BUILDING EORA: A GLOBAL MULTI-REGION INPUT-OUTPUT DATABASE AT HIGH COUNTRY AND SECTOR RESOLUTION

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ABSTRACT

There are a number of initiatives aimed at compiling large-scale global Multi-Region Input-Output (MRIO) tables complemented with non-monetary information such as on resource flows and environmental burdens. Traditionally, MRIO construction and usage has been hampered by a lack of geographical and sectoral detail; currently the most advanced initiatives opt for a breakdown into around 50 regions and 120 sectors common to all countries. Further shortcomings are the absence of a continuous time series, margins and tax sheets, and information on reliability and uncertainty. Despite these limitations, constructing a large MRIO requires significant manual labour and many years of time. This paper describes the results from a project aimed at creating an MRIO account that: represents all countries at a detailed sectoral level, allows continuous updating provides information on data reliability, contains table sheets expressed in basic prices as well as all margins and taxes, and contains a historical time series. We achieve these goals through a high level of procedural standardisation, automation, and data organisation.

Keywords: Multi-region input-output, constrained optimization, data conflict, automation, visualisation

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1. INTRODUCTION

During the past decade, our understanding of climate change has improved, but with it, the future outlook has worsened, in part due to newly discovered positive feedbacks (Luthje *et al.* 2006; Walter *et al.* 2006) and lower estimates for the absorptive capacity of the biosphere (Schuster and Watson 2007; Heimann and Reichstein 2008). At the same time, global emissions have during recent years approximated the more pessimistic emissions scenarios of the IPCC (Nakićenović and Swart 2000; Van Vuuren and Riahi 2008). In summary, the problem of climate change is now perceived as more severe, more urgent, and as a result more political. The latter is reflected in increasing debates about the national responsibilities for the damages expected from climate change (Munksgaard and Pedersen 2001; Peters 2008; Peters and Hertwich 2008; Peters et al. 2011). In particular, exporters of emissions-intensive commodities now argue more strongly than ever for a consumer-responsibility principle (BBC News 2009).

In response to these recent trends, various accounting, labelling, reporting, life-cycle, and policy frameworks for consumer responsibility have been created or revived (see Section 3 in Rueda-Cantuche *et al.* 2009), and some of these deal with international trade, such as the European EIPOT project. In order to underpin these initiatives, a comprehensive and reliable multi-region input-output (MRIO) database on emissions and international trade is necessary (Tukker *et al.* 2009; Wiedmann *et al.* 2009).[1] MRIO-based studies have recently been successful in bringing the issue of carbon embodied in international trade to wider audiences (Davis *et al.* 2011; Peters *et al.* 2011), and in triggering debate amongst decision-makers (BBC 2008; Lenzen *et al.* 2010b; Wiedmann *et al.* 2010). Wiedmann *et al.* 2011 provide an overview of the policy relevance of MRIO databases and studies.

Such databases should ideally cover the entire world at high sector detail, so that emissions-intensive industries or commodities can be singled out. However, previous multi-region studies have used either sector-disaggregated models for a limited number of countries, or sector-aggregated models for the world (Wiedmann *et al.* 2007; Moran *et al.* 2009; Wiedmann 2009b). At present there are a number of initiatives aimed at compiling large-scale global MRIOs (EXIOPOL 2008; Global Trade Analysis Project 2008, WIOD 2010). The MRIO databases generated by these initiatives have different purposes, and this is reflected especially in their choice of sector and country detail. Most initiatives do not provide for maximum sector disaggregation, but instead most initiatives opt for a breakdown into around 50 regions and 120 sectors common to all countries.[2] Further differences relate to whether a continuous time series is generated or not, and how many valuation sheets exist. Most databases do not provide quantitative information on reliability and uncertainty (see Andrew *et al.* 2009, Appendix B).

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[1] In the following, we will refer to a multi-region input-output database extended with physical information simply as an MRIO.

[2] GTAP 7: 57 sectors and 113 regions; EXIOPOL: EU27 and 16 non-EU countries, and about 130 sectors; WIOD: 27 EU countries and 13 other major countries in the world, more than 30 industries and at least 60 products.

2. MOTIVATION

The aim of this work is to address a number of shortcomings, and to go beyond existing ambitions for MRIO compilation. Our goals are:

- **Detail**: Disaggregation of countries and sectors to the maximum possible level of detail, in order to assist environmental life-cycle and footprint-type assessments of international trade in the most accurate way possible;
- **Dynamics**: Creation of a historical time series back to 1970, in order to allow trend and scenario analyses, and projections;
- **Flexibility**: Compilation of table sheets expressed in basic prices as well as margins and taxes, and in current and constant US$, so that calculations for different purposes can be carried out;
- **Transparency**: Minimisation of assumptions made during the compilation (such as ratios of purchasers to basic prices), and close adherence to the raw data;
- **Uncertainty**: Provision of standard deviation estimates for all MRIO elements in order to aid comparative assessments, hypothesis testing, and decision-making;
- **Reliability**: Provision of data for constraint violations in order to inform expert users and statisticians about the discrepancies between the fully balanced MRIO and disparate raw data;
- **Timeliness**: Continuous updating of the entire database, so that user analyses are relevant at the time;
- **Budget**: Implementation of the entire compilation and updating capability using less than 12 person-years initially, and less than 2 person-years per year continually;
- **Openness**: Public, free availability for research purposes, so that there is no barrier for wide dissemination.

At the time of publication, we have achieved:

- **Detail**: We disaggregate the world into 187 countries at a detail of 20-500 sectors (see Section 5.2 and Appendix 1);
- **Dynamics**: We created a historical time series spanning 1990-2009 (see Sections 5.5 and 6.3);
- **Flexibility**: We compile table sheets in basic prices as well as 2 margins, taxes on products, and subsidies on products (see Section 5.3);
- **Uncertainty**: We routinely calculate standard deviation estimates for all MRIO elements (see Section 6.2);
- **Reliability**: We have developed a web interface allowing the user to gauge overall adherence to raw data, and to query individual constraint violations (see Section 6.4);
- **Timeliness**: We are able to continuously update the entire database with a delay of about two years (see Section 5.5);
- **Budget**: The creation of the Eora database and website has required 12 person-years (see Sections 3 and 6.3);

- **Openness**: The database is available to pilot users now, and will be released to the public in mid-2012.

We achieve these goals through a high level of procedural standardisation, automation, and data organisation. This article describes the realisation of our MRIO time series.

3. ORGANISATION AND PEOPLE IN CHARGE

The Eora project was funded by the Australian Research Council (ARC) under its Discovery Project DP0985522, and carried out at the University of Sydney in Australia. The core Eora team comprises Manfred Lenzen, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke. Manfred Lenzen is the project's Chief Investigator, and developer of the bulk of the original source code, as well as diagnostics and analytical routines. Keiichiro Kanemoto's work comprises the entire raw data processing stage, including the automation and streamlining of the constraint formulation task. Daniel Moran's two main contributions were in the redesign of algorithms to better utilize high-performance hardware, and the implementation of the Eora website which features results, data visualizations, and query and analysis tools. Arne Geschke is responsible for parallel optimisation algorithms that were used in reconciling Eora's MRIO tables with raw data.

Throughout the project, a number of researchers made contributions to various technical aspects of Eora. The basic ideas for Eora's assembly and optimisation procedures were conceived by Manfred Lenzen and Blanca Gallego (Gallego and Lenzen 2009) and further developed by Ting Yu at the University of Sydney (Yu *et al.* 2009). Julien Ugon from the University of Ballarat and Ting Yu developed the basis of a Quadratic Programming optimisation algorithm, based on earlier ideas by Yalcın Kaya and Regina Burachik from the University of South Australia.

4. DATA SOURCES

We used four main types of data to construct the Eora MRIO tables:

1. Input-output tables and main aggregates data from national statistical offices (Appendix 2),
2. Input-output compendia from Eurostat 2011, IDE-JETRO 2006 and OECD 2009,
3. the UN National Accounts Main Aggregates Database (UNSD 2011a),
4. the UN National Accounts Official Data (UNSD 2011b),
5. the UN Comtrade international trade database (UN 2011), and
6. the UN Servicetrade international trade database (UN 2009).

The National Accounts Main Aggregates and Official Data compendia form the backbone of Eora's domestic country blocks. The Main Aggregates database comprises 126,152 data points for 216 countries over 38 years, expressed in current US$. There are 1,599,180 National Accounts Official Data items spanning 38 years and 216 countries. An analysis of the National Accounts Official Data shows that the standard deviations of various value-added and final-demand proportions are surprisingly small, and hence the macroeconomic aggregates are relatively stable in their structure across countries and years (Tab. 1). In addition to the macroeconomic aggregates in Tab. 1, this database contains sectoral information in terms of some 2- and 3-digit ISIC classes.

Tab. 1: Descriptive aggregate statistics for the National Accounts Official Data (UNSD 2011b).

	Value added	Final demand	Intermed demand	Househ'd cons'n	Gov't cons'n	NPISH cons	Capital formation	Inventories	Valuables
as a portion of	Gross output			Total final demand					
	51.3%	51.1%	49.1%	56.8%	19.1%	1.3%	21.9%	0.9%	0.1%
Standard deviation	0.7%	0.6%	0.7%	0.5%	0.4%	0.1%	0.4%	0.2%	0.0%
# of observations	1327	453	1338	482	482	482	482	482	482

	Comp of employees	Taxes on products	Taxes on prod'n	Subsidies on products	Subsidies on prod'n	Net gross surplus	Net mixed income	Capital cons'n
as a portion of	Total value added at purchasers' prices (GDP)							
	40.4%	11.0%	1.4%	-0.5%	-0.6%	25.9%	10.0%	12.5%
Standard deviation	0.7%	0.3%	0.1%	0.0%	0.1%	1.3%	0.5%	0.6%
# of observations	62	62	62	62	62	62	62	62

We were able to collect a total of 74 countries' national input-output tables from various statistical agencies (Appendix 2), and these data provide the best support for the input-output relationships of the respective countries. Finally, we utilised a small number of tailor-made data sets, such as a time series of Australian Supply-Use Tables (Wood 2011), an extended input-output table for the United Kingdom (Wiedmann 2010), and survey-based input-output tables for Central Asian countries (Müller 2006; Müller and Djanibekov 2009), and an extraction of Hong Kong's production structure from the SALTER database (Jomini *et al.* 1994).

Countries are represented by their ISO 3166 acronyms (ISO 2006). Their classifications in the MRIO are represented by a classification acronym (for example 'NACE'), or by their ISO 3166 acronym if the national SUTs or IOTs are used.[3] We stored data only expressed in their original currencies and units, and only converted to other currencies and units within the constraints writing, with the aim of making the search for constraint realisation (and violation) adhere as closely as possible to the original data, which are known to local statisticians. All raw data were warehoused using 8 specifiers[4]: Year, valuation, country of origin, entity (industry or commodity) of origin, sector of origin, country of destination, entity of destination, and sector of destination (see following Section).

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[3] http://www.globalcarbonfootprint.com/queries/classifications.jsp.

[4] Instead of four specifiers as in Stelder and Oosterhaven 2009.

5. METHODOLOGY

In this Section we will lay out the basic elements of our MRIO time series. Characteristic, innovative features will be discussed in further detail in Section 6. Further details on our methodology that are not touched upon here are available elsewhere (Lenzen *et al.* 2010a).

