, 2008). As a consequence, the user's regional and sectoral groupings will be aggregations of the regional and/or sectoral roots. Assuming that the root comprises M regions with N sectors each, which the user groups into K aggregate regions and L aggregate sectors, this selection will result in a $(M{\bullet}N) \times (K{\bullet}L)$-sized root-to-base aggregator matrix, with elements equalling 1 wherever a root-classified region-sector pair (rows) is assigned to a user-defined base-classified region-sector pair (columns), and 0 elsewhere. This aggregator is used throughout the entire MRIO construction run – especially during the preparation and solving of the constrained-optimisation matrix reconciliation problem – for translating root-classified raw data into base-classified MRIO elements (Geschke et al., 2011).

In the Australian IELab, the root classifications are the Statistical Area Level 2 (SA2, 2214 geographical entities, ABS, 2010), and the IO product categories (IOPC, 1284 product groups, ABS, 2016), and there exist actual data sets in both classifications (the Census, ABS, 2012, and the supply-use tables (SUTs), ABS, 2016). The challenge is hence to locate a global regional and sectoral classification that is comprehensive enough to serve as a global root.

In our search for a global root classification we oriented ourselves at one of the Project Réunion's aims: to provide a proof-of-concept for the routine generation and update of at least the EXIOBASE, WIOD and Eora world MRIO tables based on unified data pools and construction pipelines. Hence, we first posed the question: which sectoral classification is (a) detailed enough to include at least as much detail as the above MRIO frameworks; and (b) used in at least one data set covering all countries? It turned out that at the time of writing no classification existed that satisfied these criteria (see Table 1).

Failing our search, we resorted to constructing a root classification from a number of incomplete or partially aggregated databases. The basic idea here is to assemble a collectively exhaustive union set from the most disaggregated parts of various disparate databases (for comparison, see approaches used in EXIOBASE, Section 3.1 in Wood et al., 2015). Proceeding this way, the final root classification will be (a) more disaggregated than any of the databases considered in its construction process, and (b) exclusively based on measured information reported in the individual databases. The logic of the construction process is to

(1) nominate one database to provide the initial data set covering all regions that the final root classification should cover; and
(2) use the information of the remaining databases to iteratively disaggregate the initial data set until the maximum disaggregation is reached.

Table 1. International and national databases with detailed sectoral and/or regional coverage.

International databases	Type of data	Years	Product/Industry classifications	No of countries	Sector levels	No of goods	No of services	Comments
Trade Analysis System on Personal Computer (PC-TAS HS revision 2)	Import/Export	2007–2011	HS1996	176	6-digit[a]	5114	0	No services data
Trade Analysis System on Personal Computer (PC-TAS SITC revision 3)	Import/Export	2006–2010	SITC rev 3	181	5-digit	3121	0	No services data
Industrial Statistics Database 3- and 4- level of ISIC (INDSTAT4 2012)	Output/ Employment	1990–2011	ISIC rev 3	59	4-digit	148	146	Limited country coverage
Industrial Commodity Statistics Database ICS	Output	1950–2008	CPC v1.1	200	5-digit	1152	970	Lack of monetary value data
UN Comtrade Database	Import/Export	1962–2013	SITC rev 1–4, HS1992-HS2012	293	5-digit(SITC), 6-digit(HS)	> 5000	0	No services data
OECD National Accounts Statistics	Value Added	1990–2014	ISIC rev 3 &4	46	n/a	3	15	Aggregated to 18 ISIC classification
OECD ITCS database[b]	Import/Export	1988–2014	SITC rev 2–3, HS1988–2007	41(SITC), 37(HS)	5-digit(SITC), 6-digit(HS)	> 5000	4	Limited to OECD country data and trade partner. Aggregated services data
OECD Statistics on International Trade in Services	Import/Export	1993–2008	EBOPS	35	n/a	–	14	Limited services classification
OECD STAN Bilateral Trade Database by Industry and End-use category (BTDIxE)	Import/Export	1990–2015	ISIC rev 3, ISIC rev 4	154	2 to 4-digit	66	1	Aggregated industries data. Service sector is aggregated in 'Other activites'
BACI: International Trade Database at the Product-Level	Import/Export	1994–2014	SITC, HS1992–2002	239	6-digit	5041	0	No services data
WITS: World Integrated Trade Solution (World Bank)	Import/Export	1988–2015	SITC rev.2, HS1988–1992	275	5-digit (SITC), 6-digit (HS)	5228	0	Aggregated services data
UN MA Database	Value Added	1970–2015	ISIC rev 3	218	n/a	3	4	Aggregated to 7 ISIC classifications
UN Official Country data	Value Added	1970–2015	ISIC rev 3	223	n/a	6	10	Aggregated to 16 ISIC classifications
UN Service Trade Database	Import/Export	2000–2014	EBOPS	199	n/a	0	121	Limited services classification
UNCTAD Database	Import/Export	1980–2013	SITC rev.3	237	3-digit	3121	0	Aggregated classification on services

(*continued*).

Table 1. Continued.

National Classification	Type of data	Years	Links to international classification	Country	Sector levels	No of products	No of services	Comments completeness/gap
NAICS – North America Industry Classification System (2012)	Employment	1975–2015	ISIC rev.4	USA	6-digit	502	563	Detailed employment data up to 6-digit level
NAPCS – North America Product Classification System	–	–	CPC		11-digit	564	603	Data not available. System under development
JSIC – Japan Standard Industrial Classification	Employment	1953–2015	ISIC	Japan	4-digit	753	702	Aggregated data at 2-digit level
JSCC – Japan Standard Commodity Classification	Import/Export	1995–2012	HS		6-digit	13,757	0	No data on output or employment. Import/export data are detailed up to 6-digit level
CNAE version 2.0 (Industry)	Output	2007-	ISIC rev.4	Brazil	5-digit	583	718	Data available up to 4-digit level.
PRODLIST (Product)	Output	2005–2013	CPC		8-digit	4216	50	Data available up to 8-digit level. Limited services classification
NIC – National Industrial Classification	Output/ Employment	1998–2014	ISIC rev.4	India	5-digit	498	536	Detailed output/employment data up to 4-digit level
NPCMS – National Product Classification for Manufacturing Sector	Output	2010–2014	CPC v2		7-digit	1501	0	Detailed data up to 7-digit level
NPCS – National Product Classification for Services Sector	–	–	CPC		8-digit	0	1825	New classification. Data not available.
ICNEA 2011 – Industrial Classification of the National Economic	Output	2012–2015	ISIC rev.4	China	4-digit	630	464	Data are aggregated at 2-digit level
PCS – Product Classification for Statistical Use	Output	2011–2015	CPC v1.0		10-digit	23,998	4999	Available output data for major industrial products at highest-level detail.

[a] Individual countries can extend the HS code and add more detailed, that is, > 6 digit sector levels for reporting their trade transactions. Japan and USA, for example, provide trade data at the 9-digit (for Japan) and 10-digit (USA) HS code level, corresponding to their national IO classifications.
[b] OECD ITCS has the same coverage as UN Comtrade, ie approximately 200 countries reporting at 6-digit HS. The OECD's analytical bilateral trade in goods (BTDIXE) has ISIC3 and ISIC4 data and Trade in Services is expressed in 12–15 EBOPS categories.

