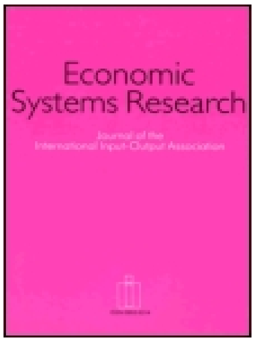

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HARMONISING NATIONAL INPUT–OUTPUT TABLES FOR CONSUMPTION-BASED ACCOUNTING – EXPERIENCES FROM EXIOPOL

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Environmentally extended, multi-regional, input–output (MRIO) databases have emerged to fulfil the need for mapping the impacts of globalisation, following resource-intensive supply chains crossing country borders. EXIOBASE is one such data set designed for use in analysis relevant to resource use and European Union policy. It provides the most detailed harmonised sector classification in any MRIO and integrates data from a wide range of sources. We review the necessary steps in order to harmonise source data in MRIO databases, and describe methods to increase the product and industry detail of aggregate supply and use tables (SUTs) in order to provide a homogenous classification across countries that allows resource-specific modelling. We cover mathematical programming approaches used to reconcile data sets, and investigate some implications of reverse engineering symmetric input–output tables and disaggregating the SUTs. We focus particularly on the footprint multiplier at the product level, where policy formation is targeted.

Keywords: Supply Use Tables; Multi-regional input–output analysis

1. INTRODUCTION

Multi-regional input–output (MRIO) analysis has come a long way in the last decade (Tukker and Dietzenbacher, 2013). Whilst MRIO at the global scale started with tentative estimates in the early 2000s (Munksgaard and Pedersen, 2001; Lenzen et al., 2004), the use of it for addressing issues of carbon leakage related to limiting greenhouse gas emissions (Peters, 2008; Hertwich and Peters, 2009; Minx et al., 2009; Davis and Caldeira, 2010) has advanced development significantly. Now, a considerable number of studies of environmental issues congruent with 'footprint' approaches use MRIO analysis in order to fully account for life-cycle impacts of consumption (Wood et al., 2009; Daniels et al., 2011; Wiedmann et al., 2011; Lenzen et al., 2013; Wiedmann and Barrett, 2013).

EXIOPOL was an EU-funded project which had a goal of creating a transparent, harmonised, environmentally extended, global, MRIO database for use in analysis relevant to EU policy. The EXIOPOL database, known as EXIOBASE, focuses on regional detail for 27 EU member states as well as 16 non-EU countries.[1] Each country's economy is

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[1] Non-EU countries included in EXIOBASE are: USA, Japan, China, Canada, South Korea, Brazil, India, Mexico, Russia, Australia, Switzerland, Turkey, Taiwan, Norway, Indonesia, and South Africa, as well as a residual 'Rest of the World'.

represented by 129 industrial/product sectors as well as nine subcategories of value added and five categories of final demand. In addition, the database contains environmental extensions consisting of 16 agricultural products; 7 forestry, fishing and cattle products; 9 metal categories; 9 non-metallic minerals; 6 fossil fuels; 59 energy product categories; as well as 28 pollutants released to air, 3 to water, and 8 to soil. The 16 non-EU countries included in EXIOBASE were selected on the basis of contribution to global GDP, trade with the EU and the amount of pollution embodied in trade. Together, the 16 selected RoW countries cover 92% of non-EU global GDP and over 80% of trade with the EU (Tukker et al., 2009). Trade with and economic activity of all other RoW countries is modelled as 'true Rest of the World' to make the inter-industry portion of the model a closed system.

Tukker et al. (2013) present the general construction of EXIOBASE and external costs, environmental emissions, and resource requirements associated with the EU's final consumption, with focus on those parts mediated through international trade. In this paper, we focus on methods for the construction of the supply and use table (SUT), including the disaggregation and harmonisation of sector detail; estimation of margin and tax layers, and analyse the impact on information-gain of product-level indicators achieved by this disaggregation. We focus on methods generic to MRIO construction, and refer the reader to detailed documentation (Wood et al., 2010) for specific methods of adjustment unique to EXIOBASE. Here, we address the key topics in MRIO development, and provide insights into methods to address these issues.