5.1 Structure of the MRIO database

Our MRIO features an 8-tiered hierarchy. The first tier describes the accounting year. The second tier describes the valuation of the table. The remaining tiers denote the country, entity, and sector of transaction origin (3-5), and the country, entity, and sector of transaction destination (6-8). Entities are industries, commodities and value added/final demand (Fig. 1).

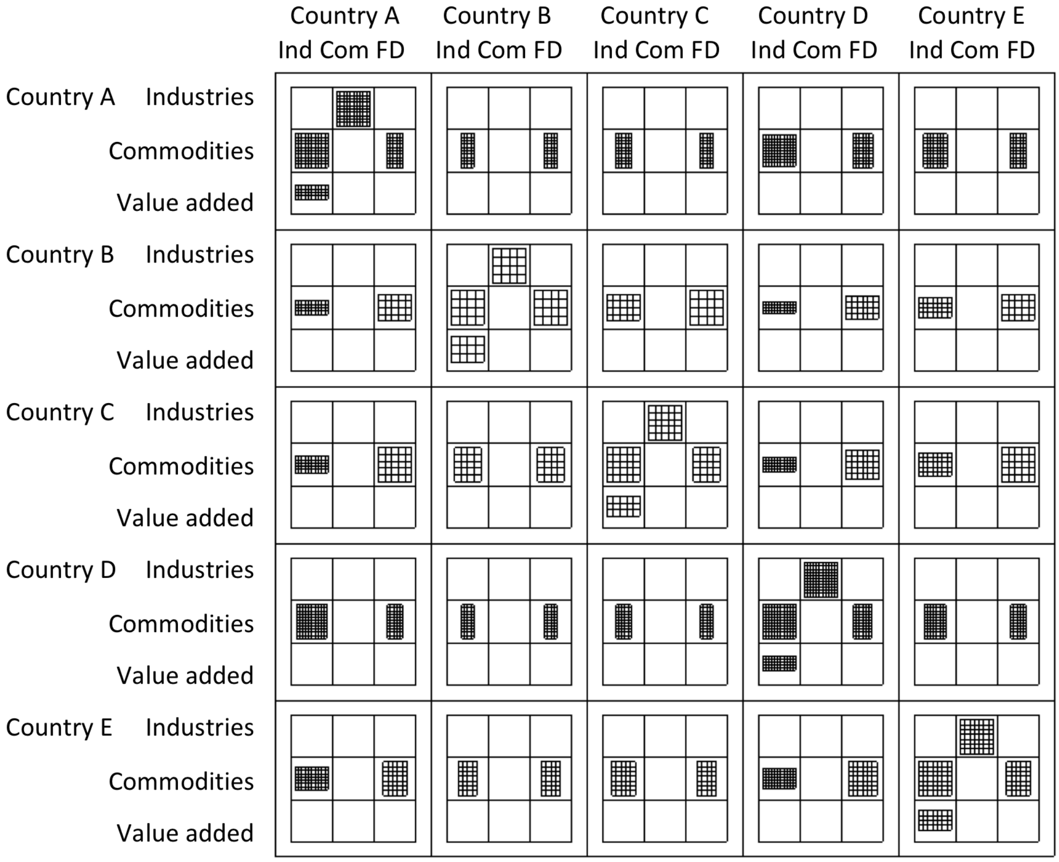

Fig. 1: Supply-use MRIO structure (Ind = industries, com = commodities, FD = final demand). The well-known supply-use blocks $\begin{bmatrix} & \mathbf{V} \\ \mathbf{U} & \end{bmatrix}$ contain national supply and use matrices, **V** and **U**. Off-diagonal trade blocks exist only as use matrices and final demand.

We assume that international trade of value added is zero (see Fig. 1). This can be justified by a comparison of country statistics for the period 1970 to 2007, where the differences between GDP and GNI[5] are around or less than 1% (UNSD 2008c; d). Similarly, but by definition, inter-national supply blocks are empty.

5.2 Sector and country classification

The 187 countries covered in the MRIO database and their currencies are listed in Appendix 1. We consider this coverage of the world complete[6] and hence do not explicitly construct a 'Rest-of-the-World' region. After the table has been compiled (as described below under Compilation process) we create a Rest-of-the-World region to contain any remaining residuals in the event that the compiled table is not 100% balanced. New countries and their precursors were treated as different entities coming in and out of life over time. National classifications were adopted, except where those were less detailed than a common ISIC-type classification spanning 25 sectors (Appendix 3). The latter tended to be the case for most of the countries; this group will be referred as the "common-classed" countries, as opposed to the detailed "separately-classed" countries. Since data for most of these countries was taken from the United Nations' SNA National Accounts Main Aggregates Database (UNSD 2011a) and National Accounts Official Data (UNSD 2011b), the classification for value added and final demand of those common-classed countries is based on SNA93 definitions (Fig. 2).

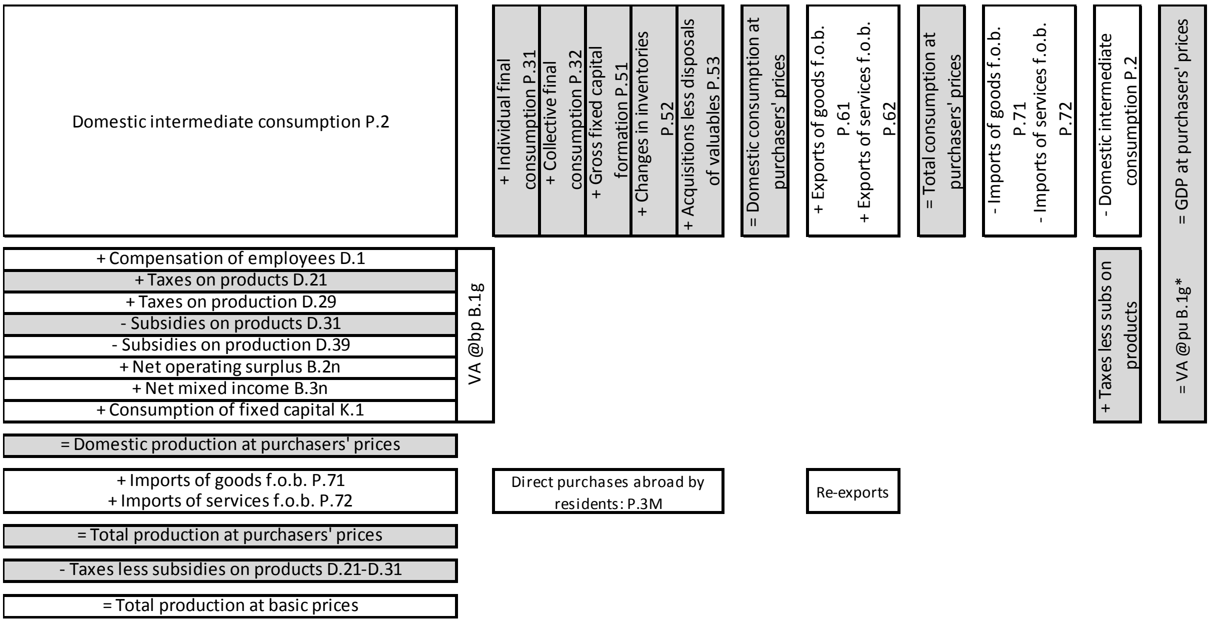

Fig. 2: Basic structure of IOTs for common-classed countries, including SNA93 item descriptors (UNSD 2009).

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[5] Gross national income (GNI) is GDP less primary incomes (net taxes on production and imports, and compensation of employees and property income) payable to the rest of the world (non-resident units) plus the corresponding items receivable from the rest of the world.

[6] The UN SNA Main Aggregates and Official Country databases list 252 geographical entities. Amongst the 65 entities excluded in our MRIO are small nations (Vatican, Monaco, Niue, Tokelau, Nauru), disputed territories (Western Sahara), and small dependencies (Mayotte, American Samoa, Guam, Gibraltar).

For many of the common-classed countries, the choice of a 25-sector classification means that a majority of available raw data will be more aggregated than 25 sectors. This sometimes leads researchers to aggregate the minor, detailed part of the raw data, into the largest classification common to all data sets, with a resulting loss of valuable information. A common view is that disaggregation is not desirable, especially when there is no sound information basis on which to construct disaggregation weights. However, disaggregating aggregated raw data in order to match available detailed data, is a superior strategy for input-output multiplier calculation. This is true even if detailed data points are few, and weights for disaggregating do not exist (Lenzen 2011), hence our decision for a disaggregated classification for all countries.

5.3 Valuation

Attempts at constructing MRIO databases are generally hampered by raw data being expressed in different valuations, for example at basic prices, or including various combinations of margins and taxes. This is true for data on domestic transactions as well as international trade (Van der Linden and Oosterhaven 1995; Lenzen *et al.* 2004; Oosterhaven *et al.* 2008). We construct our MRIO at all levels of valuation, distinguishing margins and taxes from basic prices (Fig. 3). This way, all kinds of raw data can be used as constraints on the table without further conversion, and also the table can be used for different purposes.[7]

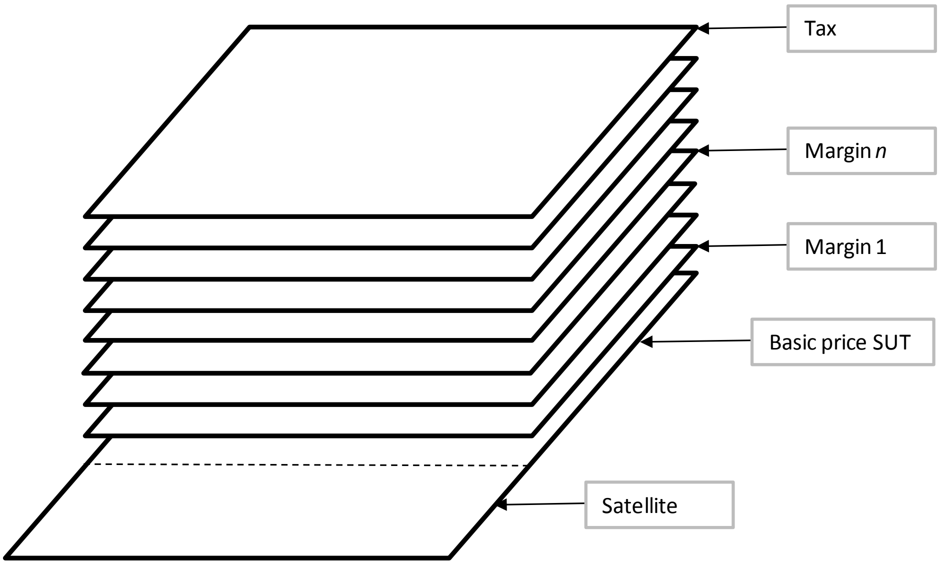

Fig. 3: Stack of MRIO tables expressed in different valuations. The physical satellite accounts exist only as extensions to the basic-price table.

In our work we separate from the basic price sheet three margins (trade, transport, and other), and one sheet containing taxes less subsidies (net taxes) on products. In addition, trade transactions are often valued “free on board” (f.o.b.) and “cost, insurance, freight” (c.i.f.). Oosterhaven *et al.* 2008 (Fig. 2) present an overview of how f.o.b. and c.i.f. differ from basic and purchasers’ prices.