The regional coverage of the final root classification is defined by the regional coverage of the initial data set. The following algorithm[4] then disaggregates the sectoral classification of each region, until the root classification is reached:

(1) choose a database providing a sectorally disaggregated data set for all countries. For the Global MRIO Lab we chose sectoral value added in the UN Main Aggregates (MA, UNSD, 2016b). Call this database #1. The MA value added by sector[5] for all countries is denoted $\mathbf{w}(:,1)$, where the colon stands for all region-sector pairs.

(2) disaggregate the initial data set iteratively according to the following steps. Loop over databases $n = 2{:}N$.

  (2.1) Choose a database (#n) that is deemed to provide reliable and detailed sectorally disaggregated quantitative information on value added, or a suitable proxy thereof, for at least one country.

  (2.2) Loop over countries $c = 1{:}C$ in the root classification. Let $\mathbf{w}(c,n-1)$ be the $n-1$st iterate of value added belonging to country c. If database #n contains data for country c, then do the following:

    (2.2.1) Obtain concordance matrix: Acquire or construct a concordance matrix $\mathbf{C}(c,n-1)$ between the classifications of country c's sectors in databases #n (columns) and #$n-1$ (rows).

    (2.2.2) Interrogate the concordance matrix for disaggregation possibilities: Examine the concordance matrix $\mathbf{C}$ and find rows with more than one non-zero element. Such rows identify sectors in database #$n-1$ that are represented by more than one sector in database #n, that is, sectors whose #$n-1$-datum of value added can be disaggregated on the basis of information in database #n. If no such instances can be found, then set $\mathbf{w}(c,n) = \mathbf{w}(c,n-1)$.

    (2.2.3) Disaggregate: If at least one disaggregation possibility is found, $n-1$-classed sectors earmarked for disaggregation in step 2.2.2 are disaggregated on the basis of database-n information $\mathbf{w}^*_\nu$ for ν sectors. This is achieved via prorating using a map $\mathbf{M} = [\widehat{\mathbf{C}\mathbf{w}^*_\nu}]^{-1}\mathbf{C}\widehat{\mathbf{w}^*_\nu}$ (see Section 4.2 in Lenzen et al., 2012a), according to $\mathbf{w}(c,n) = \mathbf{w}(c,n-1)\,\mathbf{M}$.

    (2.2.4) Next country: Repeat steps 2.2.1 to 2.2.3 for the next country in database #n.

  (2.3) After the looping over all countries of database #n is finished, the new iterate $\mathbf{w}(:,n)$ is completed.

(3) Examine the next database.

Throughout this process, the labels of the individual sectors are updated, and the concordances constructed in step 2.2.1 are saved for further use. The final root vector $\mathbf{w}(:,N)$ sums to the same global total as the Main-Aggregates-based value added $\mathbf{w}(:,1)$; however, its detailed sectoral and regional splits will depend on the data $\mathbf{w}^*$ used for disaggregation. These data may not even be on value added, but instead on gross output or employment, for example. Therefore the final root vector $\mathbf{w}(:,N)$ is merely a *proxy* for global value added.

[4] The global root algorithm is explained in more detail in the Appendix.

[5] Agriculture, hunting, forestry, fishing (ISIC A-B), Mining and Utilities (ISIC C&E), Manufacturing (ISIC D), Construction (ISIC F), Wholesale, retail trade, restaurants and hotels (ISIC G-H), Transport, storage and communication (ISIC I), Other Activities (ISIC J-P).

Note that the final root is also dependent on the sequence of the databases applied for successive disaggregation. In general, databases applied earlier in the process will have more influence on the root's structure than those applied later. It is therefore advisable to call the databases in order of decreasing perceived reliability. The advantage of such a recursive disaggregation approach is that there is a high degree of transparency, where more aggregate data are trusted over more disaggregate data. A downside of the approach is that it cannot disaggregate many-to-many concordances, and beyond the reliability implied by the ordering of the *n* data sets, does not allow further uncertainty information to be included.

2.2. Adjusting MRIO construction workflows

Three conceptual steps characterise the process of constructing an MRIO table: System definition (regions and sectors), linking of primary data to the system, and reconciling the system with the data. The third step involves a typically underdetermined problem, requiring that the table be constructed based on (a) an initial estimate, and (b) a set of constraints that are reconciled by some kind of optimisation problem solver (Geschke et al., 2014). However, whilst the EXIOBASE, WIOD and Eora databases all feature these basic ingredients, they differ for example

(1) in their choice of supporting data,
(2) in the way the initial estimate is set up,
(3) in the type of optimisation method used, and
(4) in the number and partitioning of optimisation steps.

(1) There are some databases such as the Eurostat Supply and Use Tables (Eurostat, 2016) that are used in all three MRIO databases, but there are other data that these frameworks use exclusively. Especially the EXIOBASE MRIO database distinguishes a number of detailed agricultural, energy and waste sectors that do not feature in WIOD and Eora. (2) The initial estimates follow different recipes; for example they use different assumptions for prorating known totals across unknown MRIO elements (Geschke et al., 2014). (3) A number of variants of the RAS biproportional method are in use for table balancing (Junius and Oosterhaven, 2003; Oosterhaven, 2005; Lenzen et al., 2009; Temurshoev and Timmer, 2011; Temurshoev et al., 2011), as well as some constrained-optimisation approaches (Wood et al., 2014; Wood et al., 2015). There are three considerations for choosing balancing techniques: the incorporation of a flexible topology of constraints (Lenzen et al., 2006); the ability to handle conflicting constraints (Lenzen et al., 2009); and the ability to reconcile a single large-scale system (billions of variables in a full-MRIO model). Only KRAS (Lenzen et al., 2009) has been shown to satisfy all three requirements. (4) The construction of the EXIOBASE and WIOD tables proceeds in two steps, where in the first step national SUTs are prepared in EXIOBASE and WIOD classification, and in the second step these tables are trade-linked and balanced using international trade data.[6] In the Eora workflow this is done in one step.

[6] EXIOBASE 1 and 2 followed this "country first" approach. EXIOBASE v.3 first reconciles trade, and imposes this balanced trade on country SUT (Stadler et al., in press).

In the Global MRIO Lab these differences are dealt with in a number of ways. (1) Various MRIO databases share the same raw data (e.g. the UN MA) for defining the initial estimate and constraints. In the Global MRIO Lab, data sources are offered via standardised datafeeds. This is a key example for the benefits of a virtual laboratory architecture, because a feed for a particular data source only needs to be written once by a researcher working on any of the MRIO variants, and the feed's standardisation ensures that other researchers will be able to use it without further work, by selecting the feed from a web-based menu. The collaborative lab architecture also means that users are not restricted to select the constraint suite used in the original database; they are free to include more constraints, exclude some constraints, or mix constraints between different MRIO databases, and thus create new MRIO variants. (2) Different initial estimate procedures are offered in the Global MRIO Lab as user options, controlled via the lab's user interface. When implementing the various initial estimates, database-specific original procedures were adhered to as much as possible. Code was generalised to allow any regional and sectoral classification. This means that in the global lab, EXIOBASE, WIOD and Eora databases could be built at classifications other than their original regions and sectors. (3) Similarly to the initial estimate, the lab's user interface allows a choice of optimiser method. Subjecting GRAS or SUT-RAS routines to conflicting constraint sets may lead to non-convergence of the optimisation step. (4) In the Global MRIO Lab the two-step procedures were unravelled and re-aligned into a one-step process. This particular feature is discussed in detail in two other articles in this Special Issue (Abd Rahman et al., 2017; Reyes et al., 2017) and will therefore not be dealt with here.