Since input–output (IO) data come from a variety of sources, a number of issues need to be addressed in order to harmonise the economic data into a consistent detailed database for any MRIO. While most European countries publish SUTs in accordance with the System of National Accounts (SNA) and the Eurostat standard, other countries publish only input–output tables or SUTs following different standards. Furthermore, EXIOBASE includes estimates of individual pricing layers to make the step from modelling in basic prices to the purchasers' prices paid by consumers, and converts to a standardised detailed classification across all countries.

Other MRIO projects, for example, Eora or Global Trade Analysis Project (GTAP), have different approaches to deal with some of these issues. For example, GTAP works directly in symmetric input–output tables (SIOTs) format – effectively limiting the use of the database for analysis at the supply/use level, and embodying modelling assumptions in the database work (Narayanan et al., 2012). Similarly, Eora works in native classification of individual countries, and in the native form of the input–output data – whether it be SUT or SIOT for individual countries (Lenzen et al., 2013). This is a novel approach to harmonise classifications only in the trade block rather than the domestic block, whilst implicitly implying technology assumptions in the multi-regional SUT (MRSUT) format of Eora. WIOD (Timmer, 2012; Dietzenbacher et al., 2013) provides perhaps the most similar approach to constructing an MRIO as EXIOBASE, but without the product-level detail as the other models.

The high level of detail in EXIOBASE required disaggregation of the MSUTs and allowed linking of detailed environmental stressors to a more detailed product/industry classification such that impacts of consumed, and more importantly, traded, products could be analysed discretely. Such an approach brings in both concepts and data from the field of life-cycle assessment (LCA), allowing differences in upstream impacts of, for example, bauxite and iron ore to be modelled separately. The approach explored here includes incorporating specific input coefficients and sales coefficients with estimates of industry and product output. The detailed classification allows tracing of detailed resource extractions (such as fodder crops) through specific supply chains (cattle farming, meat production), thus mitigating aggregation error in the use of the database. Adding this precision should increase the accuracy of the model, as described in Lenzen (2011). Disaggregation necessitates applying assumptions or reconciling data, or both – and there is a possibility that accuracy actually decreases through disaggregation. Whilst a 'true' state is never known, we can test for hypothetical accuracy of different levels of aggregation (Section 5). Furthermore, the disaggregation of EXIOBASE broadly matches the detail included in the environmental extensions – such that rather than aggregating away information on individual environmental stressors, these can be mapped uniquely in the classification schema. Whilst some environmental stressors may also need to be disaggregated (e.g. energy use or greenhouse gas emissions) – the majority of major flows (e.g. emissions in steel production) can have extensions mapped directly to a disaggregated classification, and minor emission flows (e.g. direct emissions from the services sector) are disaggregated according to auxiliary data.

We list the summary of major issues to be dealt with in producing MRIO tables (Box 1).

Box 1. Major considerations in harmonisation in MRIO

Data harmonisation in MRIO – summary of issues:

- estimation of SUTs from SIOT (as required);
- estimation and harmonisation of margin and tax layers;
- estimation of basic price use table;
- split of domestic and imports from basic price table.
- classification of products industries (aggregation and disaggregation); and
- correction of inconsistent data.

We can broadly categorise all harmonisation steps needed for EXIOBASE in two parts:

(1) Transformations to complete an aggregate, disconnected database (pricing layers, table availability), including harmonising the tables into a common currency and base year (Section 2).
(2) Transformations to harmonise to a common classification and detail (disaggregate) environmentally important sectors (Section 3).

Analysis of impacts of these methodological choices follows (Section 4) before conclusions are made (Section 5).

2. METHOD PART (1) SUTS IN ORIGINAL AGGREGATION

2.1. MRSUT Structure

In EXIOBASE, SUTs are used according to Eurostat's ESA95 accounting format (Tables 1 and 2). In addition, we include margin and tax layers – in order to maintain balances for the

TABLE 1. Supply table.

