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A flexible adaptation of the WIOD database in a virtual laboratory

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ABSTRACT
The World Input-Output Database provides a time series of world input–output tables (WIOTs) that have been used for example to understand the manifold effects of the increased integration of markets through international trade. In order to enhance the flexibility of research on global trade issues using WIOD, we implement the WIOT workflow in a collaborative, cloud-based virtual laboratory environment. We demonstrate that a lab-based adaptation of WIOD is able (a) to continuously create and update versions of the WIOTs in a timely, consistent, and cost-effective way, (b) to enhance original information with accompanying information on standard deviations, and (c) to enable flexible re-casting of the entire WIOT time series into user-specific geographical and sectoral classifications.

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Multi-region input–output database; virtual laboratories; constrained optimisation

1. Introduction

The World Input-Output Database (WIOD; Timmer et al., 2015) provides an accounting framework that can be used to understand the effects of the increased integration of markets through international trade, such as changes in productivity and income inequality; the fragmentation of production processes; requirements of skills, labour, and resources; and environmental pollution (Dietzenbacher et al., 2013b). The database contains a time series of global inter-country input–output tables (world input–output tables, WIOTs) assembled from national accounts data, harmonised supply–use tables (SUTs), and data on international trade in goods and services (Dietzenbacher et al., 2013a). These are accompanied by satellite accounts on a wide range of environmental and socio-economic indicators. At the time of writing, two versions of WIOD have been released. The initial project, which yielded the WIOD 2013 release was funded between 2009 and 2012 by the European Commission as part of its 7th Framework and was officially launched in Brussels on 16 April

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2012. The second version is the WIOD 2016 release, an update of the former version, which was launched on 8 November 2016.[1]

The first version of WIOD is a time-series WIOTs spanning 1995–2011 (Dietzenbacher et al., 2013a), and the updated WIOD 2016 release covers 2000–2014 (Timmer et al., 2016). The most recent WIOD dataset is constructed following accounting identities governed by the structure of the most recent System of National Accounts (the SNA 2008). The former version WIOD database has been used in a number of high-impact research projects, mainly on global value chains (GVCs) (Johnson, 2014; Koopman et al., 2014; Timmer et al., 2014a; Los et al., 2015), but also on the effect of fragmentation of global production on labour markets and incomes (Timmer et al., 2014b), and on accounting for emissions (López et al., 2014; Kander et al., 2015).

However, 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). Furthermore, flexibility in terms of classifications and country coverage is often desired. These circumstances constitute the motivation for the work described in this paper.

Limited frequency and timeliness of publication of input–output databases due to limited finances and human resources are not a new phenomenon. For example, in Australia, the irregular publication of national input–output tables (IOTs) induced the development of a novel, collaborative approach of the Australian Industrial Ecology Virtual Laboratory ('AusIELab', Lenzen et al., 2014).[2] (see summary by Wiedmann, 2017, in this special issue). The AusIELab breaks with traditional approaches to input–output database construction, because it operates in a collaborative wiki-style cloud-computing environment that enables data pooling, code sharing, and workflow standardisation, permitting (MR)IO compilation to be more frequent and timely and at the same time less time- and labour-intensive.

The aim of the work described in this article is therefore to enable the ongoing construction of the WIOD database in a virtual laboratory environment with a set-up largely similar to the AusIELab. Our specific objectives are (a) to implement a web-based collaborative workflow resulting in an as-close-as-possible replication of the original 2005 base set of WIOTs, and to test this closeness, (b) to equip WIOTs with accompanying information on the standard deviations of their elements, and (c) to enable flexible re-casting of the entire WIOT time series into user-specific geographical and sectoral classifications. Our work is focused on comparing our findings to those of the WIOD 2013 release, since the 2016 release was not available when we started the WIOD-related work in the virtual laboratory.

The rest of our paper is structured as follows. In Section 2, we provide an overview of the WIOD database, explain the infrastructure of the WIOD construction pipeline in the virtual laboratory (in the following abbreviated by WIOD-Lab in contrast to WIOD as in the database), describe our data sources, outline the methods we use in addressing our research goal, and highlight the departures of WIOD-Lab from the WIOD construction procedures. Section 3 shows our results that demonstrate empirically to what extent we have attained our objectives, highlighting both commonalities with, and deviations from the original

[1] See http://www.wiod.org/new_site/database/wiots.htm.

[2] Australian IELab was funded from the National eResearch Collaboration Tools and Resources project (NeCTAR, 2013) and steered by a consortium of seven Australian research institutions.

approach. In Section 4, we provide further discussion of our results and conclude with an outlook for future research.

2. Methods

In this section, we first present a brief overview of the WIOD database and its features, then describe the overall architecture of the WIOD-Lab infrastructure that is capable of updating the WIOD database in a virtual laboratory, followed by an overview of work-flow procedures, construction steps, and reconciliation methods, and rounded up by more detailed explanations of data sources. Most importantly we highlight deviations of our procedures from the original WIOD compilation protocol. Finally, we explain the methodology that we used to compare results from WIOD-Lab to existing WIOD data.

2.1. Overview of the WIOD database

The WIOD database covers 40 countries (all 27 European Union [EU] countries and 13 major economies), plus the rest of the world (RoW) as one representative region. The database gives detailed inter-industry data on national production recipes and international trade of goods and services. All 40 regions are initially represented by a domestic supply–use structure, which is then extended into international supply–use blocks after considering the trade data. It covers 59 products and 35 industries classification following to classification of product by activity (CPA) and NACE rev. 1 classifications, respectively.[3] It spans annual time-series data from 1995 to 2011. WIOD also offers a number of valuation matrices in addition to the basic-price sheet.[4]

The latest version of WIOD expands the country coverage by including three more countries namely Norway, Switzerland, and Croatia and retains the existing countries. The products and industries coverage has been extended to 56 sectors, respectively, and these sectors are following the recent product and industry classification (i.e. CPA2008 and NACE rev. 2). In general, the construction of this latest WIOD version is similar to the construction methodology of the former version; however, some improvements have been undertaken to increase data consistency and to improve the modelling of the parts related to the RoW.

Note that the WIOD database has some distinctive features in that (a) it uses only publicly available and official data, (b) it relies on SUTs rather than IOTs,[5] (c) it is fully benchmarked to frequently revised national accounts statistics as the SUTs are only periodically published by national statistical agencies, (d) it has applied improved allocation of imports of goods that is an alternative estimation method to the standard import proportionality assumption, and (e) the 2013 release is available in current prices and previous year's prices.

The construction process of the WIOTs in the WIOD database has been described in detail by Dietzenbacher et al. (2013a), starting from the data collection to the final output of

[3] See http://ec.europa.eu/eurostat/ramon/ for more information on CPA and NACE classifications.

[4] The valuation matrices in the WIOD database feature the basic price, trade and transport margins, and net taxes.

[5] Due to the idea that the SUTs can be linked consistently to trade, socio-economic and environmental data at product and industry levels. An SUT is also preferred because it allows for secondary production, compared to a symmetrical IOT that assumes that each industry produces only one product class of goods and services.

the WIOT. Some improvements in the methodology of the new WIOD release are covered in Timmer et al. (2016). Figure 1 depicts the WIOD construction pipelines: The national SUTs (NSUTs) and national account statistics form the backbone of WIOD's domestic country blocks. The benchmark SUTs are adapted to national account statistics to ensure their consistency.

Then, the benchmark-year NSUTs are aggregated or disaggregated into the WIOD classification (59 products, 35 industries). The SUT–RAS method is applied to obtain balanced benchmark NSUTs.[6] A time-series construction procedure is used to estimate the non-benchmark-year NSUTs to complete the entire time series. The next step is to apply the SUT–RAS method for a second time to reconcile the estimated tables. The export and import vectors of the NSUTs are then integrated with UN Comtrade international trade data in goods and various data sources regarding trade in services and expanded into a coherent international trade block for each region, to form the international supply and use tables (ISUTs). All regions' ISUTs are then combined to obtain the world supply–use table (WSUT). Finally, the WSUT is transformed into a symmetric WIOT (by applying model D in Eurostat, 2008, Chapter 11).[7]

2.2. WIOD-Lab infrastructure and data processing workflow

The AusIELab's data processing pipeline is built on high-performance computing hardware and the MRIOLab suite (see editorial of this special issue: Geschke and Hadjikakou, 2017) that features the following functional components in a fully automated build pipeline: (a) raw and processed data repositories, (b) a graphical user environment for the preparation of construction runs (see Geschke et al., 2011), (c) a constrained-optimisation matrix reconciliation engine (Lenzen et al., 2009), (d) a visual diagnostics suite (Lenzen et al., 2013), and (e) an analytical toolbox including software for undertaking life-cycle assessments (Heijungs and Suh, 2002; Suh et al., 2004; Suh and Huppes, 2005; Suh and Nakamura, 2007) and various environmental footprints (Foran et al., 2005; Wiedmann, 2009).