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[7] For example, one may want to undertake a life-cycle or footprint analysis for a multi-national company, using Leontief’s quantity input-output model for a classical demand-pull exercise. It is likely that the expenditure vector of that company exists only in terms of purchasers’ prices. Having all margins matrices at hand, such an expenditure vector can readily be converted into basic prices without requiring further assumptions and data.

5.5 Currencies

Whilst national data as well as UN National Accounts Official Data are expressed in national currencies (see Appendix 3), other data such as the UN National Accounts Main Aggregates are expressed in current US\$. We constructed our base MRIO in current US\$, mainly so that we could apply balancing constraints across the entire MRIO, but also so that countries could be compared against each other. For the conversion of national currencies into current US\$, we used exchange rates based on a mixture of IMF Official Exchange Rates, Price Adjusted Rates of Exchange (PARE), and UN Operational Rates (UNSD 2008b; a).

5.6 Compilation process

The time series is constructed iteratively, by setting up a 2000 initial estimate of the entire MRIO, reconciling this with all 2000 constraints, and taking the solution as the initial estimate for a subsequent year. A unique feature of our approach is that both forecasting and back-casting can proceed simultaneously (Lenzen *et al.* 2012). A balanced table for one year will be an inappropriate initial estimate for the subsequent year if significant economic change has occurred during the prior year. Therefore, we have constructed initial estimates by scaling all prior solutions with inter-year ratios $\text{ß}^{rs}_{\mathbf{T},\mathbf{y},\mathbf{v},\mathbf{V}}$ specific to transactions (use, trade) $\mathbf{T}$, final demand $\mathbf{y}$, value added $\mathbf{v}$, and supply tables $\mathbf{V}$. These ratios were derived from country time series data on GDP, exports, imports, and value added (UNSD 2011a).

MRIO tables were obtained by applying large-scale optimisation approaches to each set of initial estimate and constraints data. Balanced tables were created using either a quadratic programming approach (Van der Ploeg 1988), or a non-sign-preserving KRAS variant of the RAS method. These methods were chosen because of the considerable conflict in the raw data[8], as well as sign-changing raw data. Both are problems that pose unsurmountable convergence problems to the conventional widespread RAS method (Lenzen *et al.* 2009; Lenzen 2012). Vectorising our MRIO into a $N\times1$ column vector $\mathbf{P}$, and arranging our raw data into a $M\times1$ column vector $\mathbf{c}$, we were able to formulate a system of linear equations $\mathbf{GP} = \mathbf{c}$, and a set of box constraints $\mathbf{l} \le \mathbf{P} \le \mathbf{u}$, to be met as much as possible by the MRIO solution $\mathbf{P}$. The quantification of the criterion "as much as possible" depends on the optimisation method chosen, and in particular on the type of objective function. The $M\times N$ matrix $\mathbf{G}$ holds constraints coefficients connecting raw data to elements of the MRIO. Balancing rules are also incorporated in $\mathbf{G}$, for example as differences between row and column sums, with elements of $\mathbf{c}$ set to zero. Elements of the lower and upper bound vectors $\mathbf{l}$ and $\mathbf{u}$ were set so that all MRIO elements were strictly positive, except values for changes in inventories, and subsidies. In addition to the raw data $\mathbf{c}$, and a prior matrix $\mathbf{P}_0$, optimisation techniques that are capable of dealing with conflicting constraints need some information on the reliability, or uncertainty, of the entries in c and P0, for example standard deviations $\sigma_{\mathbf{c}}$ and $\sigma_{\mathbf{P}}$. Constraints posed by raw data $\mathbf{c}$ are usually violated by the constraint realisations $\mathbf{GP}$, and more so for smaller constraints than for larger constraints (Fig. 4). This feature will be revisited in Section 6.2.

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[8] On conflict between balancing rules and raw data, see Peters 2011 and Wiebe *et al.* 2012. On conflict within the UN Comtrade database, see Lenzen *et al.* 2010a, and Bouwmeester and Oosterhaven 2008.

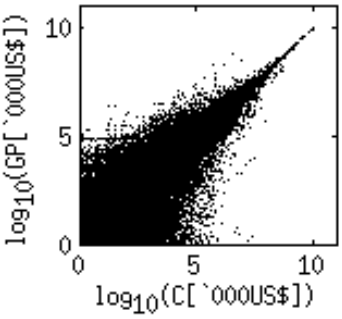


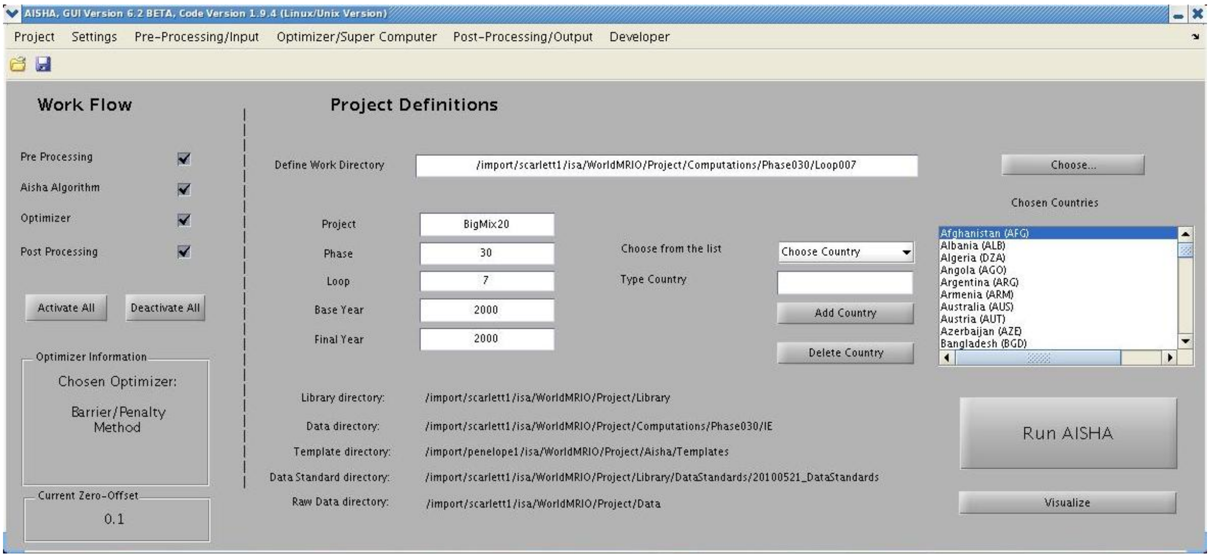
Fig. 4: A “rocket graph” showing adherences of constraints **c** to constraint realisations **GP** in absolute US$ terms. Because the externally fixed raw data represented by the constraints **c** conflict, the optimiser can generally not find a solution **P** where the realisations **GP** perfectly match all constraints **c**. Constraints on large values are better obeyed (top right) than constraints on small values (lower left). If the MRIO table perfectly satisfied all constraints this plot would be a 45° line.

Standard deviations $\sigma_{P,j}$ of MRIO table entries P_j were determined post-optimisation from the standard deviations $\sigma_{c,i}$ of the raw data, by propagating errors of **c** = **GP** according to $\sigma_{c,i} = \sqrt{\sum_j \left(G_{ij}\sigma_{P,j}\right)^2}\ \forall i$. The $\sigma_{P,j}$ are severely underdetermined by the $\sigma_{c,i}$ ($M \ll N$), but since the problem is generally RAS-feasible, we modified a standard RAS method so that, instead of balancing **GP** = **c**, it balanced the error propagation above. The initial estimate $\sigma^0_{P,j}$ was taken as the shift that the MRIO elements experience during the table balancing run: $\sigma^0_{P,j} = P_j - P_{0,j}\ \forall j$. Constraints were sorted according to descending $\sigma_{c,i}$, so that the more reliable c_i are always dealt with by RAS after the less reliable c_i, and hence the $\sigma_{P,j}$ are determined on the basis of the best information available. For further details on the method, see Wiedmann *et al.* 2008 and Lenzen *et al.* 2010b. In general, the reliability of a balanced table increases with the quality and amount of superior data used for balancing (Lenzen *et al.* 2006; Oosterhaven *et al.* 2008).

At the time of publication, the Eora tables measured $N \approx 1.2\times10^9$, supported by $M \approx 5\times10^6$ data points. Handling optimisation at such dimensions requires a combination of parallel programming and advanced computational resources. First, we utilised a purpose-built cluster with 72 cores and 600 GB of RAM. Second, since commercial solvers are unable to deal with optimisation problems at this scale, we needed to develop new mathematical approaches and algorithms, and to tailor hardware to these algorithms.

In order to manipulate and integrate a large number of different datasets we created a custom data processing language (AISHA, Geschke *et al.* 2011). This language contains commands for locating specific sections of the MRIO table time series and is linked to a library of concordance matrices that assist with the aggregation, disaggregation, and reclassification steps necessary to align disparate data. Conceptually this language is the reverse of a database query language: instead of selecting and aggregating portions of a multidimensional dataset, we want to populate it. For each input data source (national IO table, UN database, etc.) AISHA reads the processing script and uses it to insert the raw data into the MRIO as constraints or as a portion of the initial estimate.

In order to handle data assembly, constraint writing, optimisation, visualisation, and quality assurance procedures with minimum labour, we developed a Graphical User Interface (GUI, Fig. 5) that enables rapid variation of MRIO run configurations such as country selection, time series span, sector detail, path for file storage etc. The GUI was crucial in terms of keeping an overview of test runs during the development of the Eora tables.



Pre Processing ☑
Aisha Algorithm ☑
Optimizer ☑
Post Processing ☑

Optimizer Information
Chosen Optimizer:
Barrier/Penalty Method

Current Zero-Offset
0.1

Define Work Directory: /import/scarlett1/isa/WorldMRIO/Project/Computations/Phase030/Loop007

Project: BigMix20
Phase: 30
Loop: 7
Base Year: 2000
Final Year: 2000

Afghanistan (AFG)
Albania (ALB)
Algeria (DZA)
Angola (AGO)
Argentina (ARG)
Armenia (ARM)
Australia (AUS)
Austria (AUT)
Azerbaijan (AZE)
Bangladesh (BGD)

Library directory: /import/scarlett1/isa/WorldMRIO/Project/Library
Data directory: /import/scarlett1/isa/WorldMRIO/Project/Computations/Phase030/IE
Template directory: /import/penelope1/isa/WorldMRIO/Project/Aisha/Templates
Data Standard directory: /import/scarlett1/isa/WorldMRIO/Project/Library/DataStandards/20100521_DataStandards
Raw Data directory: /import/scarlett1/isa/WorldMRIO/Project/Data

Fig. 5: Graphical User Interface for controlling Eora runs.

6. CHARACTERISTIC FEATURES

In this Section we will focus only on those aspects of the Eora tables that are innovative in the sense that they differ from features of existing global MRIO databases. Since the Eora tables were only launched in 2012, no applications have yet been completed. Applications and their policy relevance in general has been described in detail by Wiedmann *et al.* 2011, who provide an overview of the role of MRIO frameworks for decision- and policy-making. One of the better known concepts that utilise these frameworks are carbon footprints (Minx *et al.* 2009; Wiedmann 2009a).