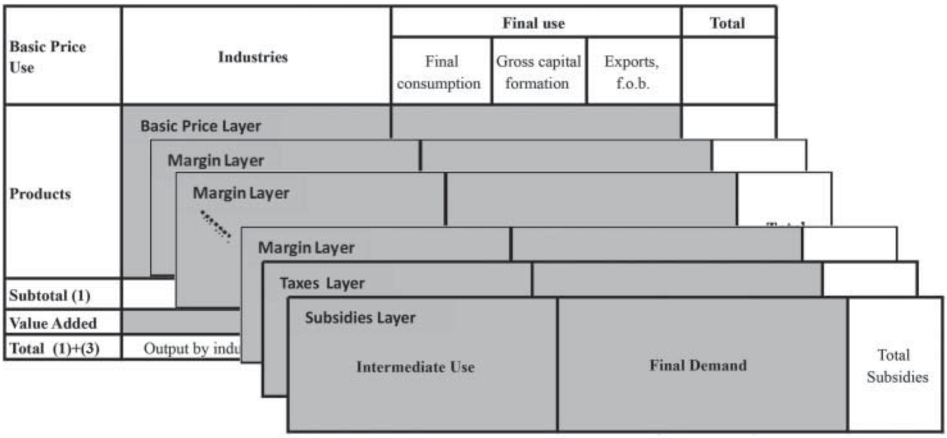
	Industries	Imports (c.i.f)	Total	Valuation	Total
Products	**Production matrix:** Output by products and industries	**Imports** broken down by products	Supply of products at basic prices	**Valuation adjustment items by product**: + Taxes less subsidies on products +Trade and transport margins	Supply at purchasers' prices
Total	**Output by industry at basic prices**	Total Imports	Total supply at basic prices		**Total supply**

TABLE 2. Use table in purchaser prices.

	Industries	Final use			Total
		Final consumption	Gross capital formation	Exports, f.o.b.	
Products	**Intermediate consumption at purchaser's prices by product and industry**	**By house-holds, NPISH, government**	**Gross fixed capital formation and changes in inventories**	**Intra- and extra EU**	Use at purchasers' prices
Subtotal (1)	Total intermediate consumption by industry	Total final use by type			**Total use**
Compensation of employees Other net taxes on production Consumption of fixed capital Operating surplus, net	**Components of value added by industry**				
Subtotal (3)	Value added				
Total (1)+(3)	**Output by industry at basic prices**				

15 individual margin products in EXIOBASE, and to facilitate converting expenditure data from purchaser to basic prices, each margin was modelled as an individual layer (including, in aggregate, wholesale and retail trade, transport) and taxes, and subsidies (Table 3, and supplementary information, Appendix A). The orientations of both the SUTs are products by industries. Using SUTs as a basis for building up an IO framework accommodates both linkages of environmental extensions (to industries) and final demand (to products). SIOTs are either product-by-product or industry-by-industry orientated. Starting with an

TABLE 3. Use table showing pricing layers.



SUT framework therefore creates the flexibility for end users to choose their own assumptions (Kop Jansen and ten Raa, 1990; Londero, 1999; Almon, 2000; Scherer, 2003; ten Raa and Rueda-Cantuche, 2003; ten Raa and Rueda-Cantuche, 2007; Majeau-Bettez et al., 2014).

There are several caveats using SUTs as basic building blocks for the IO database. Usually, the supply table is published in basic prices, and the use table in purchasers' prices. In order to produce an SIOT, both tables need to be in the same valuation. For this reason, valuation matrices giving taxes less subsidies and trade- and transport margins are needed to convert the use table from purchasers' prices into basic prices.

Using SUTs as starting point for the creation of EXIOBASE implies that different transformations of the basic tables are needed, dependent on the way National Statistical Institutes (NSIs) publish their tables.