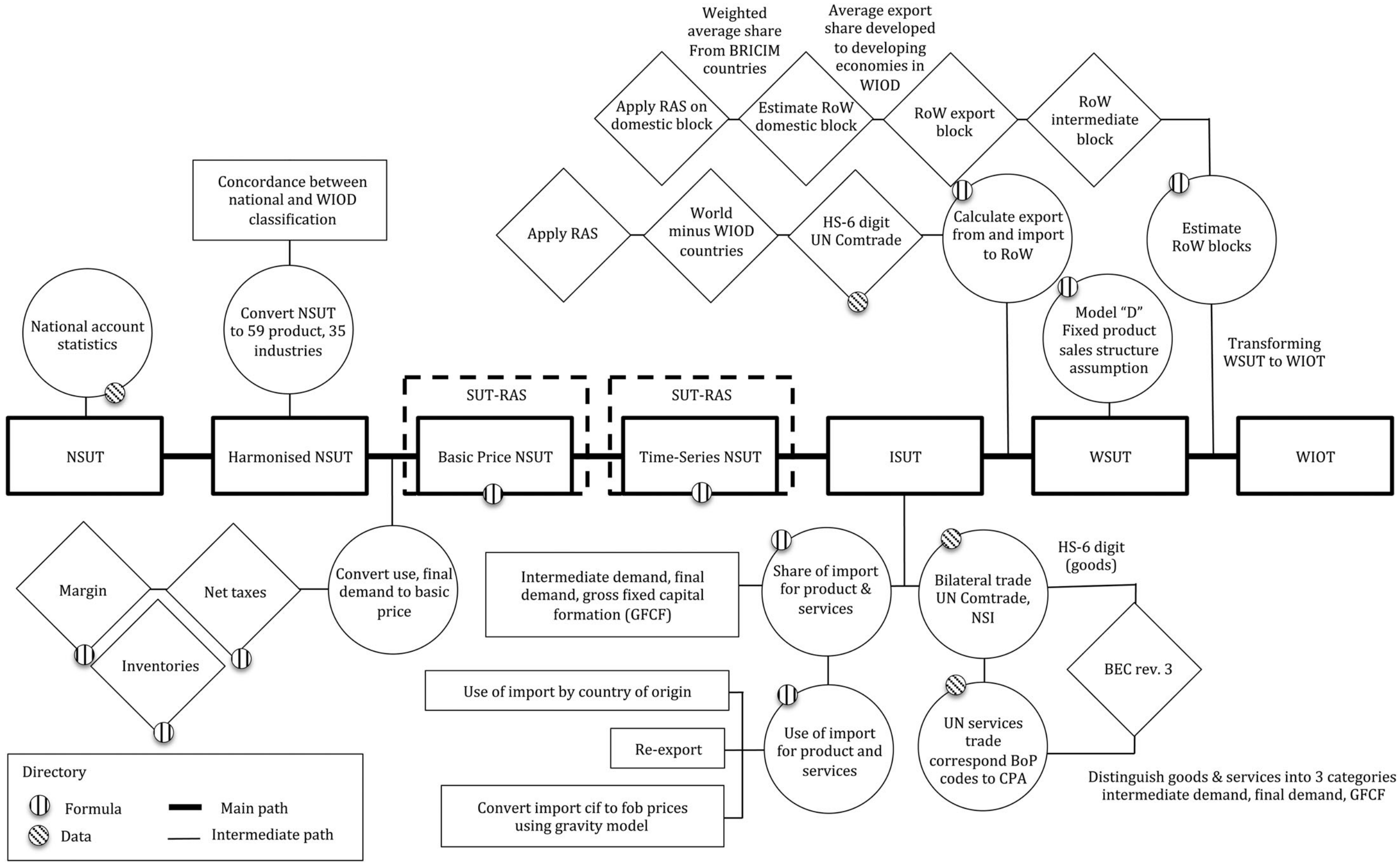
In the AusIELab, a classification feedstock is used (called the 'root', compare with the 'Master' table in Wittwer and Horridge, 2010), standardised workflows, as well as each other's data and code to construct their own individual MRIO versions (called 'base tables') at completely flexible geographical and sectoral delineation, enabling them to be selective in placing detail on regions and sectors that matter most in addressing their particular research questions.

We adopt the data processing concepts of the AusIELab and extend them to a global setting. Figure 2 shows the logical structure and information flows when building databases in the WIOD-Lab. Within the virtual laboratory environment, WIOD's original construction procedures (as briefly described in Section 2.1 and illustrated in Figure 1) are replicated as closely as possible. WIOD-Lab is built on a fully automated computing platform, featuring interconnected algorithms with different unique functions, such as initial estimate data feeds, constraint data feeds, and optimisation routines. In order to fit WIOD into a virtual laboratory, we coded an algorithm that delivers the construction procedures as indicated

[6] See Temurshoev and Timmer (2011) for details of the SUT–RAS procedure.

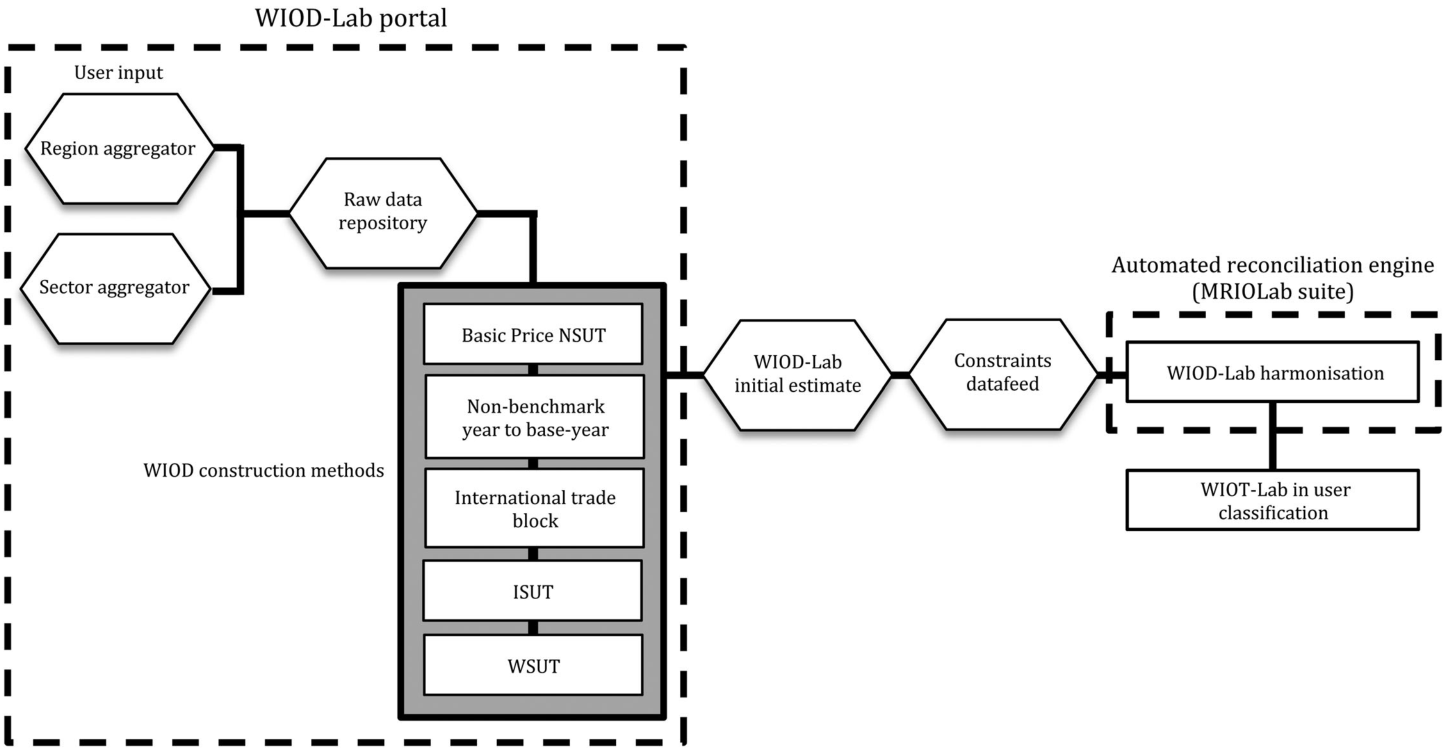
[7] Detailed explanations of the WIOD international trade construction procedure can be found in Sections 4.1–5.3 of Dietzenbacher et al. (2013a).