Offering a set of alternative choices for the data sources, the initial estimate and the optimiser means that the user can mix characteristics from EXIOBASE, WIOD and Eora. An example for the outcomes of such combinations of construction elements is demonstrated in Geschke et al. (2014).

2.3. Enabling inhomogeneous MRIO classifications

The Australian IELab offers one root-to-base aggregator for all regions, meaning that only homogeneously classified base tables can be constructed. Applied in the global lab, this setting would be too restrictive for two reasons. First, it would not allow the construction of the inhomogeneously classified Eora MRIO tables, with varying IO or supply-use structures, or varying numbers of sectors across countries. Second, and more importantly, it would not allow users to construct tables with region-specific sector detail (as in adaptive networks). Such tables are beneficial whenever a research problem demands low-resolution global coverage but high detail in particular regions of interest, such as cities or industrial hubs. If only one root-to-base aggregator existed, all regions would have to be represented at the sector detail of the region of interest, potentially leading to prohibitive table size.

As a result, all initial estimate and constraint build procedures, as well as the IELab's root-to-base casting (see Lenzen et al., 2014, Section 2), had to be modified in order to allow for region-specific root-to-base aggregation. As a result, the lab allows generating MRIO tables with varying IO and supply-use structures, and varying sector numbers.

2.4. Standard deviations

The GRAS and SUT-RAS variants of the RAS matrix balancing method do not require any information on raw data reliability, and as a result these methods do not generate any information about the uncertainty of elements in the final balances MRIO table. The KRAS method uses information on data reliability in order to determine compromise solutions for conflicting sets of constraining information. An output of the KRAS method is a complete table of standard deviations accompanying the MRIO transactions table. KRAS and standard deviations tables are already implemented for Eora (Lenzen et al., 2012a; 2013). The generation of standard deviation tables for EXIOBASE and WIOD is described in this Special Issue in articles by Reyes et al. (2017) and Abd Rahman et al. (2017), respectively.

For Lab users, the ability to incorporate data reliability information means that any primary data set can be tagged with standard deviation estimates, thus providing users with the control to put emphasis onto, or away from, or even exclude particular data sources.

3. Results

In the following we will present results for the methodological innovations described in Sections 2.1 – the global root – and in Section 2.3 – flexible regional and sectoral structure.

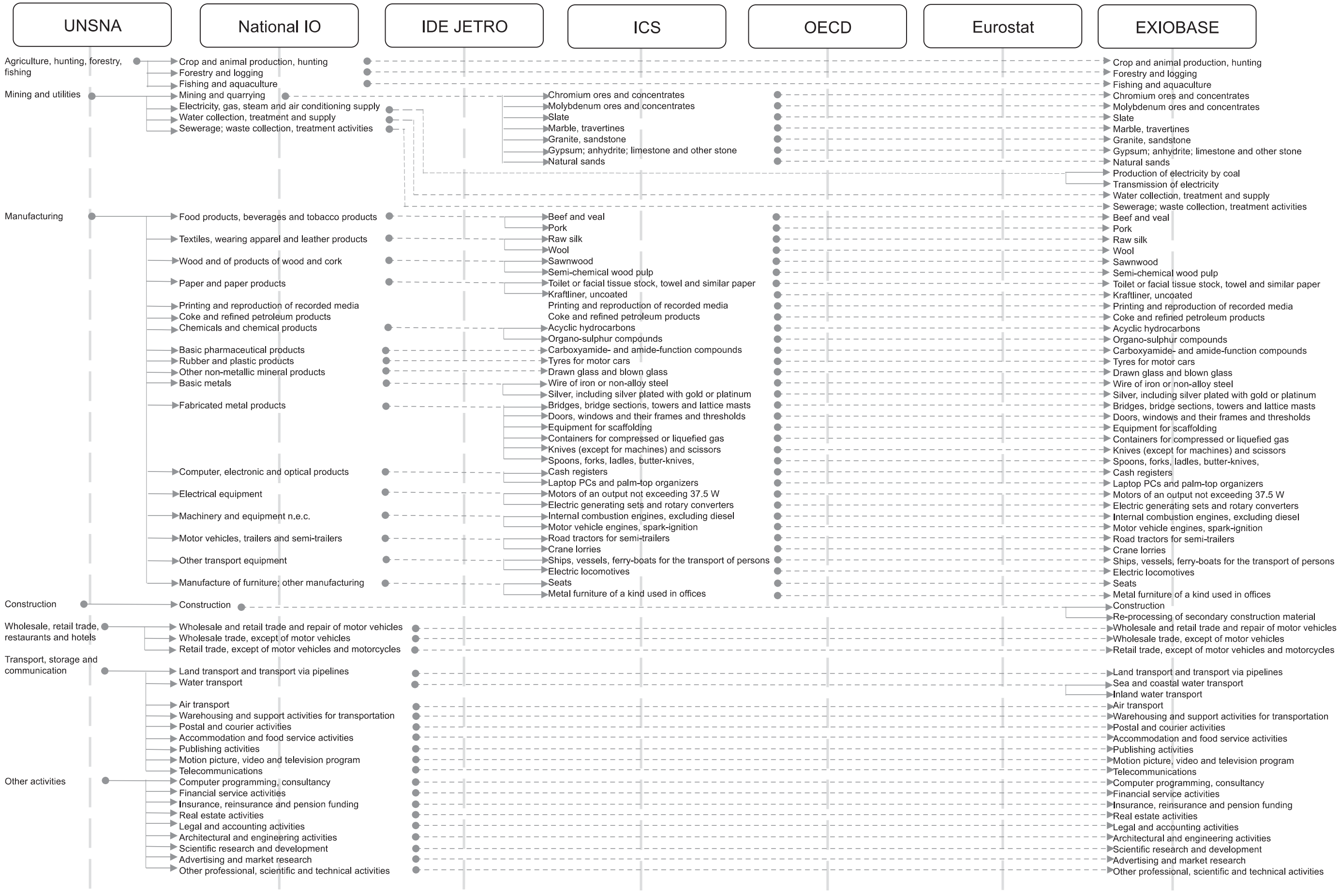
3.1. Global root

The outcome of a global root assembly procedure spanning $n = 7$ databases is shown in Figure 1. As explained in Section 2.1, the point of departure is the value added data set from the UN SNA MA database ($n = 1$; UNSD, 2016b), spanning $C = 220$ countries at a resolution of 7 sectors.[7] We now focus on Italy as an example country. The global root assembly run shown in Figure 1 then queries the Italian national IO table ($n = 2$) for disaggregation opportunities, and finds them for example for the UN SNA MA sector 'Agriculture, hunting, forestry, fishing', which is disaggregated into three subsectors: 'Crop and animal production, hunting', 'Forestry and logging', and 'Fishing and aquaculture'. Similarly, mining, manufacturing, trade, transport and other industries are disaggregated. The run then queries the Institute of Developing Economies (IDE-JETRO) database ($n = 3$; IDE-JETRO, 2015), and naturally does not find any disaggregation opportunities because Italy is not distinguished in this database. The Industrial Commodity Production Statistics ($n = 4$; UNSD, 2016a) is then exploited to disaggregate the manufacturing group. Following, OECD ($n = 5$; OECD, 2015) and Eurostat ($n = 6$; Eurostat, 2016) databases are both more aggregated than the 4th iterate of the global root. Finally, the EXIOBASE classification ($n = 7$; EXIOBASE, 2012) allows doubling of the electricity, construction and water transport sectors. Even though EXIOBASE is an MRIO database itself,[8] it is needed for the

[7] Note that the UN SNA Main Aggregates database is an industry classification. Disaggregating this classification further using product classification may lead to minor inconsistencies, for example if the Main Aggregates primary industry "Agriculture" contains agricultural services that are reported as tertiary services in other classifications.