2.2. Obtaining SUT in Basic Prices and Price Layers from Purchaser Price Tables

Ideally, all NSIs would publish SUTs in basic prices, distinguishing domestic from imported products, which could then be incorporated in a standardised database by only bridging between sector classifications. However, many EU countries provide a supply table in basic prices, a use table in purchasers' prices, as well as SIOTs in basic prices for imports and domestic products to the European Statistical Agency (Eurostat) in a standardised 59-sector format. Rueda-Cantuche et al. (2007) and EUROSTAT (2008) laid the groundwork for the creation of harmonised tables, distinguishing imports and exports based on the Eurostat ESA 95 data set. The options for estimating harmonised, basic price SUTs are ultimately limited by the data provided by Eurostat and national statistics. The options we considered in this work include the following:

(1) The simplest option to go from an SUT in purchaser prices is to use the structure of imports and the shares of trade and transport margins and taxes less subsidies from another similar country to estimate those of the country of interest. Benefits of this option are that it will always produce a reasonable table and that it is reasonably simple to implement.

Drawbacks are that trade and transport margins as well as taxes less subsidies may vary widely across countries, and the countries for which we have information may not be similar to the country of interest.[2]

(2) A second option for estimating basic price tables in cases where a supply table (in basic prices) is provided is to reverse engineer the use table from the SIOT (Rueda-Cantuche et al., 2007; EUROSTAT, 2008). Additionally, where SIOTs for domestic and imported products are provided separately, they could be reverse engineered separately. Reverse engineering requires solving the equation used to determine the SIOT for the use table.

The basic method for estimating the basic price use table is to use the product-technology assumption to reverse engineer from product-by-product SIOTs and the fixed industry sales structure to reverse engineer from industry-by-industry SIOTs. The drawback of this method is that the use table produced is not necessarily reflective of the actual use table used by the NSI to create the SIOT. This method is desirable because it is simple, allows the user to reproduce the original table by calculating the table using the appropriate simple technology assumption, and it never creates negative values in the use table where they do not already exist in the SIOT. In addition, this method incorporates the additional information provided by the SIOT for imports in the use table for imports. We implemented this method to reverse engineer basic price use tables using data provided by Eurostat and national statistical offices and performed two tests to validate the results.

The first test we performed was to reverse engineer basic price use tables for Belgium, Denmark, and Finland, the only three countries for which basic price supply and use and SIOT were available via Eurostat. This allowed us to compare the results of reverse engineering to the original basic price use table. We found that for the simplest technology assumptions, product-based technology or fixed industry/product sales structure, the reverse-engineered basic price use tables differed significantly from those provided to Eurostat. Structural differences were most problematic where basic price estimates corresponded to zero purchaser price or vice versa.

A second test we performed on reverse-engineered data was on the analysis of implicit tax rates from the reverse engineering process. Whilst for many products, it is impossible to directly distinguish between the various margin mark ups and the taxes being applied, for services, there are usually no applicable margins so that the difference between the basic price and purchaser price values can be fully attributed to taxes less subsidies. The results were less than ideal – see supplementary information, Appendix D for some examples of implied tax rates. From the estimated results, it was clear that there was a major

[2] In the case of transportation, Denmark, Belgium, and Finland each have their own particularities. Denmark consists of many islands which complicates transportation logistics and is expected to increase costs. Belgium is relatively densely populated and centrally located within Europe which suggests that shipping costs may be comparatively low. Finland is sparsely populated and not centrally located which suggests that more shipping would be done by truck and at a higher cost. In the case of taxes and subsidies, it is also difficult to determine similarities between countries. For example, while Denmark and Finland might be considered to share similar tax and subsidy policy with other Scandinavian countries such as Norway and Sweden, consistency between government policy and the resulting incentives is in no way guaranteed. Once again as a small country, it is difficult to determine the generalisability of Belgium's taxes and subsidies. As many of their products are imported, information about taxes and subsidies for these industries is not present. Finally, the estimation of the use table in basic prices in this way does not allow for the recalculation of the SIOT that matches the original provided by Eurostat or the NSI.

discrepancy between the reverse-engineered basic price table and the published purchaser price table.