Figure 1. The WIOD construction pipeline.



Notes: The workflow (left to right) is illustrated based on Dietzenbacher et al. (2013a). Multi-step reconciliation methods are applied to model consistent time-series data sets, which then form the major departure from our work (more discussion in Section 2.4).

Figure 2. WIOD-Lab in the virtual laboratory.



Note: Original WIOD construction procedures were replicated methodically within the virtual laboratory to ensure closest representation of the original database and combined into one routine.

in the grey-shaded box. This code is called the 'WIOD-Lab initial estimate' routine; it is written to incorporate detailed building steps and apply series of formulas and equations, as outlined in the original WIOD guidelines (Dietzenbacher et al., 2013a). This includes basic data harmonisation into user's classification, derivation of basic-price NSUT and valuation sheets, adjusting non-base-year SUT into base-year data by means of the original WIOD time-series estimation procedure, allocating trade data by use category and by country-of-origin to arrive at ISUTs, and estimating the RoW. However, the reconciliation methods (i.e. SUT–RAS) are excluded from this initial estimate algorithm. Thus, the code produces an unbalanced initial estimate MR–SUT base table, which is then, accompanied by the user's set of constraints, passed to the MRIOLab suite for reconciliation. At this point, no more input is required from the users. Finally, a balanced MR–SUT table is produced and saved in a designated repository, and thus ready for further application. Note that the WIOD-Lab produces two outputs: (1) an MR–SUT database and (2) an MRIO database in which the tables are in IOT structure.

In order to operate WIOD-Lab, users are required to complete the following steps:

(1) Define the regional and sectoral aggregation matrices. Each matrix is a binary concordance matrix, which maps the WIOD classification to the root classification. In the WIOD-Lab, the regional root classification features $N_r = 216$ countries included in the UNSNA Main Aggregates database.[8] If the user wanted to aggregate these 216 regions to a smaller number of regions (say M) regions, an $N_r \times M_r$-dimensional binary matrix would need to be constructed.

At the time of writing, the sectoral root classification of the WIOD-Lab is a combination of the HS1996 product classification (UNSD, 2016d) and the CPC version 1.0 services classification (UNSD, 1998), comprising a total of $N_s = 6357$ sectors. As WIOD features a different sectoral resolution for the industry and product classification across all regions, separate sectoral aggregators must be constructed for both classifications in the WIOD-Lab. Concordances for M_p products and M_i industries to root classification (N_s) are then sized $M_p \times N_s$ and $M_i \times N_s$, respectively.

(2) Select the constraint data feeds that the final MR–SUT elements should adhere to. The following data feeds are available in the WIOD-Lab's data feed repository and currently include: National official data from statistical agencies (see Lenzen et al., 2012 supporting information appendix pp. S27–S39), UNSNA Main Aggregates (UNSD, 2016b) and Official Country (UNSD, 2016c) data sets, UN Industrial Commodity Production Statistics (UNSD, 2016d), industrial statistics (UNIDO, 2016), UN Comtrade (UNSD, 2016d), and UN services trade data (UNSD, 2016e).

The communication between users and WIOD-Lab is handled by the MRIOLab suite, which is also used for the Australian IELab, but its functionality is extended to align with the global economic structure, requiring specific background settings, for example, the

[8] The UNSNA database has the most detailed list of countries. Currently there are 215 countries listed in the UNSNA database, but Taiwan is excluded. We gathered data for Taiwan from its national statistical agency. So, if one desires to use specific regions, for example, 40 countries in a base MRIO table for WIOD-Lab, a binary concordance matrix of 40 × 216 must be defined.

definition of the regional and sectoral root classification, and the specification of valuation sheets, in order to work with the WIOD-Lab. The WIOD-Lab database is then built according to the construction method described in the editorial of this special issue (Geschke and Hadjikakou, 2017), as well as in Lenzen et al. (2014) and Geschke et al. (2011).

Due to the design and the level of automation in the virtual laboratory approach, there are aspects of departure from the original WIOD work. In particular, these are (a) the introduction of only one base-year initial estimate, (b) a single-step reconciliation procedure, and (c) regional and sectoral flexibility for the resulting MR–SUT table structure. These aspects will be discussed further in Section 2.4.

2.3. Data sources

In essence, we use the same data sources as in the original WIOD database, and tag these to the root classification using concordance matrices (see Lenzen et al. 2017 regarding the root classification). The role of the root classification is to provide a consistent feedstock against which all input data can be mapped (Lenzen et al., 2014). This fixed reference point ensures that data re-aggregation into flexible user's classifications can be carried out easily. In addition to that, any available supplementary data sources can be easily aligned to main data sources and therefore used as additional constraints.

We now describe the main monetary data that have been used in constructing the WIOD-Lab. They are:

(1) *National data: national accounts, SUTs, IOTs.*

As in the original WIOD project, this information is the starting point of our construction process. However, whilst in WIOD, the NSUTs are converted immediately into WIOD's products and industries classifications, and benchmarked with national account data before optimisation procedure was undertaken, WIOD-Lab corresponds the data to its root classification, and the so-called 'mapping' procedure is performed within the initial estimate routine to re-cast the sectoral classification based on the specifications given by users. National data were obtained from various sources such as Eurostat for EU members and national statistical institutes for most non-EU members.[9]

(2) *International trade data: UN Comtrade, OECD trade data, and UN Services trade data.*

There are more than 5000 products detailed in the UN Comtrade (UNSD, 2016d) and 121 service sectors in the UN Services trade data (UNSD, 2016e). However, all trade information for Taiwan is taken from the OECD database, which already matches to UN Comtrade's HS classification.[10] Following the original WIOD procedure, we use an improved version of the Broad Economic Categories (BEC revision 3, UNSD, 2016a) classification to distinguish three end-use categories (intermediate demand, final demand, and gross fixed capital formation). Then, we calculate the share of imports to split use tables into

[9] Data from Eurostat were taken from its website http://ec.europa.eu/eurostat/web/main/home.
[10] OECD data were retrieved from http://stats.oecd.org.

imported and domestic use tables, and finally split the use of imported products according to the country of origin.

(3) *UN National Accounts Main Aggregate Database (UNSNAMA) and UN Official Country data (UNSNAOC).*

WIOD depends highly on national accounts data such as total exports, total imports, total changes in inventories, total margins, and total net taxes. These data are used to benchmark and balance the SUT estimates so that they are consistent with national official statistics.

2.4. Departures from the original compilation procedures

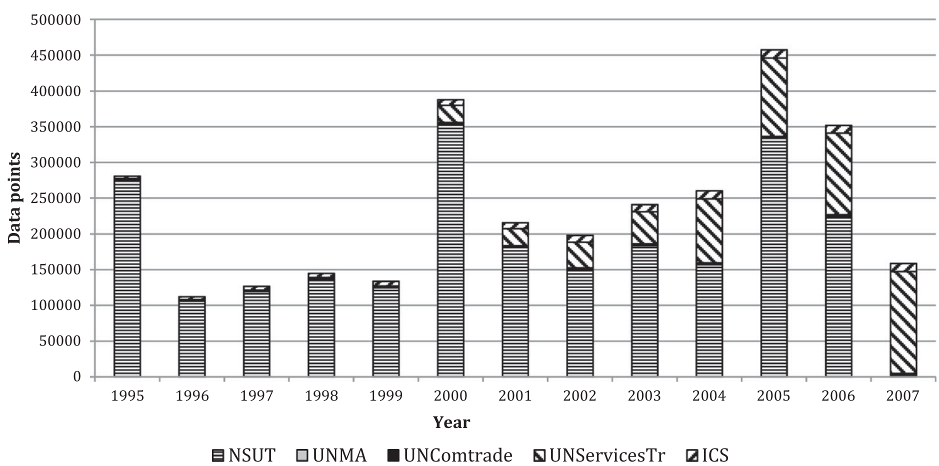
Constructing the WIOD database in a virtual laboratory environment of the WIOD-Lab implies that our work cannot but deviate slightly from the original construction protocols. In this section, we discuss the major departures of our approach from the original WIOD.