6.1 Technology assumptions

In contrast to existing MRIO databases, Eora retains the technology assumption made by the providers of raw data. It combines a mix of supply-use (SUT), as well as industry-by-industry (IIOT) or commodity-by-commodity tables (CIOT), linked into one compound MRIO. This strategy was pursued in accordance with one of Eora's guiding principle – avoiding transformations of the original raw data as much as possible for the sake of transparency.

Supply-use tables have advantages for analytical modelling[9], however supply and use matrices are only available for a limited number of countries. The remaining countries have to be represented by

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[9] Supply-use frameworks were suggested previously for use in Life-Cycle Assessment (Heijungs and Suh 2002; Suh *et al.* 2010).

input-output tables, which can be compiled according to a range of technology assumptions, with the commodity and industry technology assumptions being the most widespread amongst data sets provided by Statistical Offices around the world (Ten Raa and Rueda-Cantuche 2007). Each assumption has its drawbacks, and there is no definite overall advantage of one over the other assumptions (Kop Jansen and Ten Raa 1990). Further, a choice can be made with respect to industry-by-industry or commodity-by-commodity tables. In accordance with one of the guiding principle in this work – avoiding departures from the original raw data – we decided to keep the technology assumption made by the respective data provider. Hence, we combine supply-use, as well as industry and commodity input-output systems in one compound MRIO. This has significant advantages for impact analysis (Rueda-Cantuche 2011; Lenzen and Rueda-Cantuche 2012).

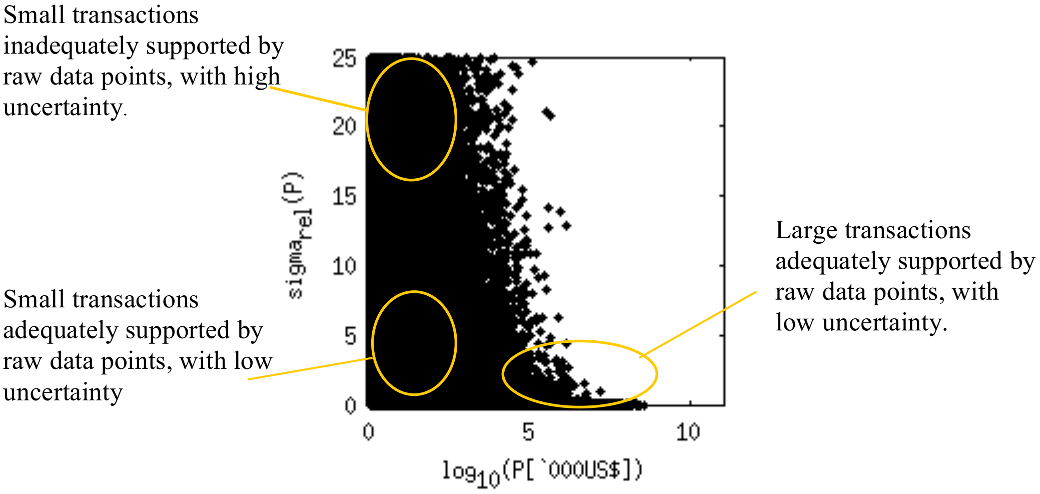
6.2 Reliability

A centrepiece of Eora's innovative approach is the simultaneous estimation of information on data reliability. Users of the Eora tables are being asked to view all quantitative information in light of its varying degree of reliability, and make use of the information provided only within the bounds of its statistical significance. For example, analysts may choose to aggregate the Eora database into a format that is more suitable for their purposes, and in this case Eora's accompanying standard deviation matrices provide the input necessary for calculating the standard deviations of any aggregated table, using standard error propagation.

The method used in the Eora tables for determining MRIO standard deviations is described in Lenzen *et al.* 2010b (compare with Weber 2008 and Wilting 2012). In essence, this method fits an error propagation formula to the standard deviations of raw data $\sigma_{c,i}$. These standard deviations can in most cases only be guessed, since very little information is available on the uncertainty of macroeconomic and input-output data. Hence, the standard deviations of raw data, and as a consequence also the standard deviations of the MRIO table elements, are based on assumptions, or *choices*. The Eora tables as published at the time of publication were estimated assuming that national input-output tables were most reliable, with the narrowest standard deviation settings, followed by UN Main Aggregates and Official Country data (UNSD 2011a; b) (for years where national input-output data do not exist), and then followed by UN Comtrade data (UN 2011). The latter were considered least reliable, partly because of severe conflict and errors (Oosterhaven *et al.* 2008). As a result, a set of Eora tables should be viewed as *based on a particular world view of uncertainty, or reliability*. For other world views, one could re-specify standard deviations, and re-run the Eora construction routines. One would then obtain a different set of tables. Hence, *there is no one unique set of MRIO tables*.

The Eora MRIO tables contain many elements that are small and/or highly fluctuating between years. One might ask: What is the reliability and significance of such elements? To understand this feature, let us recall that the estimation of any large MRIO table is an underdetermined problem. This means that the number M of raw data items c_i that can serve as support points for the MRIO matrices is much smaller than the number N of matrix elements P_j (see Section 5.6).

During the optimisation, or matrix *balancing* process, elements that are supported by only few raw data, and hence restricted by only few constraints, can be subject to large adjustments, and hence their reliability is low. On the other hands, for large and important IO table elements, there usually exist supporting raw data, so that the adjustment of these elements is usually minimal, and hence their reliability is high. This circumstance is reflected in Eora's online "hillside" graphs (Fig. 6).



Small transactions inadequately supported by raw data points, with high uncertainty.

Small transactions adequately supported by raw data points, with low uncertainty

Large transactions adequately supported by raw data points, with low uncertainty.

Fig. 6: "Hillside graph" of relative standard deviations $\sigma_{rel,P} = \sigma_P/P$ of MRIO elements P. Large elements have a relatively small relative standard deviation as they are relatively well constrained compared to smaller transactions.

6.2.1 Mechanisms generating unreliable elements

Large balancing adjustments, and as a result unreliable MRIO elements are the consequence of the interplay between data conflict and lack of information. Conflicting data create "tensions" in the set of constraints, whilst lacking support data creates "dustbins". Understanding the workings of these tensions and dustbins is critical to achieving a realistic MRIO table. This can be illustrated using a well-known example of conflicting information. Data on country-wise total exports and imports fundamentally conflict with global trade balances. One cannot achieve a balanced global multi-region input-output table whilst at the same time respecting data on exports and imports. This means that in a real MRIO table, either balancing conditions must be violated or raw data mis-represented (compare with Wiebe *et al.* 2012). The current Eora tables have been constructed with emphasis on a) representing large data items and b) fulfilling balancing conditions for large countries. For most countries, exports and imports are smaller than GDP, and the tensions in the constraints force those exports and imports to deviate somewhat from raw data given in the UN's Main Aggregate database (UNSD 2011a). For some countries such as Singapore and Hong Kong, exports and imports are larger than GDP, and for these countries, the GDP estimates tend to deviate from raw data.

Tensions in raw data and balancing conditions in one part of the MRIO table can create undesirable outcomes in such parts that are not well constrained by available information. Faced with irreconcilable conflicts in the basic price sheet, optimisation algorithms attempts to accommodate tensions between raw data and balancing conditions through (sometimes large) compensatory adjustments of loosely constrained MRIO elements elsewhere (such as the margins, tax and subsidies sheets of international trade blocks). Such loosely constrained parts of the table are known amongst MRIO compilers as "dustbins". The intermediate demand matrices of any country-year pair where specific input-output data are not available are the most obvious dustbins (sectoral value added and final demand are always constrained by UN SNA data). Further dustbin effects found in the Eora tables are a minority of negative international trade blocks, notably due to overall negative margins sheets or excessively negative subsidies sheets, as well as margins columns that do not sum to zero.

A further but less pronounced source of conflict is constituted by unresolvable differences in definitions between the raw data and the MRIO table. For example, most raw intermediate transactions data exclude re-exports of the respective commodity, but some include them. In order to cater for the majority of circumstances, we disaggregated total re-exports as a separate sector in our MRIO classification. However this means that sectoral raw data including re-exports cannot be utilised, since their re-exports content is only part of re-exports.

6.2.2 Resolution versus reliability, and holistic versus table accuracy

Confronted with lack and conflict of data, researchers have asked the following questions:

1) Does it make sense to construct (MR)IO tables at high detail if many of the ensuing elements are insufficiently supported by raw data, and may become prohibitively unreliable?
2) Will the large number of small and unreliable elements lead to low-quality results for multipliers, footprints, and other impact measures?

With respect to the first question, one can show via Monte-Carlo simulation that it is always beneficial for IO table construction to use as much information as possible. Choosing to aggregate the table's sector classification even when only one disaggregated raw data item were available would mean losing information. Also, even if one were only interested in an aggregated final table, it would be better to construct a disaggregated table first, undertake the multiplier or footprint analysis, and then aggregate the results (Lenzen 2011).

Regarding the second question, Jensen 1980 has demonstrated that a large number of small elements can be perturbed without significantly changing estimates for multipliers or footprints. Jensen and West 1980 report that a surprisingly large number of smaller elements in an IO table can even be removed before multipliers show a significant change, because the value of these elements is often negligible compared to the combined value of a few large elements. Since Jensen's pioneering work, this phenomenon has become known as *holistic accuracy*. While table accuracy represents the conventional understanding of the accuracy of single matrix elements, holistic accuracy is concerned with the representativeness of a table of the synergistic characteristics of an economy. In this perspective, the accuracy of single elements may be unimportant, as long as the results of modelling exercises yield a realistic picture for the purpose of the analyst or decision-maker. In other words, unless the research focus is on single table elements, it does not matter to have a large number of small and unreliable elements in an IO table.

6.3 Continuity, timeliness, and cost

The Eora tables currently exist as a time series spanning the period 1990-2009. The utilisation of automated data handling systems (Yu *et al.* 2009) and advanced hardware (see Section 5.6) has enabled the reduction of construction cost to around 0.5 US$m initially, and 0.25 US$m on a continuing basis. In addition, we were able to reduce publication delays of a continuous series of tables to no more than about two years.

6.4 Visualisation and diagnostics

Eora is deployed on-line (http://www.worldmrio.com), and at the time of publication, provided a 1990-2009 time series of global MRIO tables, distinguishing 187 countries (see Appendix 1) represented by more than 15,000 sectors. The basic-price sheet is complemented by four additional sheets in the same format, containing trade and transport margins, as well as taxes and subsidies on products. The entire set of tables is accompanied by an equal-sized set of tables containing the standard deviations of all MRIO elements. Information is available for the entire table, as well as for each country separately. The monetary tables are complemented by satellite accounts containing a number of environmental and resource use indicators such as greenhouse gas emissions, energy use, and emissions to air.