We hence found that the method of using SIOTs and basic price supply tables to solve for the basic price use was found to be unworkable in recovering reasonable information on the relationship between basic price and purchaser price. We see a number of possible reasons for this. First, NSIs work with SUTs with a higher degree of sector detail than those provided to Eurostat. Second, if a commodity-technology assumption is used by the NSI, adjustments may be made to the SIOTs to correct for negative values resulting from the inversion of the normalised supply table. Third, it is possible that a method or assumption other than the two simplest assumptions, commodity-technology for product-by-product SIOTs or fixed product sales structure for industry-by-industry SIOTs, was used to create the SIOT, for example, a mixed-technology assumption. For these reasons, we concluded that it is not practical to directly reverse engineer the use table in basic prices from the symmetric IO tables using a standard technology assumption.

(3) A further option beyond suggestions by Rueda-Cantuche et al. (2007) is using an optimisation procedure which utilises estimates from proxy data alongside, available country-specific data to solve for the most probable basic price use table. The programming problem can be posed in many ways. Two options were considered in this project – (1) the estimation of the basic price SUTs in original classification (59 sectors) from the available country-specific information (including SIOTs) and (2) the direct estimation of SUTs in the final classification (129 sectors), given proxy information and aggregate purchasers' price SUTs. The first method allows for direct checking of aggregate SUT values, but comes at the expense of creating additional workflow, whilst the second method (incorporating the split of imports and valuation layers) was implemented within the disaggregation routine. In this second method, constraints can be applied directly on the known SUT values, with estimates of splits between imports and valuation layers contained within the 'initial estimate' of the balancing routine (Section 3 explains the approach in full).

2.3. Base Year and Currency Adjustment

The year 2000 was chosen as base year for EXIOBASE. When data are only available for other years, values must be scaled up or down to the appropriate base year for comparability across countries and to ensure agreement with the year 2000 trade flows. Whilst macroeconomic statistics such as GDP, imports, value added, and final demand in the national currency and in current prices, published by national statistical offices, can be used to transform the tables across years, only a simple national-level scaling was done here in order to maintain balances in the source data. This procedure is only for non-EU countries, and full details are available in Manshanden et al. (2010) and Wood et al. (2010). To allow for rebalancing the national IO tables after trade-linking, it is necessary to provide all values in a common currency, the Euro in this project, again, using a single national deflator.

3. METHOD PART (2) DETAILING THE DATA SETS AND RECONCILIATION OF DATA

A standard set of 129 industry/product sectors was defined with a sectoral structure following the NACE revision 1.1 industry classification or CPA product classification.

Details were added to sectors of particular importance to environmental policy analysis, including:

(1) agriculture and food;
(2) mining and raw materials;
(3) energy products;
(4) energy intensive metals production;
(5) electricity; and
(6) transport.

A complete overview of the sectors used in EXIOBASE is given in the supplementary information (product classification corresponds directly). Of note is that these sectors were disaggregated at both the level of gross output (UN, 1999), consumed products in final demand, traded products, and in the primary and intermediate transaction level using distinct input and sales coefficients.

The key to an MRIO/MRSUT is providing links between different data sets in order to make a single connected database. The final MRSUT was defined from the outset as a three-dimensional matrix – with the row dimensions containing products and other inputs (e.g. primary inputs and labour); the column dimension containing industries and other consumers (e.g. households and government); the third dimension containing different tables (supply, domestic use basic price, imports, margins, etc.) – as per Tables 1–3. All auxiliary data sets (Section 3.1) were then linked directly to the system description (Section 3.2), before being subject to constrained optimisation (Section 3.3).

3.1. Auxiliary Data

No country had the required level of detail of the EXIOBASE classification. Whilst some countries (e.g. USA and Japan) have around 400 products/industries, most of this detail occurs in secondary and tertiary sectors, without the required level of detail in primary industries. The International Energy Agency (IEA, 2009), SERI (2010), and the United Nations Food and Agriculture Organisation (FAO Statistics Division (FAOSTAT), 2008) provide topical data sets that can be used to help detail these sectors. In the case of EU, EUROSTAT (2010) also provides Annual Enterprise Statistics containing production data at a greater level of detail to the SUTs. Most of these data sets refer to gross production and were complemented with coefficient and trade information.