2.4.1. Initial estimate

In WIOD, an initial estimate is produced from officially published national SUTs. Since WIOD has time-series data from 1995 to 2011, a large number of SUTs are required to support WIOD for each of these years with data. First, each available SUT needs to be benchmarked to national account statistics. Second, for each intermediate year for which an official NSUT table is not available, a comprehensive methodology has been outlined in order to obtain a complete time series. As a result, in WIOD, each year in the time series has individual initial estimate.

In the WIOD-Lab approach, only one base-year is set for the entire MR–SUT system. The software suite that performs the reconciliation process within the MRIOLab suite requires a fully constructed initial estimate in one year of a time series (Geschke et al., 2014). To meet this requirement (see Figure 3), we chose 2005 as a base-year after

Figure 3. Data counts comparison between years.



Notes: Annual data points are gathered from various domestic and international databases. The initial estimate year for WIOD-Lab (here: 2005) is selected based on the largest quantity of available information.

considering the most detailed and comprehensive data points that are available from national statistics, such as SUTs and IOTs, and international data from the UN National Account Main Aggregates (UNSD, 2016b) and Official Country (UNSD, 2016c) databases, as well as UN Comtrade (UNSD, 2016d) and UN Services trade (UNSD, 2016e). However, in case of countries for which an NSUT is not available for this base-year, we utilised the WIOD time-series procedure to calculate an estimated SUT for the 2005 base-year.[11] For example, India published benchmark SUTs for the years 2003 and 2006, which we then used to arrive at the 2005 base-year table by applying the WIOD time-series method.

The initial estimate is constructed in an SUT structure for all regions including the RoW. Note that domestic transactions of RoW and exports to RoW in SUT forms are not available in the original WIO, where the construction of these two sets of transaction values happen after the conversion of WSUT into WIOT (see Figure 1 and also detailed explanation in Section 5.2 of Dietzenbacher et al., 2013a). In our WIOD-Lab MR–SUT, we adopt the original WIOT RoW domestic deliveries structure (i.e. intermediate demand and final demand) and create an SUT by transforming the WIOT RoW data into WIOD-Lab's RoW use and final demand matrices, and adding a supply table that is generated by allocating detailed product output to source industry.

2.4.2. Reconciliation and table balancing

The data reconciliation is handled through the MRIOLab suite. The workflow employed within AISHA differs from the approach that was employed for the reconciliation and balancing of the original WIOD database. The MRIOLab suite reconciles data in a single reconciliation step. During this step, information from source data sets as well as balancing constraints are considered simultaneously.

Mathematically, the task of reconciling large MR–SUTs can be interpreted as a constrained-optimisation problem. In order to formulate this problem, the initial (unbalanced) MR–SUT $\mathbf{T}_0$ is vectorised into a vector $\mathbf{p}_0$. Constraints can then be imposed by using a coefficients matrix $\mathbf{G}$ to select the MR–SUT elements addressed by the constraint, and a vector $\mathbf{c}$ containing the primary constraint data. The generalised simplified reconciliation problem to obtain the final, balanced MR–SUT $\mathbf{T}$ (vectorised as $\mathbf{p}$) is then given by

$$\min_{\mathbf{p}} f(\mathbf{p}, \mathbf{p}_0, \mathbf{G}, \mathbf{c}, \boldsymbol{\sigma}_{\mathbf{p}_0}, \boldsymbol{\sigma}_{\mathbf{c}}) \quad \text{subject to Gp} = \mathbf{c},$$

where f is an objective function characterising the departure of $\mathbf{p}$ from $\mathbf{p}_0$ relative to standard deviations $\boldsymbol{\sigma}_{\mathbf{p}_0}$ of the initial estimate, and the departure of $\mathbf{Gp}$ from $\mathbf{c}$ relative to standard deviations $\boldsymbol{\sigma}_{\mathbf{c}}$ of the primary constraint data. The constraint optimisation problem is described in detail in Lenzen et al. (2012). In addition to the actual MR–SUT and the constraints imposed on it, WIOD-Lab also considers information about lower and upper bounds for each number in the MR–SUT. The standard deviations used to accompany the primary data listed in Section 2.3 were calculated according to procedures outlined in Lenzen et al. (2010). National data, and UN Main Aggregates value-added data were assigned the highest reliability, whilst international trade data were given lower reliability (compare Figure 2 in Lenzen et al., 2012, see Figure A1). Note that this is only one of many possible settings, and that alternative WIOD-Lab tables can be computed

[11] For a complete WIOD time-series procedure, one can refer to Dietzenbacher et al. (2013a).

under different worldviews of data reliability (compare Section 5.2 in Lenzen et al., 2013). The complete constrained-optimisation problem was solved using the KRAS optimisation algorithm (Lenzen et al., 2009), because unlike other RAS variants it can handle conflicting constraints. Geschke et al. (2011) discuss the reconciliation process used within a virtual laboratory in great detail.

2.4.3. Flexible base table structure

Implementing WIOD in a virtual laboratory does not limit users to define a fixed version of MRIO table. The WIOD-Lab is capable of using its data processing procedures to construct a different base MR–SUT table, depending on the regional and sectoral classification preferred by the user. This modularity requires a certain level of flexibility in the data preparation phase, which was predetermined in the original WIOD data preparation procedures.

2.4.4. Outputs

The MRIOLab suite within the WIOD-Lab system produces a number of visual and analytical outputs, which include the following diagnostic and analytical visualisation options:

(a) Uncertainty information: Within WIOD-Lab, each set of results of the MR–SUT tables is accompanied by a corresponding account of standard deviations. This information on uncertainty is crucial in any input–output analysis application because it enables researchers or policy-makers to understand the limitations and assumptions underlying the data, and thus helps them in undertaking uncertainty calculations for engaging in transparent decision-making (Lenzen et al., 2012).
(b) Heat maps: The values of spatial and sectoral representations of a WIOD-Lab MR–SUT output can be visualised as a heat map. Each cell of the MR–SUT output is represented by a coloured pixel in the heat map and its density is displayed visually. This visualisation of the transaction values helps users to obtain an immediate visual summary of their specific MRIO representation.

2.5. Measuring WIOD's and WIOD-Lab's constraint adherence and a closeness test

2.5.1. Constraint adherence test

As imposed by the optimisation condition $\mathbf{Gp} = \mathbf{c}$, the WIOD-Lab MR–SUT $\mathbf{p}$ has to adhere to primary data $\mathbf{c}$. How well the original WIOD database $\mathbf{p}_0$ and the WIOD-Lab MR–SUT $\mathbf{p}$ adhere to these constraints can be measured by matrix distances (Gallego and Lenzen, 2009; Wiebe and Lenzen, 2016). Given that the KRAS optimisation algorithm (see Equation (23) in Lenzen et al., 2009) used in our work utilises a constraint relaxation technique acting on the absolute difference $|\mathbf{Gp} - \mathbf{c}|$ in multiple steps of width $\boldsymbol{\sigma}_\mathbf{c}$, the most appropriate adherence measure for $\mathbf{p}$ is the mean number of standard deviations $MSD = \sum_i (|\mathbf{Gp} - \mathbf{c}|/\boldsymbol{\sigma}_\mathbf{c})_i/N$, where N is the number of primary data items in $\mathbf{c}$. The original WIOD reconciliation procedure employs the SUT–RAS algorithm (Temurshoev and Timmer, 2011), and so we also evaluate constraint adherence in terms of the RAS information loss, or entropy $RAS = \sum_i |\mathbf{Gp}|_i \ln\left[\,(\mathbf{Gp})_i/\mathbf{c}_i\right]$. Finally, we are interested in the mean absolute differences $MAD = \sum_i (|\mathbf{Gp} - \mathbf{c}|)_i/N$, and mean relative differences

$MRD = \sum_i (|\mathbf{Gp} - \mathbf{c}|/\mathbf{c})_i/N$.[12] However, we are not considering the RoW deliveries (i.e. the domestic intermediate inputs and final demand) in this analysis due to the WIOD-Lab's departures as discussed in Section 2.4.1.