[8] Strictly speaking, the use of the EXIOBASE (v.2.3) MRIO as an input into the global root construction constitutes a conceptual inconsistency. In principle, one could use the various data sources underlying EXIOBASE's disaggregation. However, some of these would be rather distant and therefore inadequate proxies for splitting value added ($\mathbf{w}^*$, as explained in Section 2.1). For example, for most economies UN Comtrade data constitute a small percentage of domestic economic activity. In any case, including EXIOBASE as a whole allows covering many disparate databases in one step.

Figure 1. Extract from a global root classification for Italy, resulting out of the procedure described in Section 2.1, involving the following databases (not in order of perceived reliability, but just for illustration): UNSD (2016b), national IO tables, IDE-JETRO (2015), UNSD (2016a), OECD (2015), Eurostat (2016) and EXIOBASE (2012). OECD and Eurostat databases are more aggregated than the 4th iterate of the global root.



global root assembly, because none of the first six data sources offers a sector classification detailed enough to represent EXIOBASE.

The global root assembled as shown for Italy in Figure 1 is more detailed than Italy's EXIOBASE, WIOD and Eora classification, and is therefore suited for a virtual laboratory setting in which these three databases are to be generated.

3.2. Flexible, user-specific regional and sectoral MRIO structures

Using the Global MRIO Lab, a range of existing MRIO frameworks can be updated. Given that the EXIOBASE and WIOD tables are being dealt with in individual articles of this Special Issue (Abd Rahman et al., 2017; Reyes et al., 2017), we demonstrate here how MRIO databases in the structure of the OECD, IDE-JETRO, Global Trade Analysis Project (GTAP) and Eora MRIO tables can be derived as base tables from a common global root classification (Figures 2–5).

In the numerical runs shown in this section we used the Eora initial estimate procedure and the KRAS optimisation engine, and reconciled a pre-defined regional and sectoral MRIO structure with a range of data such as national IO tables, European IO tables (Eurostat, 2016), System of National Accounts MA (UNSD, 2016b) and Official Country (UNSD, 2016c) databases, United Nations' Comtrade (UNSD, 2016d) and services trade (UNSD, 2016e) data, industrial output statistics (UNIDO, 2016) and industrial commodity production data (UNSD, 2016a). This means that OECD, IDE-JETRO, GTAP and Eora classifications were defined through four root-to-base aggregator matrices, initial estimates were assembled for MRIO systems and then optimised at their respective regional and sectoral base classifications (see Section 2.1). Figures 2–5 show the results of this process: four basic-price MRIO sheets including intermediate demand (top left), final demand (top right) and value added (bottom left).[9]

The 2015 lab version of the 2011 OECD inter-country input–output (ICIO) tables (Figure 2; 61 regions[10] with 34 sectors[11] each) clearly discerns major OECD economies such as France and Germany (around row 370), Japan (610), the USA (1150), China (1320) and India (1560). The final region holds the rest of the world. As with the template 2005 Asian International IO table, the 2015 lab version (Figure 3) adheres to the original regional sequence (Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Taiwan, Japan, USA, India, Hong Kong, the EU and the rest of the world) and 76 sectors (IDE-JETRO, 2015). In both OECD and IDE-JETRO lab versions, the rest-of-the-world region is quite sizeable, including countries such as Ukraine, Bangladesh, Pakistan, Egypt, Nigeria, Serbia, Kazakhstan, Iran, Venezuela and Vietnam. The 2015 GTAP lab version (Figure 4; with 140 regions[12] with 57 sectors[13] each the largest MRIO system shown here) and the 2015 Eora-26 lab version (Figure 5; 189 countries with 26 sectors each[14]) look similar in

[9] Time series of these MRIO databases will be available for download at http://www.isa.org.usyd.edu.au/mrio/mrio.shtml/globalMRIOlab.
[10] http://www.oecd.org/sti/ind/ICIO2015_Countries_Regions.pdf.
[11] http://www.oecd.org/sti/ind/ICIO2015_Industries_Items.pdf.
[12] https://www.gtap.agecon.purdue.edu/databases/regions.asp?Version = 9.211.
[13] https://www.gtap.agecon.purdue.edu/databases/v9/v9_sectors.asp.
[14] http://www.worldmrio.com/simplified/.

Figure 2. Basic-price MRIO sheet in the regional and sectoral classification of the 2011 OECD-ICIO tables (OECD, 2015), for the year 2015. Colours are scaled as $\mathrm{sgn}(x)\,\log_{10}(|x|)$, with x expressed in current US$, so that levels 6 and −6 correspond to transactions of 1 million and −1 million US$, respectively.

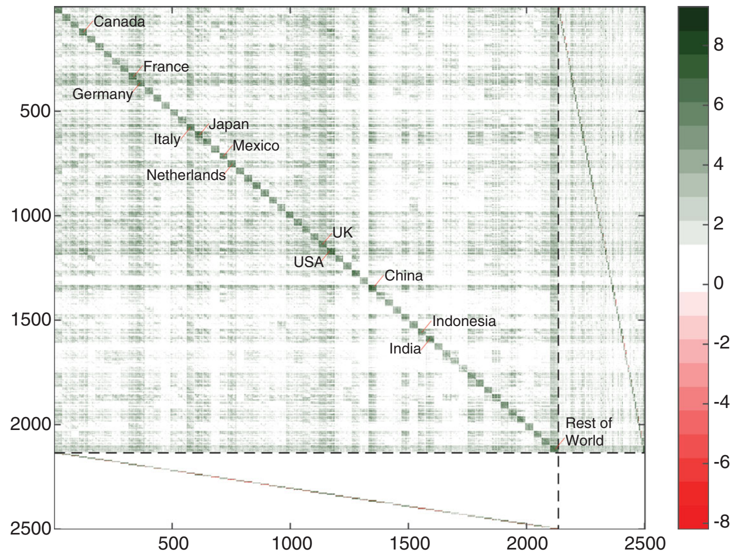
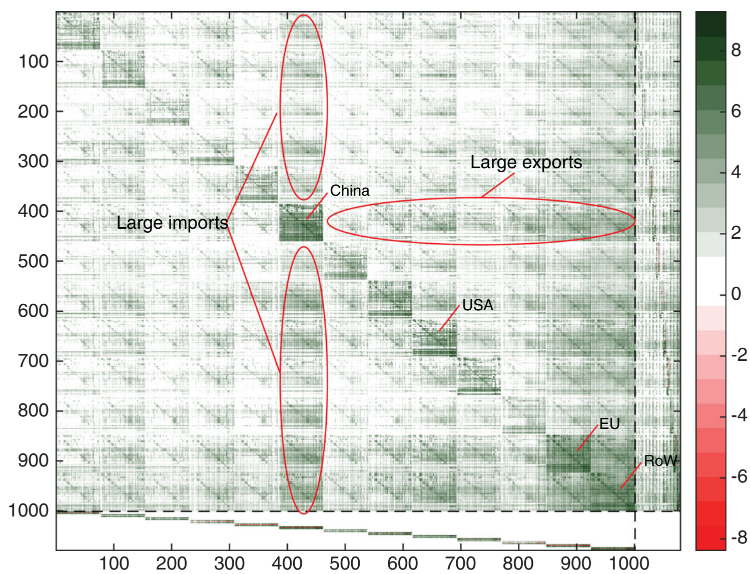


Figure 3. Basic-price MRIO sheet in the regional and sectoral classification of the 2005 Asian international IO table (IDE-JETRO, 2015), for the year 2015. Colour scaling as in FIGURE 2.



their distinction of many individual world countries. Due to GTAP's country sequence, the 3 × 3-sized North American Free Trade Agreement (NAFTA) block is clearly visible. Eora's simplified sector classification means that the final demand block is relatively large.