6.4.1 Heat maps

Accompanying the numerical data are a number of visualisations, which during the development of the Eora database played a crucial role. One such tool is a topographical map, or heat map, which shade-codes the absolute values (in units of US$) of MRIO entries according to a logarithmic scale.[10]

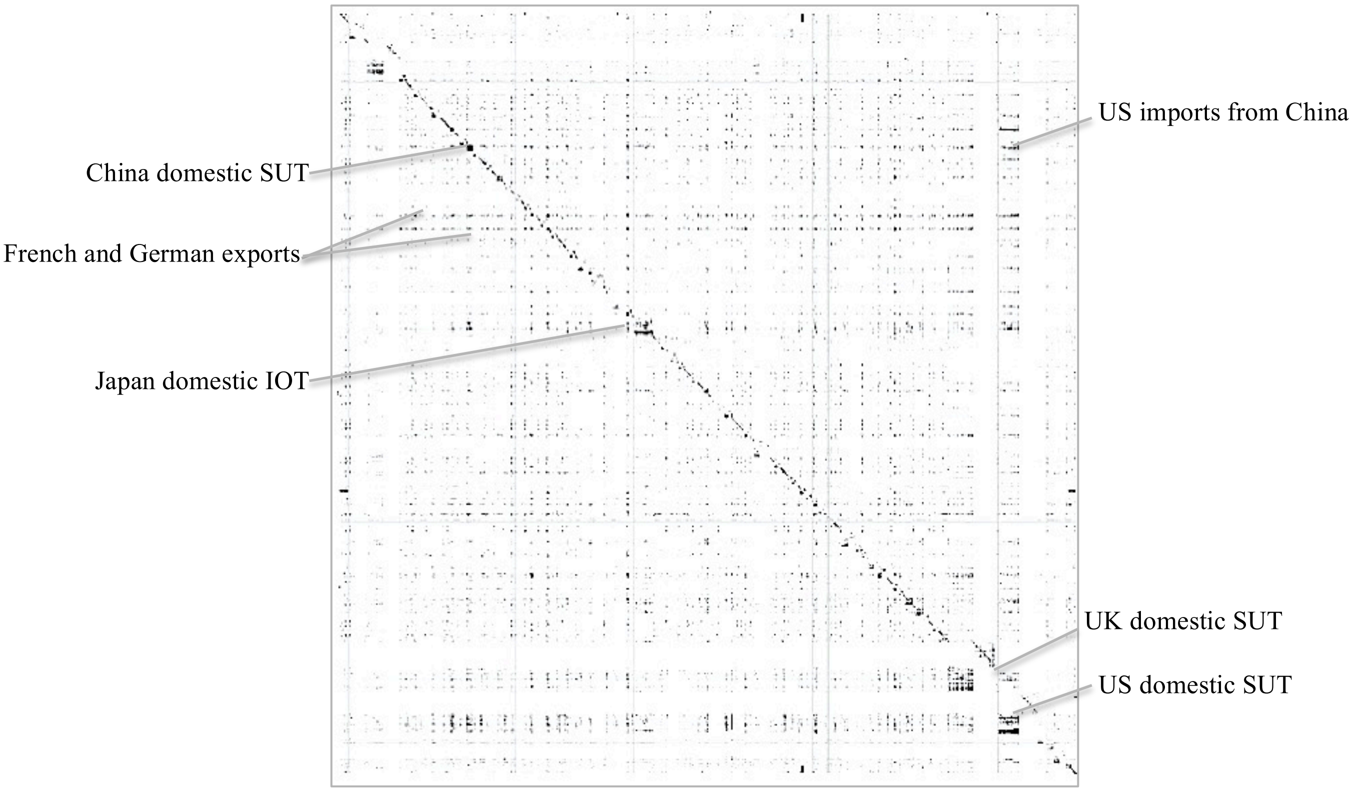


Fig. 7: Visualisation of the basic-price sheet of the 2009 Eora world MRIO. Diagonal blocks are domestic tables, and off diagonal blocks contain international trade transactions. French and German exports are discernible as dark grey rows, and US imports as a dark grey column. Domestic transactions are usually more important in monetary terms than international trade.

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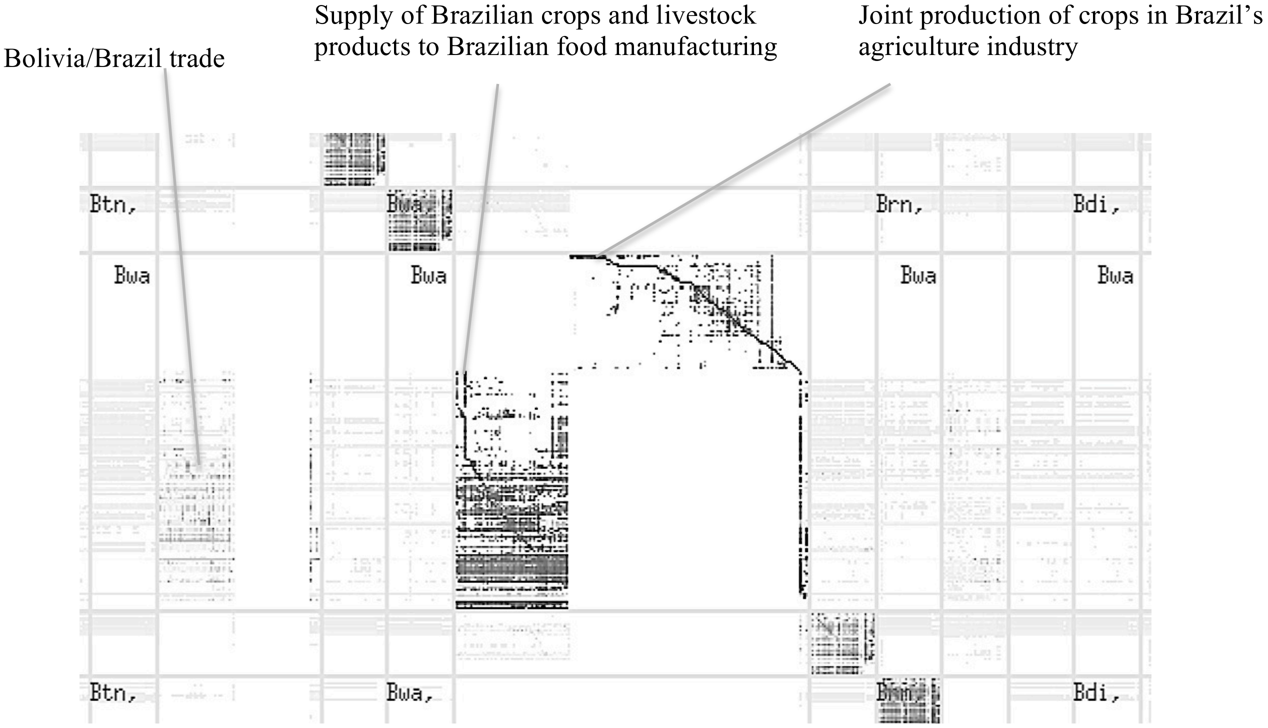
[10] The Eora website features colour-coded maps in order to distinguish positive and negative entries by magnitude.

Heat maps allow for rapid quality inspection immediately after table balancing. Any gross errors in the table structure or magnitude would show up as conspicuous dark shadings. Eora's world MRIO heat map is equipped with a zoom-in/zoom-out facility that allows the user to focus on certain regions. Brazil's strongly asymmetrical supply-use structure (55 industries and 110 commodities) is clearly visible (Fig. 8), with the main joint production occurring in the agricultural and food manufacturing sectors represented as a horizontal line in the supply matrix. The dark vertical line in the top left corner of the use matrix represents the supply of agricultural goods to Brazil's food manufacturing sectors.



Bolivia/Brazil trade

Supply of Brazilian crops and livestock products to Brazilian food manufacturing

Joint production of crops in Brazil's agriculture industry

Fig. 8: Close-up of Fig. 7. Brazilian supply-use tables embedded in transactions matrices for Bhutan, Bolivia, Bosnia, Botswana (to the left), and Brunei, Bulgaria, Burkina Faso, and Burundi (to the right).

The integration of supply-use tables (Italy) with industry-by-industry input-output tables (Jamaica) and commodity-by-commodity input-output tables (Japan) gives rise to four types of international trade matrices (Fig. 9): two commodity-by-industry trade matrices, one for Italian exports to Jamaica and one for Japanese exports to Jamaica ①, a commodity-by-commodity trade matrix for Italian exports to Japan ②, an industry-by-industry trade matrix for Jamaican exports to Italy ③, and an industry-by-commodity trade matrix for Jamaican exports to Japan ④.

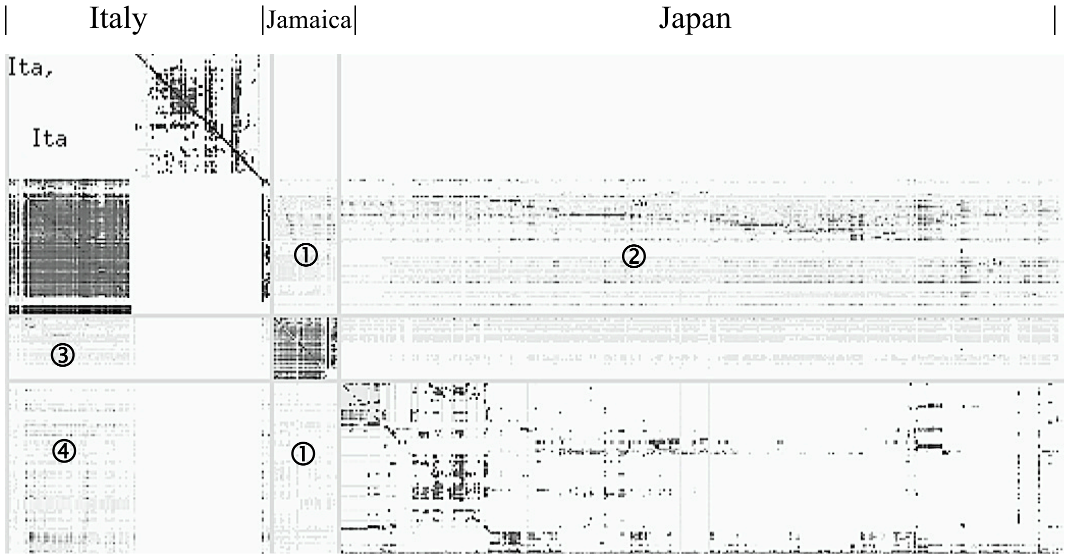


Fig. 9: Close-up of Fig. 7. Interconnected supply-use tables of Italy, industry-by-industry input-output tables of Jamaica, and commodity-by-commodity input-output tables of Japan. The numerical labels denote four types of international trade matrices described in the main text. Japan's 401-sector table is only partly shown in the bottom right corner of the figure.