2.5.2. WIOD and WIOD-Lab closeness tests

Apart from testing the constraints adherence, we also perform a comparative evaluation to examine the closeness of the MRIO constructed in WIOD-Lab to the original WIOT. Therefore, we use the WIOT output of the WIOD-Lab to ensure comparability. We compare both databases in two ways: (1) on the closeness of the actual table elements and (2) on the basis of GVC tables derived from both databases (see Timmer et al., 2014a).

The GVC table (see Figure 4) provides information on the extent to which country-industries (like the Mexican transport equipment industry or the British financial services industry) contribute value-added to the production of specific final products (like transport equipment finalised in the US). The GVC accounting scheme is derived from the standard input–output identity: $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly}$, where $\mathbf{x}$ stands for the gross output vector and $\mathbf{y}$ contains final demand. $\mathbf{I}$ denotes the identity matrix, $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ is the input coefficients matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse (of dimensions $MN \times MN$, with M the number of countries and N the number of industries).[13] The worldwide final demand for the outputs of country-industries is computed as $\mathbf{y} = \mathbf{Yu}$, in which $\mathbf{u}$ denotes an MF-summation vector containing ones (F is the number of final demand categories). If we post-multiply the Leontief inverse $\mathbf{L}$ by the diagonal matrix $\hat{\mathbf{y}}$, we obtain an $MN \times MN$ matrix with gross output levels in each of the country-industries in the rows required to produce the final demand for output of each of the country-industries in the columns. Finally, we pre-multiply this matrix by a value-added coefficient vector, $\mathbf{v}(\mathbf{v} = \mathbf{V}\hat{\mathbf{x}}^{-1})$, which yields $\mathbf{V}^* = \hat{\mathbf{v}}\mathbf{L}\hat{\mathbf{y}}$. The elements of $\mathbf{V}^*$ are contained in the GVC table in Figure 4.

For measuring the closeness of matrices, we adopt a cross-entropy (CE) approach introduced by Abd Rahman et al. (2017), who applied the CE approach to comparing IOTs for the year 2011 from five MRIO databases (i.e. WIOD, Eora, EXIOBASE, OECD, and GTAP), after these had been converted to a common industry and country classification. The computational steps are briefly explained in the supplementary material. The method is not only useful to analyse the overall similarity of matrices, but also to identify the levels (broad aggregates, more narrowly defined aggregates, individual cells) at which two MRIOs considered differ from each other, using the decomposability properties of CE measures. If two MRIOs or GVC tables derived from these MRIOs are identical, the CE indicator is zero. The CE indicator is not bounded from above, however. For the purposes of this study, we aggregate the industries in the WIOD-Lab MRIO for 2005 to a common classification (see Table A1), with the purpose of interpreting the differences with reference to the magnitudes of differences observed between MRIOs published by various research consortia (more details can be found in Abd Rahman et al. (2017). Following Abd Rahman et al. (2017), we also use CE values obtained from comparisons between tables in the original WIOT time-series as an indicative measure of matrix distance. If, for example, the CE for the MRIOs for 2005 in the WIOD-Lab and the WIOD database would be larger than the CE

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[12] *MSD*, *RAS*, *MAD*, and *MRD* are equivalent to the *WDIF*, *IGS*, *MAD*, and *AMRD* measures in Table 2 in Wiebe and Lenzen (2016).

[13] A hat indicates a diagonal matrix.

Figure 4. GVC accounting scheme.

<table>
<tr><td colspan="3" rowspan="3"></td><td colspan="7">Final products of a global value chain, identified by country-industry of completion</td><td rowspan="3">Value added</td></tr>
<tr><td colspan="3">Country 1</td><td rowspan="2">…</td><td colspan="3">Country M</td></tr>
<tr><td>Industry 1</td><td>…</td><td>Industry N</td><td>Industry 1</td><td>…</td><td>Industry N</td></tr>
<tr><td rowspan="7">Value added from country-industries participating in global value chains</td><td rowspan="3">Country 1</td><td>Industry 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Industry N</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>…</td><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Country M</td><td>Industry 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Industry N</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Total final output value</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>World GDP</td></tr>
</table>

Notes: A cell in a row represents value-added from a participating country and industry. A column shows GVCs of a final product distinguished by country-industry-of-completion, where all value-added originated. Since all final products are consumed somewhere in the world, expenditure equals output values. Finally, the final row and last column represent the global final expenditure and global value-added, respectively, adding up to equal world GDP. (Source: Timmer et al., 2014a).

obtained by comparing the original WIOD MRIO for 2005 to the original WIOD MRIO for 1995, it could be argued that the WIOD-Lab and original WIOD MRIOs are rather different, in view of the large structural changes the world economy has experienced between 1995 and 2005.

3. Results

In this section, we present the results of a comparative analysis of results from the WIOD-Lab and the original WIOD, with respect to their adherence to constraints data and the closeness of both databases.

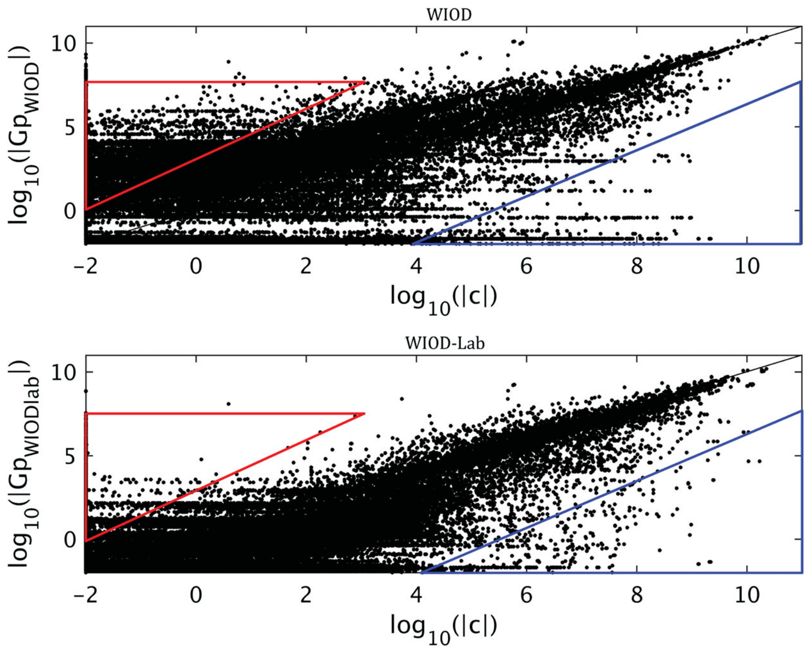
3.1. Results of constraints adherence test

One way to depict constraint adherence without resorting to matrix distance measures is via a rocket plot (Figure 5, compare Figure 4 in Lenzen et al., 2013). A first visual inspection shows indeed that the WIOD-Lab rocket has more data points crowded towards the tip point (left hand side), meaning that large constraint values are realised comparatively well by the WIOD-Lab MR–SUT. Both WIOD and WIOD-Lab show large deviations from small constraints. Following the holistic accuracy concept of Jensen (1980), such small constraint values may be violated without significantly affecting input–output multipliers, which is one of the reasons for us to include not only a closeness assessment of the MRIOs themselves, but also of results (the GVC tables) obtained from these.

It is essential to understand the main causes of the fact that Figure 5 shows that WIOD-Lab tends to adhere better to the constraints than WIOD itself.[14] A first cause of the differences between both panels of Figure 5 relates to the fact that WIOD-Lab constructs

[14] More detailed comparisons, which confirm the findings in Figure 7, can be found in the supplementary material.

Figure 5. Primary constraint data values c versus constraint realisations Gp.