Owing to the flexibility and automation of the Global MRIO Lab, it would be relatively straightforward to generate (a) tables using hybrid compilation sequences, combining data

Figure 4. Basic-price MRIO sheet in the regional and sectoral classification of the 2011 GTAP9 database (GTAP, 2016), for the year 2015. Colour scaling as in FIGURE 2.

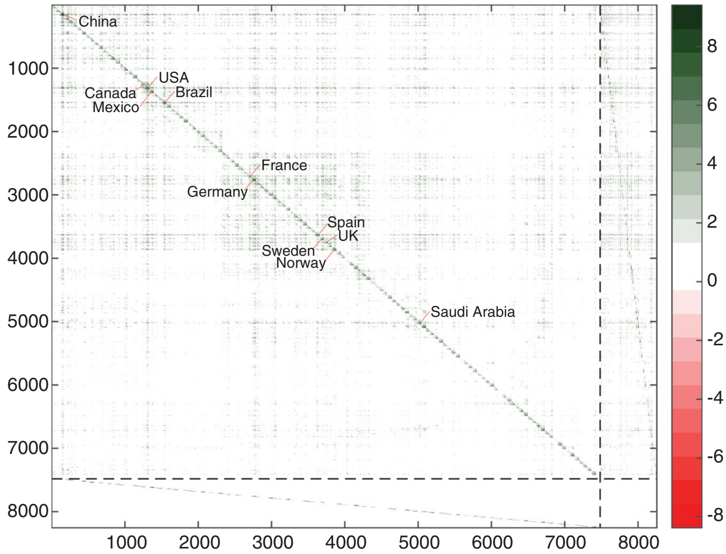
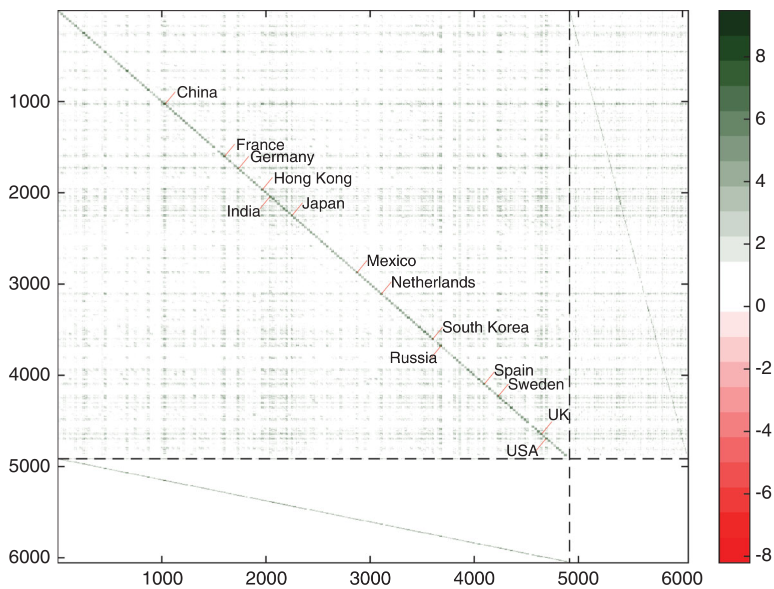


Figure 5. Basic-price MRIO sheet in the regional and sectoral classification of the Eora-25 database, for the year 2015. Colour scaling as in FIGURE 2.



sources, initial estimate method and reconciliation engines of different origins, (b) tables in hybrid classification, featuring the regional classification of, say, Eora, and the sectoral classification of the OECD database, and (c) continuous annual time series thereof.

4. Discussion: reflections from the Project Réunion journey

The purpose of this discussion section is to provide members with a space for expressing their thoughts about rationales, process, outcomes and lessons learned from Project Réunion.

4.1. The beginnings: changing rationales for Project Réunion (Erik Dietzenbacher)

In 2010, several groups of researchers were working at the same time on seemingly very similar, major projects, which was new to the IO community. Everybody was convinced that such projects had an enormous potential. At the IO conference in Sydney, Manfred Lenzen initiated these database developers to meet briefly. It was decided to arrange a more thorough discussion in the near future. The direction of the-then-future discussion, however, was yet to be determined. Should we co-operate and merge all our efforts into one large database (the 'happy family' scenario)? Should we compete and improve upon each other (the 'may the best win' scenario)? Should we divide the tasks and designate a particular area for each group (the 'specialisation' scenario)? One group develops a database with a focus on environment and resources, another group focuses on socio-economic phenomena, a third group on constructing time series and a fourth on maximising the number of countries. Or should we adopt the 'live and let live' scenario, where we would just wait and see how things would develop?

At that stage, we were aware of the existence of other databases or of the work on constructing a database, but little information was publicly available. In hindsight one could say that global multi-region IO (GMRIO) tables were a sign of the times, given the large number of initiatives that were undertaken. Globalisation had made an enormous progress (with a major role for China and other emerging economies) and linking national IO tables with the use of trade data seemed feasible. But when starting their own project, each of the groups felt it was working on something unique, something that might change the world a little.

When we met the first time, in 2011 on Réunion Island, no one knew exactly what to expect. How much precious information should we (representing one of the groups) reveal about our own project? Should we protect our little babies? And if we revealed all, what would we get in return? At the start, we were a bit suspicious but that feeling did not last very long. Pretty soon we reached a couple of important decisions. Given that we knew so little about each other's projects, exchange of information was the first thing. We learned that different groups had applied different philosophies for their estimation. For example, because IO tables do not match international trade data, a choice had to be made: take the IO tables as given and adapt the trade data or, vice versa, take the trade data as given and adapt the IO tables, or an 'intermediate' option. It also became clear that this venture was big enough for all of us. Discussing what a GMRIO database in its ideal form would look like (which we termed 'the mother of all GMRIO tables'), it appeared that we would never be able to reach that stage. So, it would – also in the future – be the case that a different question or perspective would call for the use of a different database. A consequence of this, so we realised, was that it was of crucial importance that users get informed with a maximum of transparency. This means that the public should not only learn about the strong points of each database but also about the weaker points. Only then can users select the database that is most appropriate for their research question or problem at hand. The guest-edited special issue of *Economic Systems Research* (Tukker and Dietzenbacher, 2013) was the ultimate outcome of the first meeting on Réunion Island.