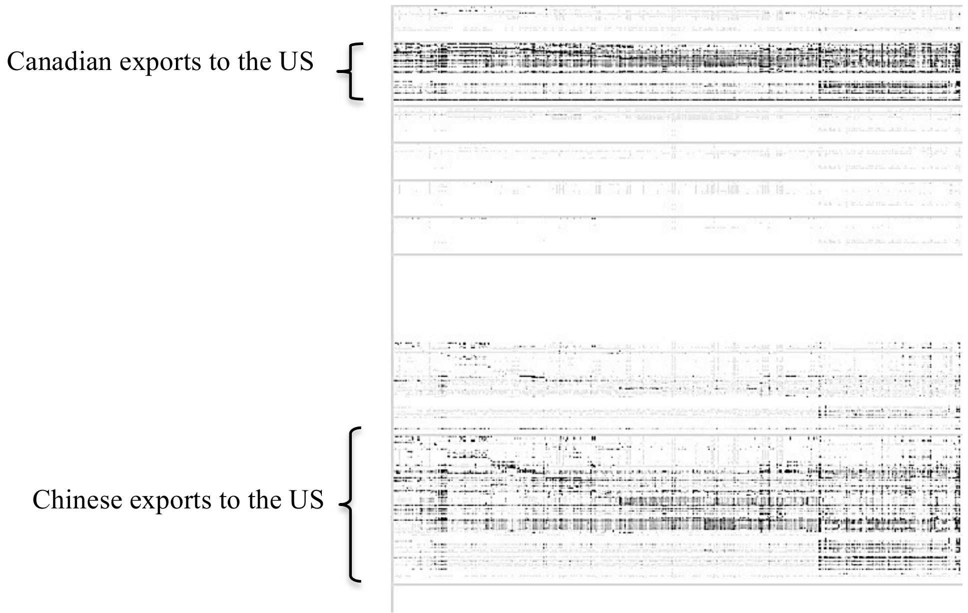


Fig. 10: Close-up of Fig. 7. The Canadian export block has its top part dominated, signifying important trade flows of primary commodities such as minerals. The Chinese export block has its central part dominated, signifying important trade flows of manufactured commodities. The remaining trade blocks include exports of Chad and Chile to the US.

6.4.2 Quality statistics

In addition to the rocket and hillside graphs illustrating MRIO table reliability (Figs. 4 and 6), the Eora website offers diagnostic statistics that can be used to judge the performance of the optimisation runs, and as a result the overall quality of results. These include optimiser performance histograms (Fig. 11) and size distributions of constraints and MRIO elements (Fig. 12). All types of diagnostic visualisations are available for the entire MRIO table, as well as for individual countries.

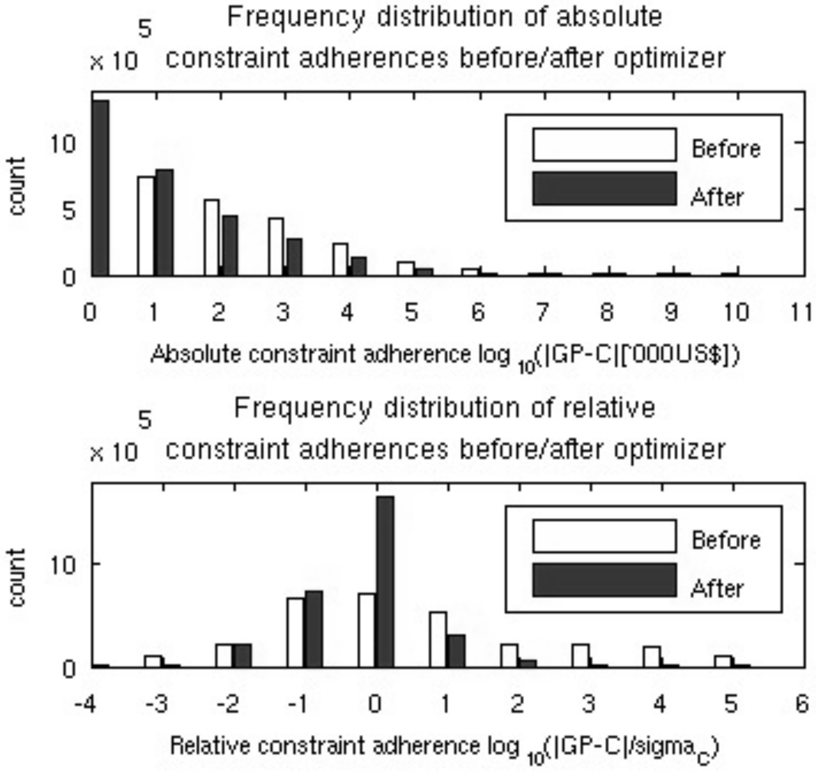


Fig. 11: Performance histograms for optimisation runs, taken from the Eora website. The bars show the frequency distribution of constraint adherences |**GP** – **c**|, before and after optimisation, in absolute (‘000 US$) terms (top histogram), and in relative terms as multiples of σ_c (bottom histogram). Large constraint violations are situated to the right of the histogram. After optimisation, more counts are registered in the left part of the histograms, representing better constraint adherences. In this example, virtually all initial constraint violations in excess of 100 standard deviations have been eliminated by the optimiser.

The optimiser performance histograms (Fig. 11) allow the user to judge how much the optimiser has improved the constraint realisation **GP** of the MRIO solution **P** to constraints posed by raw data **c**, compared to the constraint realisation $\mathbf{GP}_0$ of the MRIO initial estimate. Usually, counts of large constraint violations are low both in absolute terms, and in relative terms as multiples of σ_c. The frequency distribution for the MRIO solution **P** is always skewed towards better adherences, compared to the frequency distribution for the MRIO initial estimate $\mathbf{P}_0$. Constraint realisations are also available from the website as ranked lists, one showing top-adhering constraints, well matched by the MRIO, and top violators. Especially the ranked list of violators proved helpful in detecting any quality issues with the raw data.

Size distributions of constraints **c** and MRIO elements **P** (Fig. 12) are helpful in understanding the optimisation problem. First, the different vertical-axis scales for the constraints size counts and table element size counts show once again how underdetermined the optimisation problem is (compare with Section 5.6). Second, a comparison of the two distributions shows that whilst constraints are to a large extent based on aggregates ranging between 100,000 US$ and 100 million US$, the actual MRIO table is dominated by elements sized 10,000 US$ and less, lending support to Jensen's (1980) view on holistic accuracy.

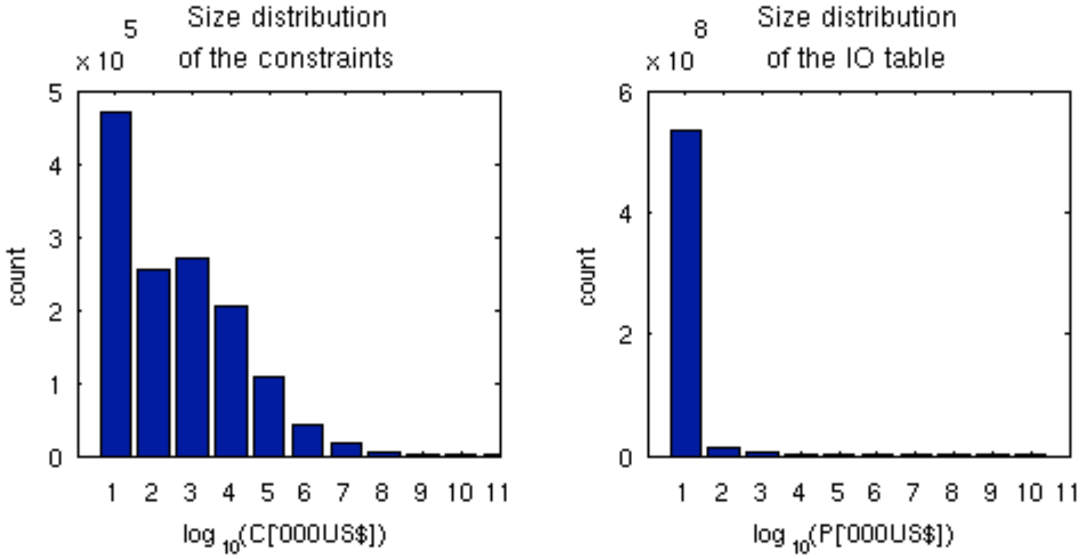


Fig. 12: Size distribution of constraints **c** (left), and of MRIO table elements **P** (right). The horizontal axis is expressed in logarithms of '000 US$, and is cut off at values smaller than 1000 US$.

7. CONCLUSIONS

By focussing on standardisation, automation and advanced computation, we have achieved a method for rapid, timely, and at the same time low labour- and time-intensive construction and updating of high-resolution MRIO tables. Through these achievements we have addressed a number of shortcomings identified with respect to MRIO compilation (Wiedmann *et al.* 2011). A key principle of our approach is the incorporation and publication of information on data reliability. The latter can be subjective, and the actual realisation of an MRIO table can depend on the choice of reliability settings. Rather than perceiving this ambiguity as a drawback, we argue that there is no unique MRIO table, and every table realisation must be understood and used in conjunction with an accompanying world view on reliability.

A crucial item on the near-future MRIO research agenda is the comparative evaluation of existing MRIO frameworks (Wiedmann *et al.* 2011). This task is part of the mission of the the Réunion Project (http://www.isa.org.usyd.edu.au/mrio/mrio.shtml). The Réunion Project is aimed at linking the top global institutions involved in the compilation of global extended Multi-Region Input-Output (MRIO) accounts, and at initiating a large-scale research collaboration that will be able to harmonise world-wide activities on environmental-economic MRIO database compilation. The idea for this collaboration originated from a meeting of the present researchers at the 18th Input-Output Conference held in 2010 at the University of Sydney (see http://www.isa.org.usyd.edu.au/io_2010/index.html). This meeting clearly demonstrated the opportunities of a world MRIO network for shaping environmental databases, sustainability reporting and environmental policy around the world. The University of Sydney subsequently provided seed support from its International Program Development Fund (IPDF), in order to enable these leaders in the field to meet twice, and to implement the envisaged global collaboration. The first meeting was held in L'Hermitage-les-Bains, Réunion, during 27–29 March 2011, with founding members representing the EXIOPOL, GTAP, IDE/JETRO, WIOD and Eora initiatives. Following this meeting, IDE/JETRO made available funds for a third meeting, which was scheduled ahead of the second Réunion meeting, to be held in Tokyo during 30 January – 2 February 2012.

The ideal outcome of a reunion of MRIO initiatives would be the creation of an international collaborative research platform, through which data could be pooled and shared, and MRIO tables released in a regular and timely manner. A “mother of all MRIOs” could incorporate a maximum of information, and all tailored, purpose-focused MRIO tables such as the current EXIOPOL, GTAP, WIOD and Eora tables, could be derived from this mother. Joint methodologies would combine the best of all existing approaches. Such an international collaborative research platform would transform MRIO tables from their current status as expensive, complicated, one-off undertakings, into affordable, consistent, and internationally governed and standardised tools. Once placed into easy reach of policy analysts, such tools could vastly improve geopolitical decision-making.

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REFERENCES

Andrew, R., G. Peters and J. Lennox (2009) Approximation and regional aggregation in multi-regional input-output analysis. *Economic Systems Research* 21, 311–335.

BBC (2008) *UK in 'delusion' over emissions*. BBC News http://news.bbc.co.uk/today/hi/today/newsid_7536000/7536617.stm, London, UK, British Broadcasting Corporation.

BBC News (2009) *China seeks export carbon relief*. Internet site http://news.bbc.co.uk/2/hi/science/nature/7947438.stm.

Bouwmeester, M. and J. Oosterhaven (2008) Methodology for the construction of an international supply-use table. *International Input-Output Meeting on Managing the Environment*. Sevilla, Spain.

Davis, S.J., G.P. Peters and K. Caldeira (2011) The supply chain of CO_2 emissions. *Proceedings of the National Academy of Science* 108, 18554-18559.

Eurostat (2011) *ESA 95 Supply Use and Input-Output tables*. Internet site http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks, Luxembourg, Luxembourg, European Commission.

EXIOPOL (2008) *A new environmental accounting framework using externality data and input-output tools for policy analysis*. Internet site http://www.feem-project.net/exiopol/, European Commission.