Notes: Ideal constraint adherence would see all points lie on the diagonal. A visual inspection shows that, at least towards the larger constraint values, WIOD-Lab realisations (bottom graph) crowd more towards the diagonal (compare the content in the triangles on right-hand side of both plots). Large variations on the small constraints are expected to cause differences between WIOD-Lab and original WIOD (compare the content in the triangles on left-hand side of both plots).

the MRIO in a single step (see Geschke et al., 2014), while WIOD attains this via a sequence of reconciliation procedures. The step in which the RoW blocks are inserted (see Figure 1) requires an additional matrix-balancing round, which has an impact on the import shares.

It is impossible to quantify the contributions of the potential sources of differences, but most probably the harmonisation processes that precede the WIOD's MRIO construction procedure depicted in Figure 1 is the most important factor. The export figures in National Accounts statistics in the US and China, for example, have been obtained from procedures that treat re-exports in a way that is different from the procedures adopted by Eurostat for the EU-countries. In the WIOD project, publicly available data and reports from various sources have been used to make the national account statistics for the countries involved as comparable as possible, before entering these into the construction procedure (for details, see Erumban et al., 2012). A second example refers to careful improvements made in the BEC-classification, which allows for a better assignment of internationally traded products into sales to other industries, sales to households and sales to meet investment demand. Such harmonisation procedures lead to differences between the values of constraints to which WIOD tries to adhere and the values to which WIOD-Lab tries to adhere. These differences also reflect the main difference in perspectives between the approach of the WIOD consortium and the collaborative virtual laboratory approach. In WIOD, a lot of effort is put into activities to make the data as good as official and publicly available data allow. The major downside of this approach relates to the costs and the timeliness of data. In the collaborative virtual laboratory approach, available data are taken at face value. This reduces the compliance of the MRIOs with Eurostat standards, but these can be constructed at lower cost and can be revised or updated as soon as new data become available.

Given these differences in construction philosophies, it is important to study the empirical magnitudes of the differences between the two tables.

3.2. Closeness test results

3.2.1. WIOD-Lab and original WIOT heat map visualisations

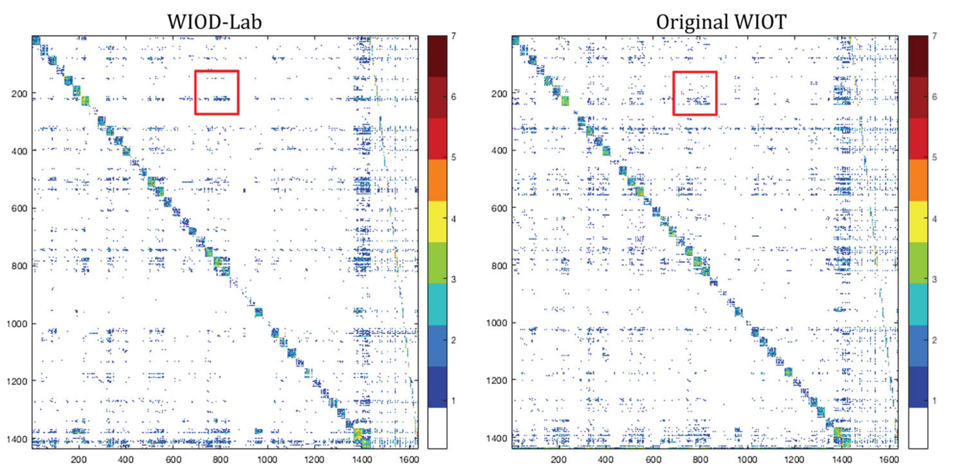
The overall structure of the original WIOD and WIOD-Lab tables can be visualised in a heat map that illustrates every cell of the MRIO (see Figure 6). We find that, at a macro view, both MRIOs' structures are relatively similar. There are no conspicuous differences between the two tables.

In the following we will first describe the results from the closeness test, and then discuss the reasons for deviations.

3.2.2. Comparison of the WIOD-Lab and original WIOT data set

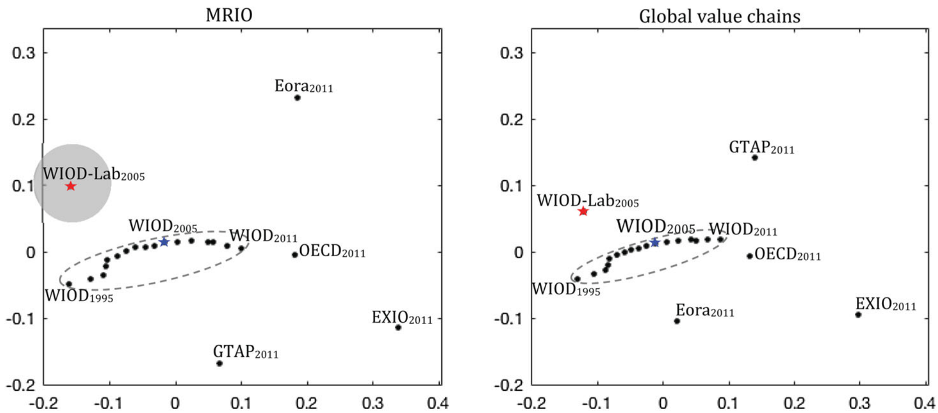
The total CE between WIOD-Lab and original WIOT is 0.18 (Table 1), which is similar to the CE between the original WIOTs for 2001 and 2011. Its magnitude is also comparable to the what we find when the 2011 MRIOs for 2011 in the WIOD and OECD–TiVA databases are compared. The observed difference is smaller than the CE between WIOD's 2011 MRIO and 2011 MRIOs from EXIOBASE, Eora and GTAP, respectively (Figure 7). Given these differences between the two MRIOs, it is important to know whether these mainly

Figure 6. WIOD-Lab and original WIOT heat maps.



Notes: Heat map visualisation of the 2005 WIOT basic-price sheet, for both WIOD-Lab and original WIOT plotted using a $\log_{10}$ (['000USD]) scale. Some structural differences exist in the off-diagonal inter-country transactions of the intermediate demand matrices, for example, exports of China services sectors to Italian manufacturing sectors (see transactions within the squares).

Figure 7. Multidimensional scaling of CE magnitudes.



Notes: The *x*-axis and *y*-axis refer to the coordinates configuration based on pair-wise total cross-entropy levels. The distance between the WIOD-Lab MRIO and the original WIOT 1995–2011 datasets cluster (left, in the dotted-line ellipse) is comparatively similar to the distance of OECD 2011 to those WIOT's tables within the reference cluster. In term of GVC tables, the distance from the WIOD-Lab GVC tables to the WIOT GVC tables for 1995–2011 cluster (right, in the dotted-line ellipse) is also approximately similar to the distance of GVC from OECD 2011 to WIOD's reference tables. More detailed discussions can be found in Abd Rahman et al. (2017).

Table 1. CE of WIOD-Lab and original WIOT data sets.

			T			Y		V
Level of decomposition	Total CE				0.18			
Level 1	Between				0.00			
	Within		0.10			0.07		0.01
		Domestic		Imported	Domestic		Imported	
Level 2	Between		0.00			0.00		
	Within	0.05		0.05	0.04		0.03	
	CAN	0.01		0.00	0.00		0.00	
	CHN	0.01		0.00	0.00		0.00	
	KOR	0.01		0.00	0.01		0.00	
	USA	0.01		0.01	0.01		0.01	
	ROW	0.00		0.01	0.00		0.01	
	Others	0.01		0.03	0.02		0.01	

Notes: The 'Between' term refers to the difference in the sum of all elements of the respective MRIO component. The term indicates how much this sum contributes to the total CE. The 'Within' term reflects the differences only within the defined component. The total CE is equal to the summation of the between and within terms.

stem from differences between the building blocks of which these MRIOs are comprisedor from differences in cells within these components.

In the first decomposition reported in Table 1, we define three components: **T** stands for the intermediate inputs block, **Y** for the final demand block, and **V** for the value-added block (which includes net taxes on products, among other things). The differences in the sums of all elements in **T**, in **Y**, and in **V** – as indicated by the 'between **T**, **Y**, **V**' term – are negligible, which implies that the two MRIOs do not differ much if broad aggregates are considered. Most of the differences (0.10 and 0.07) stem from differences between elements within the **T** and **Y** blocks, whilst the value-added blocks appear to be closer (0.01) to each other.

Table 2. Differences in GVC of WIOD-Lab and original WIOT for year 2005.