4.2. The compromises: diverging purposes, approaches and outcomes (Arnold Tukker)

Many of the thoughts provided by Erik Dietzenbacher (Section 4.1) obviously also crossed my mind. As described in Tukker and Dietzenbacher (2013), around 2010 only the GTAP database and GMRIOs based on the OECD database were available. These databases had clear limitations. They could deviate significantly from available national statistics, making assessments of trade in value added (TiVA) complicated. From an environmental perspective, particularly the high level of aggregation in resource extraction and electricity generation sectors was a disadvantage. In that period, different research groups won grants to improve this situation, starting to create the WIOD, EXIOBASE and EORA databases. Each team had its own philosophy. EXIOBASE was built for environmental purposes and, given that environmental pressures can differ highly amongst in environmentally relevant subsectors of agriculture, resource extraction and electricity generation, had to estimate transaction at a level of detail often beyond what national statistical offices would supply. WIOD focused on TiVA, aiming to keep transactions as close as possible to those reported in national tables, and hence chose for an aggregated sector detail that was the best common denominator across national tables. Since in most modern economies the added value of agriculture and mining is a limited part of a country GDP, the high level of detail EXIOBASE sought was not relevant there. And, as indicated, EORA was based on the principle of using original tables only and a one-step reconciliation procedure, leading to a differentiated sector classification by country. All these approaches have their merit. Earlier I wrote:

> Brutally forcing one standard could create an unproductive scientific monoculture in a field that is characterized by complexity. In such trans-scientific cases, wisdom in policy support is probably better guaranteed by providing insights from different perspectives. Or, as pitched by Schwarz and Thompson (1990): 'Divided we stand' Having a few different (EE) GMRIO databases around, where each meets basic quality standards, is probably a good thing.

While I still stand behind this statement, it is clear that times have moved on. At Réunion in 2011 and even at Kurokawa Onsen in 2013, hardly any comparative research had been done between databases. What differences in footprints and value added do we see? What causes these differences? The pioneering PhD thesis of Owen (2017) and various other recent papers in the context of the EU DESIRE, Carbon CAP and other projects by now have shed light on this (Arto et al., 2014; Moran and Wood, 2014; Owen et al., 2014; Stadler et al., 2014; Owen et al., 2016). We see that often the use of non-harmonised extensions across GMRIOs causes the largest differences in country-specific footprints. Country's GDP shares in global GDP also diverge across databases. Perhaps surprisingly, it is not the estimated structure of trade, but differences in the structure of domestic SUT/IOT in a specific GMRIO database that creates most differences in calculated footprints, TiVA, and so on. A Global MRIO Lab is an excellent way to ensure that such basic, and often unnecessary differences are ironed out. It allows selecting an identical set of extensions in combination with different GMRIOs. It allows ensuring that all country tables in the different GMRIOs are scaled to the same common GDP database. It allows creating a trade-linked table using constraints that minimise adjustments of country SUT/IOT.

Having said this, the experience of Reyes et al. (2017) with adjusting EXIOBASE for the Global MRIO Lab shows that capturing the complex construction procedures in a virtual lab is not always easy – or even possible. EXIOBASE has a complex, though automated way of taking original SUT of countries and detailing them with all kind of auxiliary data. Reyes et al. (2017) found it too difficult to mimic this step in the virtual lab setting. They took the detailed country SUT already produced by the EXIOBASE team, and used the Global MRIO Lab merely to experiment with different trade linking procedures, trying to find one that minimised adjustments of the detailed country SUT. Moreover, the root classification can be at such a detail that even though the lab can produce results at this level of detail, these may not be supported by any meaningful empirical data. For less-experienced researchers there can be a temptation to use data at a level of detail that should not be made available in the first place. Second, the high level of automation may imply that procedures and hence outcomes become 'black-boxed', taking outcomes for granted, without any sensibility checks by experienced practitioners of the intermediate and finally produced tables.

4.3. Let us learn from the past: the Asian International IO project (Satoshi Inomata)

In 2015, the Asian International IO project by the IDE-JETRO officially closed its history of more than 40 years, with the 2005 table as the last product of the series.

The basic philosophy behind the compilation of the AIOT was to pursue the highest level of statistical consistency and comparability across the constituent national IO tables. This strategy was feasible because the AIOT embraces a relatively limited number of countries (nine Asian economies and the USA), which enabled the compilers to conduct individual and in-depth manual adjustments. Accordingly, the scope and the degree of data harmonisation went far beyond unifying product categories and valuation schemes, to the extent of integrating the 'presentation format' of national IO tables. This included consideration on special statistical treatment such as dummy sectors, scraps and by-products, FISIM, and government industries.

Well, this is a story of a happy old time. With the emergence of 'big guys' like WIOD, EXIOBASE, OECD-ICIO, Eora, and so on, and against the backdrop of rapid transformation of the world economy, the AIOT project was suddenly dragged from a peaceful solitary life into the world of tough competition among gigantic MRIO tables. When the AIOT project was initiated in the 1960s, it was just sufficient to cover several major economies in East Asia in order to capture the dynamics of regional integration. But now, the cross-border production networks evolve at the global scale. Today's MRIO table users demand large country coverage, fine product resolution, and more variety in satellite accounts, rather than meticulous data adjustment and harmonisation for a common presentation format. Who cares about the difference in FISIM treatment when it incurs only a negligible impact in terms of multipliers? All of sudden, the AIOT compilation strategy, focusing on limited countries yet with a high degree of statistical comparability, became a 'luxury concern' for MRIO table compilation.[15]

[15] Note, however, that the adjustment of presentation format still matters from the viewpoint of national statistics, say, for GDP estimation. It would be less relevant only when it comes to analytical uses such as for the calculation of carbon footprints or trade in value-added. See Inomata (2016) for a detailed description of the adjustment method for the AIOTs.

When and why did things go wrong? The answer is quite straightforward. The AIOT project did not try to look around the world for what was going on outside, resting on the long-reserved seat of a statistical monopoly. The compilation methodology was just being passed on from one generation of compilers to another without any critical assessment of the routines. The project failed to keep up with the changes in users' needs, in estimation techniques (non-survey methods and optimisation algorithms) and in statistical availability (data from emerging economies and socio-economic accounts), until it found itself completely outdated for the ongoing global practices.

What can we learn from the history of the AIOT project? Surely, the Global MRIO Lab seems to run ahead in the light of meeting new user demands, but the world keeps changing at increasing speed. Currently, the Lab's setup ('global root') relies on the pool of national/regional statistics, equipped with a powerful algorithm to make the maximum use of available information. This said, however, can we not envisage a futuristic picture where MRIO tables are to be constructed, for example, entirely from Big Data?[16] It may sound like a science fiction right now, yet, in retrospect, nobody was able to imagine at the outset of the first AIOT project that something like Global MRIO Lab would come into reality.

So, here is a message: an MRIO scheme should continue to evolve as a 'work-in-progress', standing open and attentive to the changing environment, that is, the data, technologies and the people using it.

4.4. *The importance of digging into the causes of uncertainties in MRIO construction (Bart Los)*

The authors of the previous subsections have provided overviews of the causes and consequences of the project that was initiated by Manfred Lenzen at the 2010 international IO conference and later became known as the Project Réunion. In my view, the single most important outcome of the project is the knowledge that the participants obtained about the philosophies behind each other's MRIO data construction efforts and the implications of these for the actual compilation procedures. Fortunately, this knowledge has not only been shared among the participants, but has also been disseminated to the user community at large. The Special Issue of *Economic Systems Research* (edited by Tukker and Dietzenbacher, 2013) played an essential role in this respect.