Gallego, B. and M. Lenzen (2009) Estimating generalised regional input-output systems: A case study of Australia. In: M. Ruth and B. Davíðsdóttir (eds.) *The Dynamics of Regions and Networks in Industrial Ecosystems* Boston, MA, USA, Edward Elgar Publishing 55-82.

Geschke, A., D. Moran, K. Kanemoto and M. Lenzen (2011) AISHA : A tool for constructing time series and large environmental and Social Accounting Matrices using constrained optimisation. *19th International Input-Output Conference,* http://www.iioa.org/Conference/19th-downable_paper.htm. Alexandria, USA.

Global Footprint Network (2010) *National Footprint and Biocapacity Accounts*. Internet site http://www.footprintnetwork.org.

Global Trade Analysis Project (2008) *GTAP 7 Data Base*. Internet site http://www.gtap.agecon.purdue.edu/databases/v7/default.asp, West Lafayette, IN, USA, Department of Agricultural Economics, Purdue University.

Heijungs, R. and S. Suh (2002) *The computational structure of life cycle assessment*. Dordrecht, Netherlands, Kluwer Academic Publishers.

Heimann, M. and M. Reichstein (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* 451, 289-292.

IDE-JETRO (2006) *Asian International Input-Output Table*. Internet site http://www.ide-jetro.jp/English/Publish/Books/Sds/material.html, Wakaba, Mihama-ku, Chiba, Japan, Institute of Developing Economies, Japan External Trade Organization.

ISO (2006) *ISO 3166-1*. Internet site ftp.ripe.net/iso3166-countrycodes.txt, International Standardisation Organisation, 3166 Maintenance Agency.

Jensen, R.C. (1980) The concept of accuracy in regional input-output models. *International Regional Science Review* 5, 139-154.

Jensen, R.C. and G.R. West (1980) The effect of relative coefficient size on input-output multipliers. *Environment and Planning A* 12, 659-670.

Jomini, P., R. McDougall, G. Watts and P. Dee (1994) *The SALTER Model of the World Economy: Model Structure, Database and Parameters*. Technical Report 24, Industry Commission on behalf of the Department of Foreign Affairs and Trade, Australian Government.

Kop Jansen, P.S.M. and T. Ten Raa (1990) The choice of model in the construction of input-output coefficients matrices. *International Economic Review* 31, 213-227.

Lenzen, M. (2011) Aggregation versus disaggregation in input-output analysis of the environment. *Economic Systems Research* 23, 73 – 89.

Lenzen, M. (2012) A non-sign-preserving RAS variant. *Economic Systems Research*, submitted.

Lenzen, M., B. Gallego and R. Wood (2006) A flexible approach to matrix balancing under partial information. *Journal of Applied Input-Output Analysis* 11&12, 1-24.

Lenzen, M., B. Gallego and R. Wood (2009) Matrix balancing under conflicting information. *Economic Systems Research* 21, 23-44.

Lenzen, M., K. Kanemoto, A. Geschke, D. Moran, P.J. Muñoz, J. Ugon, R. Wood and T. Yu (2010a) A global multi-region input-output time series at high country and sector detail. In: J.M. Rueda-Cantuche and K. Hubacek (eds.) *18th International Input-Output Conference,* http://www.iioa.org/files/conference-1/37_20100617021_Lenen&al_GlobalMRIO_18thIOConf2010.pdf. Sydney, Australia.

Lenzen, M., L.-L. Pade and J. Munksgaard (2004) CO_2 multipliers in multi-region input-output models. *Economic Systems Research* 16, 391-412.

Lenzen, M., M.C. Pinto de Moura, A. Geschke, K. Kanemoto and D.D. Moran (2012) A cycling method for constructing input-output table time series from incomplete data. *Economic Systems Research* 24, submitted.

Lenzen, M. and J.M. Rueda-Cantuche (2012) A note on the use of supply-use tables in impact analyses. *Statistics and Operations Research Transactions*, submitted.

Lenzen, M., R. Wood and T. Wiedmann (2010b) Uncertainty analysis for Multi-Region Input-Output models – a case study of the UK's carbon footprint. *Economic Systems Research* 22, 43-63.

Luthje, M., L.T. Pedersen, N. Reeh and W. Greuell (2006) Modelling the evolution of supraglacial lakes on the West Greenland ice-sheet margin. *Journal of Glaciology* 52, 608-618.

Minx, J., T. Wiedmann, R. Wood, G.P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh and F. Ackerman (2009) Input-output analysis and carbon footprinting: An overview of applications. *Economic Systems Research* 21, 187-216.

Moran, D.D., M.C. Wackernagel, J.A. Kitzes, B.W. Heumann, D. Phan and S.H. Goldfinger (2009) Trading spaces: Calculating embodied Ecological Footprints in international trade using a Product Land Use Matrix (PLUM). *Ecological Economics* 68, 1938-1951.

Müller, M. (2006) *A General Equilibrium Approach to Modeling Water and Land Use Reforms in Uzbekistan*. Dissertation, Internet site http://hss.ulb.uni-bonn.de/2006/0801/0801.pdf, Bonn, Germany, Zentrum für Entwicklungsforschung, Rheinische Friedrich-Wilhelms-Universität.

Müller, M. and N. Djanibekov (2009) *Calibration of an Agricultural Sector Model for the Region Khorezm (Uzbekistan) based on Survey Data*. 27th International IAAE Conference, The New Landscape of Global Agriculture, http://ageconsearch.umn.edu/bitstream/50354/2/533.pdf, Beijing, China, International Association of Agricultural Economists (IAAE).

Munksgaard, J. and K.A. Pedersen (2001) CO_2 accounts for open economies: producer or consumer responsibility? *Energy Policy* 29, 327-334.

Nakićenović, N. and R. Swart (2000) *Special Report on Emissions Scenarios*. Geneva, Switzerland, Intergovernmental Panel on Climate Change.

OECD (2009) *OECD Input-Output Tables (edition 2002, 2006 and 2009)*. Internet site http://www.oecd.org/document/3/0,3343,en_2649_34245_38071427_1_1_1_1,00.html, Paris, France, Organisation for Economic Co-operation and Development.

Oosterhaven, J., D. Stelder and S. Inomata (2008) Estimating international interindustry linkages: non-survey simulations of the Asian-Pacific economy. *Economic Systems Research* 20, 395-414.

Peters, G. (2008) From production-based to consumption-based national emission inventories. *Ecological Economics* 65, 13-23.

Peters, G. (2011) Constructing an environmentally-extended Multi-Region Input-Output table using the GTAP database. *Economic Systems Research* 23, in press.

Peters, G. and E.G. Hertwich (2008) CO_2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology* 42, 1401-1407.

Peters, G., J. Minx, C. Weber and O. Edenhofer (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proceedings Of The National Academy Of Sciences Of The United States Of America*, Accepted.

Rueda-Cantuche, J.M. (2011) The choice of type of input-output table revisited: moving towards the use of supply-use tables in impact analysis. *Statistics and Operations Research Transactions* 35, in press.

Rueda-Cantuche, J.M., J. Beutel, F. Neuwahl, I. Mongelli and A. Loeschel (2009) A symmetric input-output table for EU27: Latest progress. *Economic Systems Research* 21, 59-79.

Schuster, U. and A.J. Watson (2007) A variable and decreasing sink for atmospheric CO_2 in the North Atlantic. *Journal of Geophysical Research* 112.

Stelder, D. and J. Oosterhaven (2009) Non-survey international input-output construction methods; a generalized RAS algorithm GRAS4. In: H. Kuwamori, Y. Uchida and S. Inomata (eds.) *Compilation and Use of the 2005 International Input-Output Tables*. Chiba, Japan, Institute of Developing Economies, 165-174.

Suh, S., B. Weidema, J.H. Schmidt and R. Heijungs (2010) Generalized Make and Use Framework for Allocation in Life Cycle Assessment. *Journal of Industrial Ecology* 14, 335-353.

Ten Raa, T. and J.M. Rueda-Cantuche (2007) A generalized expression for the commodity and the industry technology models in input-output analysis. *Economic Systems Research* 19, 99-104.

Tukker, A., E. Poliakov, R. Heijungs, T. Hawkins, F. Neuwahl, J.M. Rueda-Cantuche, S. Giljum, S. Moll, J. Oosterhaven and M. Bouwmeester (2009) Towards a global multi-regional environmentally extended input-output database. *Ecological Economics* 68, 1928-1937.

UN (2009) *UN ServiceTrade - United Nations Service Trade Statistics Database*. Internet site http://unstats.un.org/unsd/servicetrade/, New York, USA, United Nations Statistics Division, UNSD.

UN (2011) *UN comtrade - United Nations Commodity Trade Statistics Database*. Internet site comtrade.un.org/, New York, USA, United Nations Statistics Division, UNSD.

UNSD (2008a) *Conversions and Formulas*. Internet site unstats.un.org/unsd/snaama/formulas.asp, New York, USA, United Nations Statistics Division.

UNSD (2008b) *Exchange Rates and Population*. Internet site unstats.un.org/unsd/snaama/dnllist.asp, New York, USA, United Nations Statistics Division.

UNSD (2008c) *GDP and its breakdown at current prices in US Dollars*. Internet site unstats.un.org/unsd/snaama/dnllist.asp, New York, USA, United Nations Statistics Division.

UNSD (2008d) *GNI in US Dollars*. Internet site unstats.un.org/unsd/snaama/dnllist.asp, New York, USA, United Nations Statistics Division.

UNSD (2009) *1993 System of National Accounts*. Internet site unstats.un.org/unsd/sna1993/toctop.asp, New York, USA, United Nations Statistics Division.

UNSD (2011a) *National Accounts Main Aggregates Database*. Internet site http://unstats.un.org/unsd/snaama/Introduction.asp, New York, USA, United Nations Statistics Division.

UNSD (2011b) *National Accounts Official Data*. Internet site data.un.org/Browse.aspx?d=SNA, New York, USA, United Nations Statistics Division.

Van der Linden, J.A. and J. Oosterhaven (1995) European Community intercountry input-output analysis: construction method and main results for 1965-85. *Economic Systems Research* 7, 249-269.

Van der Ploeg, F. (1988) Balancing large systems of National Accounts. *Computer Science in Economics and Management* 1, 31-39.

Van Vuuren, D. and K. Riahi (2008) Do recent emission trends imply higher emissions forever? *Climatic Change* 91, 237-248.

Walter, K.M., S.A. Zimov, J.P. Chanton, D. Verbyla and F.S. Chapin (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443, 71-75.

Weber, C.L. (2008) Uncertainties in constructing environmental multiregional input-output models. *International Input-Output Meeting on Managing the Environment*. Seville, Spain.

Wiebe, K.S., M. Bruckner, S. Giljum and C. Lutz (2012) Calculating energy-related CO_2 emissions embodied in international trade using a global input-output model. *Economic Systems Research* 24, in press.

Wiedmann, T. (2009a) Editorial: Carbon footprint and input-output analysis: an introduction. *Economic Systems Research* 21, 175–186.

Wiedmann, T. (2009b) A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics* 69, 211-222.

Wiedmann, T. (2010) *Unpublished data*. York, UK, Centre for Sustainability Accounting.