Total CE				0.13	
Level of decomposition					
(A). Level 1 – Country of completion			Within		Between
			0.13		0.00
(B) Level 2 – value-added by country		Within		Between	
		0.12		0.01	
(C) Level 3 – value-added by broad sector	Within		Between		
	0.09		0.03		
CHN	0.01				
KOR	0.01				
USA	0.02				
ROW	0.01				
Others	0.04				

Notes: Most of the differences in the GVCs from both MRIOs originated in the differences in each value-added cell of the tables, as represented by the within term. Deeper decomposition has proved that most of the differences are concentrated in some countries, particularly the USA.

At the second level of decomposition, the within-CEs of the **T** and **Y** blocks are decomposed into CEs for the aggregate values of domestic transactions and international transactions (imports) on the one hand, and CEs within these aggregates on the other. The results show that the aggregate values for both types of transactions do not differ much, since the between-CEs are 0 for both **T** and **Y**. Most of the differences are related to MRIO-elements representing domestic transactions rather than imports, in particular for the final demand block. The most sizable differences regarding domestic transactions are found for cells related to value-added generated in South Korea and the USA.

Although the differences are notable, the deviations of the WIOD-Lab data from the original WIOT are element-specific, meaning that they are substantially associated to the differences in every single transaction in the MRIO, while at the aggregate level (as indicated by the between terms), the WIOD-Lab and the original WIOT are quite similar.

3.2.3. Comparison of GVC tables from WIOD-Lab and the original WIOD

In the previous subsection, we measure the extent to which the WIOD-Lab data differ from the original WIOT data set. Another crucial question concerns the consequences of using either of the MRIOs with respect to analytical outcomes. We use the same comparison method as before, using CE metrics.

Our results show that the GVC outcomes obtained from WIOD-Lab differ from those obtained using original WIOT by a total CE of 0.13, which is similar to the differences measured when comparing the GVC tables obtained from the original WIOT for 2011 with that of 2002 (see Table 2). As when comparing the differences between the MRIOs themselves, we also use the decomposable nature of CE measures to examine whether the results vary for larger aggregates or only at the level of individual elements of the GVC tables.

The results for the first decomposition level as reported in Table 2 present evidence on the extent to which value-added contributed by all country-industries taken together ends up in GVCs with the same country-of-completion.[15] The results show that the between-term is close to zero, but that most of the differences can be attributed to differences within

[15] In terms of the set-up of the GVC table in Figure 4, this is equivalent to asking the question whether the sums over the columns sums for industry 1 till industry *N* computed for each of the countries in the columns are similar or not.

these components. This implies that questions like ‘to what extent is world GDP due to demand for final products of Country A?’ can be answered about equally well using WIOD-Lab and WIOD, at least in 2005.

In the results for the second level, we focus on differences in the value-added contributions of countries (aggregated over industries) to GVCs with a particular country-of-completion. These are relevant for answering questions like ‘how much of the value of Country A’s final products consists of value-added contributed by activities in Country B?’. Again, there are some differences (the between-term has a value of 0.01), as a consequence of which answers to such questions based on WIOD-Lab and WIOD will generally be slightly different, but the clearly largest part is due to differences between individual values within these aggregates.

The third decomposition level addresses the question to which extent value-added contributed by broad sectors (within countries) to GVCs with a given country-of-completion vary between the two GVC tables. This information is needed if one would like to know which percentage of Country B’s value-added contributions to Country A’s GVCs is contributed by, for example, the Primary industries sector.[16] Table 2 shows that about 60% of the total differences (as measured by total CE) are in cells within these aggregates, suggesting that the choice of database will generally not have a large impact on answers to the types of questions presented so far. Only if questions related to specific industries are central to the analysis, the differences between the two underlying MRIOs will yield sizable differences between the two answers.

We find that the differences between WIOD-Lab’s GVC table and the GVC table based on the original WIOT are highly concentrated in the participation in GVCs of industries by industries in four countries, that is, China, Korea, the USA, and the RoW region. For Korea, for example, large differences are observed in the value-added contributions of industries within the domestic manufacturing sector (see Table A2). A similar observation can be made for industries in the domestic manufacturing and services sectors for the USA.

Undoubtedly, differences in the datasets should also cause variations in the obtained outcomes. Still, we find that the largest differences are not associated with a large number of countries but they emerged in a limited number of (generally) major countries and from limited sectors. Hence, answers to many (but definitely not all) research questions with respect to value-added generation will be roughly similar.

3.2.4. Visualisation of distance metrics using multidimensional scaling

Multidimensional scaling has been widely used in various studies, such as in the area of marketing (see e.g. Fenton and Pearce, 1988; Bijmolt and Wedel, 1999; Gimeno and Vila, 2007), to visualise (dis)similarity information within a defined set of distance metric elements (in our case, the CE magnitudes) in such a way that the relationship among the elements can be mapped in a spatial representation. Figure 7 shows the distance of WIOD-Lab to that of original WIOT cluster, combined with findings by Abd Rahman et al. (2017).

[16] We grouped the industries in the GVC table to four main broad sectors: Primary industries, Manufacturing, Construction and Utilities, and Services. See supplementary material for sectoral details.

3.2.5. CE uncertainty calculation based on WIOD-Lab standard deviation account

We conduct a Monte-Carlo simulation to calculate the uncertainty of the CE between WIOD-Lab and original WIOT. Referring to the CE estimation formula in the supplementary material, the simulation generates perturbed MRIO variants $P^*_{ij} = P_{ij} + (R_{ij}.\sigma^P_{ij})$, where R_{ij} is a normally distributed random variable with $\sigma^R_{ij} = 1$, and σ^P_{ij} is the element-specific standard deviation information determined during the WIOD-Lab reconciliation. Each perturbation P^*_{ij} yields a perturbed CE value, called CE*. We carry out 1000 Monte Carlo simulations and obtain the standard deviation for the CE between WIOD-Lab and original WIOT from the shape of the distribution of the CE* values. The result is shown in Figure 7 where the standard deviation of 0.057, which obtained from the simulation, is drawn as the radius of the circle around the WIOD-Lab MRIO point. This result shows that the WIOD-Lab MRIO is significantly different from the original WIOT at the 3-sigma (99%) level of confidence. This is due to the circumstances described in the previous section. Whether similar results also apply to OECD, GTAP, and EXIOBASE is not possible to verify since these MRIO databases do not feature uncertainty information. However, given the different construction principles, such significant differences are to be expected.

4. Discussion and conclusions

The purpose of this paper is to construct and update the WIOD database in a collaborative virtual laboratory, the so-called 'WIOD-Lab'. This project aims at complementing a labour-intensive, costly assembly approach with a collaborative, cost-effective, and timely MRIO database construction approach. We replicate the WIOD database construction pipelines as-close-as possible to ensure proximity to the original work in a customisable routine. Then, the routine undergoes a fully automated constrained-optimisation reconciliation engine within the AusIELab before it is ready for further usage.

To support our technical work, we have compared the WIOD-Lab's output for 2005 with that of the original WIOD for the same year. The comparison analyses have led us to conclude that there are some significant differences between the WIOD-Lab and the original WIOT. Two likely causes of these differences have been highlighted. First, the construction methodologies are very similar, with one major exception. Whereas the MRIOs in WIOD are constructed in a stepwise approach (in which conflicts between data from multiple sources are solved, before new source data are added in a next step), WIOD-Lab addresses all data conflicts in a single step. The other cause of differences reflects the major difference in the construction philosophies highlighted above. Before WIOD's construction procedure starts, a lot of effort is put into harmonising data from various sources and countries, to ensure maximum comparability of the data. WIOD-Lab aims at producing similar results in a much less labour-intensive and therefore cheaper and quicker way, allowing for as much flexibility regarding industry and geographical resolutions.

Our empirical comparisons between MRIOs for 2005 of both databases and analytical results based on these show that differences remain largely limited to individual cells in the MRIOs themselves and to analytical results related to specific industries in specific countries. As long as research questions relate to broader sets of industries or even aggregate countries, the differences are rather small. Given these results, we think that the choice for either one of the two databases should depend strongly on the analytical views and preferences of the user.

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References

Abd Rahman, M.D., B. Los, A. Geschke, Y. Xiao, K. Kanemoto, and M. Lenzen (2017) A Flexible Adaptation of the WIOD database in a Virtual Laboratory. *Economic Systems Research*, 29, 187–208.