When using data in physical units to disaggregate the SUTs, prices are needed to reconcile the monetary aggregates. Ideally, a sector would represent a single product with a unique price. In reality, however, sectors represent a collection of similar, yet distinct, products with differing prices. When prices vary, it is necessary to know the relative share of goods included in the sector and the prices of each. Trade data provide an attractive alternative for estimating the average price of an aggregated product group. When trade data are available in both physical and monetary units (United Nations Statistics Division, 2010), the average price of the import and export flows for a country can be calculated. Price data are rarely clean, however, and apart from removing irrational data points, adjustments were further automated through the data reconciliation process (Section 3.3).

The auxiliary data can be classified into different typologies (Table 4).

Not all auxiliary data follow the SNA convention, especially energy balances – and selective use of the data is required. For example, the structure of the IEA energy balances

TABLE 4. Auxiliary data used in adding detail to SUTs.

Type	Coverage	Description
Transactions matrices (Supply/Use format)	Country-specific	Agriculture social accounting matrix (AgroSAM) compiled by IPTS based on the UN Food and Agriculture Organization data Energy and electricity supply, use, and generation mix provided by the International Energy Agency
Gross output	Country-specific	Metals and non-metal minerals extraction and production provided by the US and British Geological Survey. Manufactured goods from UN ComSTAT. Prices applied. Metal price data provided by the London Metals Exchange, British Geological Survey, and US Geological Survey in that order
Coefficient data	Generic	Based on estimates from representative countries with required detail and complemented with 'engineering' knowledge on expected zero flows (e.g. nuclear industry production of wind power).
Other data	Country-specific	Trade data sourced from CommTRADE Data on royalties and rents compiled from NSI agencies

for energy supply are far from the SNA principles, only showing conversion, rather than product supply. Use structures are potentially more useful, but generally refer to 'activities' rather than industries – so where a lot of by-production or co-production takes place, they are not directly usable in detailing SUTs, and further require conversion from territorial to residence principle (Tukker et al., 2013).

A set of Social Accounting Matrices for the EU27 were developed as part of the AgroSAM project at the Institute for Prospective Technological Studies (Müller et al., 2009). These tables follow the standard Eurostat format of supply use tables in purchaser prices, but extended for feedbacks of primary inputs into final demand (not used in this project). In addition, the project provided disaggregated agricultural data for 30 primary agricultural sectors and 11 food-processing sectors. Such detail allowed the direct mapping of the AgroSAM database to the EXIOBASE classification. The AgroSAM database covers each of the EU27 countries, and thus was an important source of information for Cyprus and Lithuania which did not have official tables published at Eurostat. Whilst the bulk of the disaggregation in EXIOBASE was done firstly on the basic price table, the AgroSAMs data are in purchaser prices. As margins and taxes on agricultural products can be significant, the disaggregation of these data was performed at the purchaser price level.

For the RoW countries, AgroSAM like SUTs was not available; therefore, the agriculture and food sectors were transformed into the EXIOBASE classification using a different method, based on gross production totals from FAOSTAT[3] data (Manshanden et al., 2010; Wood et al., 2010).

The IEA Energy Balances (in supply/use format) were used as the source of disaggregation for the energy products (International Energy Agency, 2009). Energy data were

[3] See website: http://faostat.fao.org/.

mapped to specific EXIOBASE products and industries with prices applied. In order to be able to disaggregate the electricity costs, prices were applied separately for industry and households (KEMA, 2005). For five countries,[4] data on transmission and distribution/trade were directly available, whilst for other counties the average percentage share of electricity generation has been calculated from the available data. Moreover, the averages have also been calculated for the other subcategories. For most carriers/products, the price data are directly taken from the IEA. Estimates are made for missing data from countries in similar regions.

Data on gross output were estimated using a variety of sources. The gross output measures implicit in the AgroSAM and IEA databases were complemented with data on mineral extraction and manufactured goods (SERI, 2010). Where gaps still remained in making a one-to-one mapping between the detailed auxiliary data and the aggregate SUT product totals (for non-EU countries with non-standard classifications), the mix of exports was assumed to reflect the mix of domestic production. Finally, exports and value-added blocks were estimated directly, using CommTrade and labour data and resource/rent data (United Nations Statistics Division, 2010).