Wiedmann, T., M. Lenzen, K. Turner and J. Barrett (2007) Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics* 61, 15-26.

Wiedmann, T., M. Lenzen and R. Wood (2008) *Uncertainty analysis of the UK-MRIO model – Results from a Monte-Carlo analysis of the UK Multi-Region Input-Output model*. Report to the UK Department for Environment, Food and Rural Affairs, London, UK, Stockholm Environment Institute at the University of York and Centre for Integrated Sustainability Analysis at the University of Sydney.

Wiedmann, T., H.C. Wilting, M. Lenzen, S. Lutter and V. Palm (2011) Quo vadis MRIO? Methodological, data and institutional requirements for Multi-Region Input-Output analysis. *Environmental Science & Technology*, in press.

Wiedmann, T., H.C. Wilting, S. Lutter, V. Palm, S. Giljum, A. Wadeskog and D.S. Nijdam (2009) *Development of a methodology for the assessment of global environmental impacts of traded goods and services*. SKEP ERA-NET Project EIPOT, Internet site http://www.sei.se/eipot/EIPOT_Final_Report_07Aug09.pdf, York, UK, Stockholm Environment Institute.

Wiedmann, T., R. Wood, M. Lenzen, J. Minx, D. Guan and J. Barrett (2010) The carbon footprint of the UK - Results from a Multi-Region Input-Output model. *Economic Systems Research* 22, 19-42.

Wilting, H.C. (2012) Sensitivity and uncertainty analysis in MRIO modelling: some empirical results with regard to the Dutch carbon footprint. *Economic Systems Research* 24, In press.

WIOD (2010) *World Input-Output Database*. Internet site http://www.wiod.org, Groningen, Netherlands, University of Groningen and 10 other institutions.

Wood, R. (2011) Construction, stability and predictability of an input-output time-series for Australia. *Economic Systems Research* 23, 175-211.

Yu, T., M. Lenzen, C. Dey and J. Badcock (2009) Automatically estimating and updating input-output tables. In: J.D. Velásquez, S.A. Ríos, R.J. Howlett and L.C. Jain (eds.) *Knowledge-Based and Intelligent Information and Engineering Systems*. Berlin, Springer, 42-49.

Appendix 1: List of countries in the Eora MRIO database, including UN country code, and number of products (PR) and industries (IN).

UN code	Name	Sectors (PR/IN)
4	Afghanistan	26/0
8	Albania	26/0
12	Algeria	26/0
20	Andorra	26/0
24	Angola	26/0
28	Antigua and Barbuda	26/0
32	Argentina	125/196
51	Armenia	26/0
533	Aruba	26/0
36	Australia	345/345
40	Austria	61/61
31	Azerbaijan	26/0
44	Bahamas	26/0
48	Bahrain	26/0
50	Bangladesh	26/0
52	Barbados	26/0
112	Belarus	26/0
56	Belgium	61/61
84	Belize	26/0
204	Benin	26/0
60	Bermuda	26/0
64	Bhutan	26/0
68	Bolivia	37/37
70	Bosnia and Herzegovina	26/0
72	Botswana	26/0
76	Brazil	56/111
92	British Virgin Islands	26/0
96	Brunei Darussalam	26/0
100	Bulgaria	26/0
854	Burkina Faso	26/0
108	Burundi	26/0
116	Cambodia	26/0
120	Cameroon	26/0
124	Canada	49/0
132	Cape Verde	26/0
136	Cayman Islands	26/0
140	Central African Republic	26/0
148	Chad	26/0
152	Chile	75/75
156	China	0/123
170	Colombia	60/60
178	Congo	26/0
188	Costa Rica	26/0
191	Croatia	26/0
192	Cuba	26/0
196	Cyprus	26/0
203	Czech Republic	61/61
384	Côte d'Ivoire	26/0
408	Democratic People's Republic of Korea	26/0
180	Democratic Republic of the Congo, previously Zaïre	26/0
208	Denmark	131/0
262	Djibouti	26/0
214	Dominican Republic	26/0
218	Ecuador	49/61
818	Egypt	26/0
222	El Salvador	26/0
232	Eritrea	26/0
233	Estonia	61/61
231	Ethiopia	26/0
242	Fiji	26/0
246	Finland	61/61
250	France	61/61
258	French Polynesia	26/0

266	Gabon	26/0
270	Gambia	26/0
268	Georgia	47/68
276	Germany	0/72
288	Ghana	26/0
300	Greece	61/61
304	Greenland	31/0
320	Guatemala	26/0
324	Guinea	26/0
328	Guyana	26/0
332	Haiti	26/0
340	Honduras	26/0
344	Hong Kong	38/38
348	Hungary	61/61
352	Iceland	26/0
356	India	116/116
360	Indonesia	0/77
364	Iran	100/148
368	Iraq	26/0
372	Ireland	61/61
376	Israel	163/163
380	Italy	61/61
388	Jamaica	26/0
392	Japan	0/402
400	Jordan	26/0
398	Kazakhstan	0/121
404	Kenya	51/51
414	Kuwait	55/0
417	Kyrgyzstan	89/87
418	Lao People's Democratic Republic	26/0
428	Latvia	61/61
422	Lebanon	26/0
426	Lesotho	26/0
430	Liberia	26/0
434	Libyan Arab Jamahiriya	26/0
438	Liechtenstein	26/0
440	Lithuania	61/61
442	Luxembourg	26/0
446	Macao Special Administrative Region of China	26/0
450	Madagascar	26/0
454	Malawi	26/0
458	Malaysia	0/98
462	Maldives	26/0
466	Mali	26/0
470	Malta	61/61
478	Mauritania	26/0
480	Mauritius	57/67
484	Mexico	80/80
492	Monaco	26/0
496	Mongolia	26/0
499	Montenegro	26/0
504	Morocco	26/0
508	Mozambique	26/0
104	Myanmar	26/0
516	Namibia	26/0
524	Nepal	26/0
528	Netherlands	61/61
530	Netherlands Antilles	16/41
540	New Caledonia	26/0
554	New Zealand	127/210
558	Nicaragua	26/0
562	Niger	26/0
566	Nigeria	26/0
578	Norway	61/61
275	Occupied Palestinian Territory	26/0
512	Oman	26/0
586	Pakistan	26/0
591	Panama	26/0
598	Papua New Guinea	26/0
600	Paraguay	34/47

604	Peru	46/46
608	Philippines	0/77
616	Poland	61/61
620	Portugal	61/61
634	Qatar	26/0
410	Republic of Korea	0/78
498	Republic of Moldova	26/0
642	Romania	61/61
643	Russian Federation	49/0
646	Rwanda	26/0
882	Samoa	26/0
674	San Marino	26/0
678	Sao Tome and Principe	26/0
682	Saudi Arabia	26/0
686	Senegal	26/0
688	Serbia	26/0
690	Seychelles	26/0
694	Sierra Leone	26/0
702	Singapore	154/154
703	Slovakia	61/61
705	Slovenia	61/61
706	Somalia	26/0
710	South Africa	95/96
724	Spain	76/119
144	Sri Lanka	26/0
736	Sudan	26/0
740	Suriname	26/0
748	Swaziland	26/0
752	Sweden	61/61
756	Switzerland	43/43
760	Syrian Arab Republic	26/0
761	Taiwan	0/163
762	Tajikistan	26/0
764	Thailand	0/180
807	Macedonia	61/61
768	Togo	26/0
780	Trinidad and Tobago	26/0
788	Tunisia	26/0
792	Turkey	61/61
795	Turkmenistan	26/0
800	Uganda	26/0
804	Ukraine	0/121
784	United Arab Emirates	26/0
826	United Kingdom	511/511
834	United Republic of Tanzania	26/0
840	USA	429/429
858	Uruguay	84/103
860	Uzbekistan	0/123
548	Vanuatu	26/0
862	Venezuela	122/122
704	Viet Nam	0/113
887	Yemen	26/0
894	Zambia	26/0
716	Zimbabwe	26/0

Appendix 2: Availability of national input-output tables.

Country name	Year
Aruba	1995-2002
Netherlands Antilles	2004
Argentina	1997
Armenia	2006
Australia	1990-2007
Austria	1995, 1997, 1999-2005
Belgium	1995, 1997, 1999-2004
Bolivia	1999-2002
Brazil	1990-2008
Canada	1995, 2000
Switzerland	2001, 2005
Chile	1996, 2003
China	1990, 1992, 1995, 1997, 2000, 2002, 2005, 2007
Colombia	2000-2007
Czech Republic	1995-2005
Germany	1991-2006
Denmark	1990-2006
Ecuador	2000-2007
Spain	1990-2006
Estonia	1997, 2000-2005
Finland	1995-2005
France	1995-2005
United Kingdom	1992-2005
Georgia	2006-2008
Greece	2000-2007
Greenland	1992, 2004
Hong Kong	1992
Hungary	1998-2005
Indonesia	2000
India	1993, 1998, 2003, 2006
Ireland	1998, 2000-2002, 2005
Iran	1991, 2001
Israel	1995-2007
Italy	1995-2004
Japan	1990, 1995, 2000, 2005
Kazakhstan	1990

Kenya	2003
Kyrgyzstan	2001
South Korea	1990, 1993, 1995, 1998, 2000, 2005-2007
Kuwait	2000
Lithuania	2000-2004
Luxembourg	1995-2007
Latvia	1996, 1998
Maldives	1997
Mexico	2003
Macedonia	2005
Malta	2000-2001
Mongolia	2005
Mauritius	1997, 2002
Malaysia	1991, 2000
Netherlands	1995-2005
Norway	2001-2006
New Zealand	1995, 2002, 2007
Peru	1994
Philippines	2000
Poland	2000-2004
Portugal	1995-2006
Paraguay	1994
Romania	2000, 2003-2005
Russian Federation	1990, 1995, 2000
Singapore	1990, 1995, 2000
Slovakia	1995-2004
Slovenia	2000-2005
Sweden	1995-2006
Thailand	1990, 1995, 1998, 2000, 2005
Turkey	2002
Taiwan	1991, 1994, 1996, 1999, 2001, 2004
Ukraine	1990, 2003-2008
Uruguay	1997
USA	1992, 1996-2009
Uzbekistan	1990
Venezuela	1997
Viet Nam	1996, 2000, 2007
South Africa	1993, 1998-2000, 2002

Appendix 3: Common 25 ISIC-type classification.

Sector Name	**ISIC Rev.3 correspondence**
Agriculture	1, 2
Fishing	5
Mining and Quarrying	10, 11, 12, 13, 14
Food & Beverages	15, 16
Textiles and Wearing Apparel	17, 18, 19
Wood and Paper	20, 21, 22
Petroleum, Chemical and Non-Metallic Mineral Products	23, 24, 25, 26
Metal Products	27, 28
Electrical and Machinery	29, 30, 31, 32, 33
Transport Equipment	34, 35
Other Manufacturing	36
Recycling	37
Electricity, Gas and Water	40, 41
Construction	45
Maintenance and Repair	50
Wholesale Trade	51
Retail Trade	52
Hotels and Restraurants	55
Transport	60, 61, 62, 63
Post and Telecommunications	64
Financial Intermediation and Business Activities	65, 66, 67, 70, 71, 72, 73, 74
Public Administration	75
Education, Health and Other Services	80, 85, 90, 91, 92, 93
Private Households	95
Others	99