Bijmolt, T.H.A. and M. Wedel (1999) A Comparison of Multidimensional Scaling Methods for Perceptual Mapping. *Journal of Marketing Research*, 36, 277–285.

Dietzenbacher, E., B. Los, R. Stehrer, M. Timmer, and G. de Vries (2013a) The Construction of World Input–Output Tables in the WIOD Project. *Economic Systems Research*, 25, 71–98.

Dietzenbacher, E., B. Los, and M.P. Timmer (2013b) The World Input–Output Tables in the WIOD Database. In: J. Murray and M. Lenzen (eds.), *The Sustainability Practitioner's Guide to Multi-regional Input–Output Analysis*. Urbana-ChampaignIL, Common Ground, 45–53.

Erumban, A.A., R. Gouma, G. de Vries, K. de Vries, and M. Timmer (2012) "Sources for National Supply and Use Table Input Files." http://www.wiod.org/publications/source_docs/SUT_Input_Sources.pdf.

Eurostat. (2008) *Eurostat Manual of Supply, Use and Input–Output Tables*. Luxembourg, Eurostat.

Fenton, M. and P. Pearce (1988) Multidimensional Scaling and Tourism Research. *Annals of Tourism Research*, 15, 236–254.

Foran, B., M. Lenzen, C. Dey, and M. Bilek (2005) Integrating Sustainable Chain Management with Triple Bottom Line Accounting. *Ecological Economics*, 52, 143–157.

Gallego, B. and M. Lenzen (2009) Estimating Generalized Regional Input–Output Systems: A Case Study of Australia. In: M. Ruth and B. Davidsdottir (eds.) *The Dynamic of Regions and Networks in Industrial Ecosystems*. Cheltenham, Edward Elgar, 55–88.

Geschke and Hadjikakou (2017) Virtual Laboratories and MRIO Analysis – An Introduction. *Economic Systems Research*, 29, 143–157.

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, Alexandria VA.

Geschke, A., R. Wood, K. Kanemoto, M. Lenzen, and D. Moran (2014) Investigating Alternative Approaches to Harmonise Multi-regional Input–Output Data. *Economic Systems Research*, 26, 354–385.

Gimeno, C. and N. Vila (2007) Competitive Group Analysis of Public Transport Services. *Journal of Travel & Tourism Marketing*, 21, 13–29.

Heijungs, R. and S. Suh (2002) *The Computational Structure of Life Cycle Assessment*. Dordrecht, Springer.

Jensen, R.C. (1980) The Concept of Accuracy in Regional Input–Output Models. *International Regional Science Review*, 5, 139–154.

Johnson, R.C. (2014) Five Facts about Value-added Exports and Implications for Macroeconomics and Trade Research. *Journal of Economic Perspectives*, 28, 119–142.

Kander, A., M. Jiborn, D. Moran, and T. Wiedmann (2015) National Greenhouse-gas Accounting for Effective Climate Policy on International Trade. *Nature Climate Change*, 5, 431–435.

Koopman, R., Z. Wang, and S.-J. Wei (2014) Tracing Value-added and Double Counting in Gross Exports. *American Economic Review*, 104, 459–494.

Lenzen, M., B. Gallego, and R. Wood (2009) Matrix Balancing Under Conflicting Information. *Economic Systems Research*, 21, 23–44.

Lenzen, M., R. Wood, and T. Wiedmann (2010) Uncertainty Analysis for Multi-region Input–Output Models – A Case Study of the UK's Carbon Footprint. *Economic Systems Research*, 22, 43–63.

Lenzen, M., K. Kanemoto, D. Moran, and A. Geschke (2012) Mapping the Structure of the World Economy. *Environmental Science and Technology*, 46, 8374–8381.

Lenzen, M., D. Moran, K. Kanemoto, and A. Geschke (2013) Building Eora: A Global Multi-region Input–Output Database at High Country and Sector Resolution. *Economic Systems Research*, 25, 20–49.

Lenzen, M., A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, P. Daniels, C. Dey, J. Fry, M. Hadjikakou, S. Kenway, A. Malik, D. Moran, J. Murray, S. Nettleton, L. Poruschi, C. Reynolds, H. Rowley, J. Ugon, D. Webb, and J. West (2014) Compiling and Using Input–Output Frameworks Through Collaborative Virtual Laboratories. *Science of the Total Environment*, 485–486, 241–251.

Lenzen et al. (2017) The Global MRIO Lab – Charting the World Economy. *Economic Systems Research*, 29, 158–186.

López, L.A., M.Á. Cadarso, J.E. Zafrilla, and G. Arce (2014) Assessing the Implications on Air Pollution of an Alternative Control-based Criterion. *Proceedings of the National Academy of Sciences USA*, 111, E2630.

Los, B., M. Timmer, and G. de Vries (2015) How Global are Global Value Chains? A New Approach to Measure International Fragmentation. *Journal of Regional Science*, 55, 66–92.

NeCTAR. (2013) The Industrial Ecology Virtual Laboratory (Report No. http://nectar.org.au/industrial-ecology-virtual-laboratory). Melbourne, Australia.

Suh, S. and G. Huppes (2005) Methods for Life Cycle Inventory of a Product. *Journal of Cleaner Production*, 13, 687–697.

Suh, S. and S. Nakamura (2007) Five Years in the Area of Input–Output and Hybrid LCA. *The International Journal of Life Cycle Assessment*, 12, 351–352.

Suh, S., M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, J. Munksgaard, and G. Norris (2004) System Boundary Selection in Life-cycle Inventories Using Hybrid Approaches. *Environmental Science and Technology*, 38, 657–664.

Temurshoev, U. and M. Timmer (2011) Joint Estimation of Supply and Use Tables. *Papers in Regional Science*, 90, 863–882.

Timmer, M., A.A. Erumban, B. Los, R. Stehrer, and G. de Vries (2014a) Slicing Up Global Value Chains. *Journal of Economic Perspectives*, 28, 99–118.

Timmer, M., B. Los, R. Stehrer, and G. de Vries (2014b) Fragmentation, Incomes and Jobs: An Analysis of European Competitiveness. *Economic Policy*, 28, 613–661.

Timmer, M., E. Dietzenbacher, B. Los, R. Stehrer, and G. de Vries (2015) An Illustrated User Guide to the World Input–Output Database: The Case of Global Automotive Production. *Review of International Economics*, 23, 575–605.
Timmer, M., B. Los, R. Stehrer, and G. de Vries (2016) *An Anatomy of the Global Trade Slowdown Based on the WIOD 2016 Release*. GGDC Research Memorandum 162. Groningen, University of Groningen.
UNIDO. (2016) Industrial Statistics Database at the 4-digit level of ISIC (INDSTAT4) (Report No. http://www.unido.org/resources/statistics/statistical-databases.html). New York NY.
UNSD. (1998) *Central Product Classification (CPC) Version 1.0*. New YorkNY, United Nations Statistics Division.
UNSD. (2016a) *Classification by Broad Economic Categories Revision 3*. New YorkNY, United Nations Statistics Divison.
UNSD. (2016b) National Accounts Main Aggregates Database (Report No. http://unstats.un.org/unsd/snaama/Introduction.asp). New York NY.
UNSD. (2016c) National Accounts Official Data (Report No. http://data.un.org/Browse.aspx?d = SNA). New York NY.
UNSD. (2016d) UN comtrade – United Nations Commodity Trade Statistics Database (Report No. http://comtrade.un.org/). New York NY.
UNSD. (2016e) UN Service Trade Database (Report No. http://unstats.un.org/unsd/servicetrade/). New York NY.
Wiebe, K.S. and M. Lenzen (2016) To RAS or Not to RAS? What is the Difference in Outcomes in Multi-regional Input–Output Models? *Economic Systems Research*, 28, 383–402.
Wiedmann, T. (2009) Editorial: Carbon Footprint and Input–Output Analysis: An Introduction. *Economic Systems Research*, 21, 175–186.
Wiedmann, T. (2017) An Input–Output Virtual Laboratory in Practice – Survey of Uptake, Usage and Applications of the First Operational IELab. *Economic Systems Research*, 29, 296–312.
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. *Ecological Economics*, 70, 1937–1945.
Wittwer, G. and M. Horridge (2010) Bringing Regional Detail to a CGE Model Using Census Data. *Spatial Economic Analysis*, 5, 229–255.