Coefficient data (for both SUTs) were taken from a range of representative country NSI data in order to give resolution to the technologies employed within an aggregate sector (see the following section).

3.2. Disaggregation Method

The objective of the disaggregation process was to obtain a standardised set of SUTs based on either Eurostat or National Statistical tables, and disaggregated such that additional information is included to delineate production values of goods and services in each country. In addition to the disaggregation of the SUT, the imports, margins and taxes tables needed to be disaggregated, so that trade-linking could be performed at the requisite level of detail, and so that purchaser prices could be translated into basic prices (see supplementary information, Appendix A).

A simple method of disaggregation is to purely split a sector based on estimated gross inputs/outputs (UN, 1999, p. 219). In this way, the shares used to split rows are consistent across all columns, and the shares used to split columns are consistent across all rows. However, this adds very little information on origin of supply, and destination of use for each subsector. That is, the final input–output matrices do not contain any additional information on differences in technology between subsectors. It is arguable if such a method of disaggregation adds any information beyond the convenience of standardised sector classification. If additional information is added to the disaggregate flows beyond gross output of the disaggregate sectors, a disequilibrium is caused on row/column totals, and hence a balance of the adjusted coefficients is required in order to maintain row/column and aggregate data balances.

Desirable properties of a disaggregation routine: It

(1) ensures row/column balances;
(2) includes information on production technology;
(3) works on a varying set of classifications;

[4] Belgium, Czech Republic, Hungary, Ireland, and the UK.

(4) estimates confidential data;
(5) provides consistency between valuation layers;
(6) adheres to aggregate data *where possible*;
(7) maintains structure of auxiliary data; and
(8) handles negatives and zeros appropriately.

The disaggregation routine implemented in EXIOBASE is in the form of a mathematical optimisation problem where aggregate data sets are set as semi-hard constraints, ensuring that aggregate SUTs are adhered to. The constraints are 'semi-hard', as many countries had small imbalances between supply and use, or incorrectly reported negative values that were removed through the procedure. As such, the constraints were adhered to only where they did not cause a problem to the fundamental properties of the input–output data set. In the optimisation, estimates of the underlying technological structure of a disaggregate supply/use system are adhered to as close as possible. A set of monetary coefficients are used to provide an *initial estimate* of the complete set of SUTs. These monetary coefficients inform the technological structure of production in a country and, in essence, give the resolution beneath the available country-specific data. The initial estimate is in final classification and as close as possible to the final solution. A variety of data sources are available to inform the initial estimate; we used coefficients from countries with higher detail and supplemented this with some life-cycle inventory data (most particularly for the electricity generators).

Linear constraints are specified from country-specific data. These data are either in product or industry form (or both), and relate to specific parts of the input–output table. For example, Eurostat and NSI data are mapped to the EXIOBASE classification and used as constraints for each country. IEA data are mapped specifically to the energy sectors. Production totals are also mapped directly to row totals as mentioned above.

Once the data sources are defined as constraints on the input–output table elements, a target function is defined to (a) minimise distance of the final input–output table from the initial estimate (b) minimise changes in the value of the data being used as constraints.

The implementation of the auxiliary data was done in a stepwise approach in order to update the initial estimate from a first initial estimate to a modified country-specific initial estimate. The modified initial estimate is then balanced to basic price data of the respective country, and subsequently to the purchaser price data. If feasible, the aggregated base IO data are adhered to, but if there are inconsistencies in these data, then these inconsistencies are also reconciled (Section 3.3.3).

An important step in utilising this approach is to have a consistent definition of classifications such that any data can be mapped directly to a table (e.g. supply or use), region, product, and industry. Additional constraints on the input–output tables are defined for row/column balances, sign preservation, margin balances, and so on. A generic optimisation programme is then called.

The process followed in the disaggregation follows four main steps – the pre-processing of data including the creation of a standardised or ideal set of technical coefficients for each industry of the economy, plus row and column totals, value added and final demand. These data are then combined to form a country-specific initial estimate. The initial estimate is then adjusted for data from auxiliary data sets (IEA, AgroSAMs). Finally, the adjusted initial estimate is scaled up/down (balanced) to match the aggregate IO tables (Box 2).