Reading about MRIO data construction procedures is easier than replicating these. Arnold Tukker's contribution to this section reflects the problems encountered in trying to replicate the data production stages as developed by the EXIOBASE consortium in a virtual laboratory environment. Hurdles were also encountered in the 'sister project' aimed at replicating the production of WIOD's world IO tables in a more timely and less labour-intensive way. Overcoming such problems and transparently reporting about the second-best solutions adopted only adds more to the understanding of the differences between the various databases that are currently in use.

So, what should be the next steps? I fully agree with Satoshi Inomata's plea for a critical look at what has already been achieved, hopefully leading to clear ideas about what should be achieved in the near future. The fruits of research by the participants in the Project

[16] See also Dietzenbacher et al. (2013a).

Réunion (plus close associates) and developments in the 'outside world' should both play a role in shaping this agenda.

In a previous Special Issue of *Economic Systems Research* (Inomata and Owen, 2014), empirical differences between the various global MRIO databases and analytical outcomes based on these were analysed. It is of course important to have insights into the magnitude of such differences, but we should also devote attention to the causes of these. A similar argument can be made for the quantitative information on data reliability and outcome uncertainty as generated in the virtual lab while compiling MRIOs. Of course, empirical differences and high uncertainties can be caused by, for instance, imperfections in the raw data, in differences in industry/product classifications at which this data are available and in the ways in which MRIO compilers linked data from National Accounts, national SUTs or IOTs and bilateral trade data to each other. There is an additional source of empirical differences and outcome uncertainty; however, which sometimes tends to be overlooked: harmonisation efforts regarding the raw data. In his contribution to this section, Satoshi Inomata argues that focusing on statistical rigour has proven 'fatal' to IDE-JETRO's Asian IO tables project. That statement might well be correct in its specific context, but I think it would be wrong to generalise it to a statement like 'the IO community should not care about statistical rigor and focus exclusively on timeliness, extensive country coverage and industry/product detail'. While these aspects are clearly very important, we should refrain from taking the empirical differences and outcome uncertainties as exogenously given, and try to find out to what extent these can be reduced. Assessing the empirical implications of correcting for differences between the ways in which, for instance, the Bureau of Economic Analysis in the US, the National Bureau of Statistics in China and Eurostat for the EU operationalise 'simple' concepts like aggregate exports would be an important first step.

The developments in the 'outside world' to which I referred above partly relate to changes in statistical practices. The adoption of the System of National Accounts 2008 poses a series of new and very challenging questions to compilers of global MRIOs. Such MRIOs will lose substantially in importance (not only regarding socio-economic applications, but also in the environmental sphere) if compilers continue using the data construction procedures that were adopted for the first releases of the various global MRIOs, largely based on data organised according to the System of National Accounts 1993. A different type of change in the outside world relates to changes in demand by users. I believe it is fair to say that global MRIOs have so far mostly been used to quantify tendencies caused by the increasing international fragmentation of production processes. In the near future, these low-hanging fruit borne by global MRIOs will have been reaped. A shift towards other types of applications, aimed at causal analysis and modelling for policy purposes (related to taxes, trade barriers, etc.) might be seen in the not-too-distant future.[17] Some of these changes in demand might imply that for example price concepts adopted must be reconsidered, or that product-by-product MRIOs become more in vogue than the currently dominant industry-by-industry MRIOs.

Challenges like those described above will keep MRIO compilers busy. I do not think it will be desirable to move entirely from labour-intensive global MRIO construction to construction procedures that are almost fully automated. In my opinion, we should try to adopt

[17] See Los (2017) for examples of potential items on the agenda in the realm of international trade.

a dual approach, to which the Project Réunion has already contributed considerably: while some researchers specialise in the painstaking work of accommodating external changes in supply of raw data and in demand for MRIOs by means of methodological improvements, other researchers specialise in equally painstaking efforts to allow for modifications of established production pipelines in virtual labs in such a way that novel methodologies that will have proven to be worthwhile can efficiently be incorporated. In this way, the probability that the huge popularity of global MRIOs (and IO analysis in general) can be sustained is maximised.

4.5. Managing expectations in the context of long-term statistical capacity building (Norihiko Yamano)

Since the beginning of the Réunion project, the recognition of MRIO-based analyses has increased significantly among researchers and policy-makers. This is due partly to an increasing awareness of the global interconnectedness of production networks across developed and emerging economies, and related demand for metrics to provide insights into GVCs. In particular, from 2009, measurement of TiVA was strongly advocated by organisations such as the OECD and WTO at various high-level international meetings (e.g. G20) providing the impetus for the development, at the OECD, of an ICIO system. Subsequent extensions have used the capability of ICIO framework to address various policy issues concerning, for example, bilateral trade, labour markets, industrial productivity and global CO_2 emissions.

The Réunion project members recognise that various extended analyses are frequently requested by stakeholders and policy-makers. In particular there is much interest in, and demand for, wider country coverage, higher resolution of sectoral coverage and more timely databases (and related indicators), while expecting the estimates to be based on better quality data sources, that is, recognised official statistics. In order to respond to these expectations (often from high levels), practitioners and research teams have been compelled to undertake extended analysis using their own models and data sets, at least in the short term. A major challenge has thus been to manage expectations: the spreading enthusiasm for ICIO/MRIO applications coming from 'non-practitioners' is often accompanied by a limited understanding of how difficult and time-consuming it can be to construct ICIO/MRIOs – notably, the sheer volume of data involved, the numerous inconsistencies across data sets (often within countries), the adjustments required to achieve balanced tables and, of course, the resources available. The differences between the various MRIOs currently on offer and their relative strengths and weaknesses has to be explained and, as the latest results are beginning to be closely scrutinised by government agencies (particularly statistical offices), concerns are often raised about why certain results differ from their official statistics (e.g. nationally reported bilateral trade relationships). Uses and limitations of MRIOs and derived indicators could also be better communicated. Thus, to meet the needs of national policy-makers and sustain their interest, a truly global MRIO would have to address these issues; while being flexible enough to enable the rich variety of research possible with the MRIOs currently on offer. This is a long-term goal.

In the meantime, the Réunion project members should continue to discuss the technical and practical impediments that are evident in construction of MRIOs, share experiences and strive for common solutions. For example, the most detailed data sources from countries are usually published in their native languages and the terminology used in the descriptions, particularly for the format of IO/SUT data sources are widely different. It is highly recommended that formats, terminology and codes (e.g. for variables, industries and products) should conform to some international standards (e.g. the variable names and codes used by the United Nations and OECD SNA statistics). In a sense, this is happening already as OECD has started making formal requests to statistical offices to provide SUTs and IOTs using common ISIC Rev.4-based templates (cf. Eurostat SUT collection practices). The Réunion project should support such developments. Another challenge that could benefit from sharing experiences is the treatment of statistics compiled according to SNA08 and BMP6.

Ultimately, the quality of MRIOs depends on the quality, coverage and consistency of national statistics. Since the beginning of the Réunion project, an increasing number of countries have started to provide more detailed and comprehensive industrial databases required for the compilation of global MRIOs. Notably, SUTs and IO tables are becoming available on an annual basis and many countries have improved the coverage and quality of bilateral services trade in a Balance of Payments framework. However, the level of publishable detail and timeliness of data sources depends on each country's confidentiality policy and statistical resources to perform the underlying surveys on industries and households.

Ideally, in the longer term, data availability issues will become less problematic as a conspicuous number of key data sources become accessible from international organisations. In fact, one of the spillovers of heightened interest in TiVA- and GVC-related analyses has been to galvanise national agencies into improving their statistical infrastructure to better take account of economic globalisation – with the support and guidance of international and regional organisations (such as OECD, EU, ADB, APEC and various UN agencies). All MRIO compilers should benefit from this.

While statistical capacity building takes place across the globe (but with some nations clearly advancing more than others) and as dissemination of data sources improves, the global IO community of analysts and researchers can, in the meantime, continue to enhance computational methodologies and expand areas of application. For example, a number of researchers (and statistical offices) have recently succeeded in integrating firm heterogeneity information within a national economy (exporters, ownership, firm size and sub-national regions) to a country-based ICIO database. Dealing with heterogeneity within firms is an important extension when value added to output ratios, and import penetration, vary within the same industry group. Particularly, when estimating foreign content of exports for certain industries. Another direction of improvement efforts could be the transformation from standard currency unit (US dollar)-based data to alternative price valuations. For example, more studies are required to develop analyses based on the constant price in national currency units, international PPP comparison and physical units to further enrich the analytical opportunities. The Réunion project should continue to be a forum for sharing knowledge and ideas in these areas.

4.6. Will an open-source business model be sustainable? (Terrie Walmsley)

The Center for Global Trade Analysis, the home of the GTAP, came to Réunion in 2011 with a great deal of apprehension, being the only global database that had a 20-year history and sustainable model for obtaining funding and ensuring regular updates.[18] Many of the other participants in the Réunion meeting also recognised this concern – wary of creating a situation where no global databases were being constructed on a sustainable basis. While the Center recognised the benefits of any activities that might raise the quality and availability of data and was encouraging of these activities, the concern about ensuring the continued development of the GTAP database meant that they did not participate in the second stage of the project.

The success of the project since 2011 has been impressive. The Global MRIO Lab has reduced the barriers to economists of building fully reconciled global MRIO databases, allowing users to test the implications of alternative assumptions that ultimately improve the production of global databases. That said, the Global MRIO Lab needs to become sustainable, particularly if it is to 'stand open and attentive to the changing environment' as Satoshi Inomata says in Section 3.4. Sustainability will require regular updates of the underlying data and documentation, as well as regular interactions with interested parties and modifications to the programmes in order to incorporate new ideas and remain relevant.

While the open source business model has been particularly successful in the software industry and there are clear advantages to this type of approach in the production of a global MRIO database, the open sourcing business model is still largely untested in this area. Economists are less likely to obtain positive externalities from participating in open source activities, since incremental data work rarely lead to publications and these activities are less likely to be noticed by potential employers. Moreover, while many open source software developers share a common programming language, this is less likely to be the case with potential users of the Global MRIO Lab, where data and economics unite users. While updated data sets are likely to continue, major improvements to these databases will need the continued support of a dedicated core team, as well as additional funding. I would hope that continued support for data development is forthcoming, since without these data sets the analysis of global issues is limited. In the meantime, I look forward to using the Global MRIO Lab.

5. Conclusions and outlook

In contrast to previous MRIO compilation exercises, the databases described in Section 2.2 were not assembled by an individual team or a group of teams in close contact, but by individual researchers who were using datafeeds, concordance matrices and optimiser routines made by others. This was possible only through the implementation of standardised construction pipelines in a collaborative virtual laboratory environment. In the Global MRIO Lab, an individual researcher is able to integrate their own data and construct a large-scale MRIO database, because feeding data and defining user-specific MRIO structures are completely standardised, documented and controlled via graphical user interfaces. Individual researchers can also circumvent the enormous labour overhead that characterised previous MRIO undertakings, because many datafeeds and construction procedures will have already been contributed by a large number of other collaborators in the lab. This Special Issue features the China (Wang, 2017) and Indonesia MRIO Labs (Faturay et al., 2017) that

[18] At the time of the Réunion meeting, I was Director of the Center for Global Trade Analysis, now I am the Director and Senior Economist of ImpactECON, where I continue to work on issues related to global economic modeling and MRIOs.

were set up based on the Australian template. Current discussions and plans also include additional sister labs to the Australian IELab, featuring sub-national MRIO capability for the UK (Hewings, 1971), Brazil (Dietzenbacher et al., 2012), Germany (Többen, 2014), Japan (Meng et al., 2012) and India (Sinha, 2009).

Thus, the Global MRIO Lab approach breaks with (MR)IO tradition in that all information flow, for example data uploads and updates, processing, and quality assurance, occurs in a rather unsupervised way, similar to the information handling in the online Wikipedia (Lenzen et al., 2014). Whilst the lab offers a number of diagnostics features such as standard deviation information and violation reports (see e.g. www.worldmrio.com), most data and information quality issues are handled in an informal way. Data feeders and analytical users communicate via blogs, tags and comments within code and databases, alerting lab participants of potential quality issues such as typos in raw data items, errors in processing codes, questionable assumptions in concordances and the like. Only crashes in the build pipeline are handled by a central administrator.

Whilst the Global MRIO Lab has reached a critical juncture in the provision of accessible data, reconciliation and analysis routines, there is clearly a need to grow this initiative to a much broader and larger user base. Whilst not all procedures in the Global MRIO Lab are always deemed 100% fit for *all* purposes (as discussed in some of the comments above) it does provide the first and strongest backbone for the evolution of the virtual lab concept for IO users around the world.

Research funding is becoming increasingly geared towards the provision of 'research infrastructure', as policy-makers are becoming increasingly aware that there is a need to not only demand access to research results, but also to the 'ability' of top research. The EU Horizon2020 programme[19] now identifies a need to create 'wider, simplified and more efficient access' to the best research tools available, such that there should be 'common development', 'economies of scale' and 'optimisation of operations'. Due to the disparate ways the initiatives on GMRIOs have grown, there has so far been no mechanism across the community for realising these objectives and for being able to move into the shared research space necessary to capture the heterogeneity of our economic system. The goal of the Global MRIO Lab has thus been to help develop a common e-infrastructure, a standardisation, and thus the possibility to share, combine and integrate data for many different applications. Ultimately, the goal has been to 'facilitate cross-disciplinary fertilisations and a wider sharing of information, knowledge and technologies across fields and between academia and industry'.[26]

So what may the future look like? A lab that simply allows a user to, for example, produce a water account adapted to a particular MRIO database without spending six months researching FAOSTAT databases, classifications, allocation methods and reconciliation routines? Or more like a network of IO labs around the world that shares a common ontology, that facilitates the access to KRAS or other reconciliation routines, that allows adaptation of root classifications (and other lab structures) over time, and that allows changes to the Systems of National Accounts to be understandable by code, and implemented as either a data feed or adaptation of the reconciliation process?

The hope is that the Global MRIO Lab will catalyse new opportunities for research and innovation using MRIO frameworks. Breaking with tradition opens the way for new paths

[19] http://cordis.europa.eu/programme/rcn/664615_en.html.

to be tread and researchers are starting to explore and exploit the possibilities of new, collaborative applications. The litmus test for virtual MRIO laboratories will be the uptake of their outputs by non-IO stakeholders from governments, statistical offices and the private sector. Certainly, the demand for information from global MRIO databases is strong and rising, fostering the further development of virtual MRIO labs.

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