Additional items of consideration that do not have an impact on the main balancing are included in Supplementary information, Appendix B.

Box 2. Disaggregation process summary

- **Pre-processing steps**
  - (a) Monetary coefficients created in EXIOBASE classification, based on expected technical coefficients of each industry from representative countries. Ideal coefficients created for both:
    - (i) supply table;
    - (ii) use table including indirect allocation of imports.
  - (b) Estimate row totals.
  - (c) Estimate column totals.
  - (d) Create initial estimate:
    - (i) technical coefficients matrix multiplied by column totals;
    - (ii) estimate final demand block; and
    - (iii) estimate value-added block.
- **Country-specific initial estimate**

This initial estimate contains the ideal coefficients scaled to country-level production and has specific information on exports and changes in stocks. The column totals are estimated from the relative proportions of sales within an ESA 95 industry. The estimate shows, for example, transport use of fuels in the ideal coefficients (high road transport use of diesel, air transport use of kerosene) correct to country-specific total sales of diesel, and so on, and total country-specific total purchases of road transport, and so on. The system is not necessarily balanced at this stage.

1. **Updating of initial estimate**
   - (a) Initial balancing of initial estimate against aggregate IO data to ensure correct volumes of transactions:
     - (i) supply/use system;
     - (ii) supply/use system with imports and taxes and margins.
   - (b) Modification of initial estimate for product rows of auxiliary country-specific data sets (IEA and AgroSAM only used in final application).
2. **Final balancing**
   - (a) Constrained optimisation of updated estimate against aggregate IO data:
     - (i) supply/use basic price system;
     - (ii) supply/use system with imports and taxes and margins.

3.3. Constrained Optimisation

3.3.1. Constraints

Linear equations are dynamically produced over the relevant subsets of each classification for each data source. That is, for *w* data sources, we specify the equation to sum over all relevant subsets of classifications *i, j, k* according to the three concordance matrices $\mathbf{B_i}$, $\mathbf{B_j}$, $\mathbf{B_k}$, that map the data source (*w*) to the relevant products (*i*), industries (*j*), and table (*k*).

Bold denotes matrix (upper case) and vector (lower case) notation, italics denote a scalar and a single entry of a matrix or vector.

$$c_w = \sum_{i \in \mathbf{B}_i(w,i), j \in \mathbf{B}_j(w,j), k \in \mathbf{B}_k(w,k)} Z_{i,j,k}. \tag{1}$$

Equation 1 simply means that the for each data point used as constraint, the respective elements of **Z** are summed to match the value of the constraint. For example, a constraint might be a certain value equals all agricultural products (represented in $\mathbf{B_i}$), going into the food production industries (represented in $\mathbf{B_j}$) and for both domestically produced and imported products (represented in $\mathbf{B_k}$).

We then solve for all **c** whilst minimising the difference of the final estimate of **Z** from the initial estimate $\mathbf{Z^0}$. A target function is used to minimise these differences.

3.3.2. Choice of the Target Function

Two principal candidates are available for choice of the target function

(1) A RAS or minimum entropy type target function such that

$$t(\mathbf{Z}, \mathbf{Z}^0) = \sum_{i,j,k} |Z_{i,j,k}| S_{i,j,k} \ln(S_{i,j,k})$$

with

$$S_{i,j,k} = \frac{Z^0_{i,j,k}}{e * Z_{i,j,k}}.$$

(2) A quadratic (QP) type target function such that

$$t(\mathbf{Z}, \mathbf{Z}^0) = \sum_{i,j,k} |Z_{i,j,k}|^* (1 - S_{i,j,k})^2$$

with

$$S_{i,j,k} = \frac{Z_{i,j,k}}{Z^0_{i,j,k}}.$$

Here, $S_{i,j,k}$ represents the scaling factor of the final estimate from the initial estimate. This target function is equivalent to the normalised least-squares difference. Minimum entropy target functions (Robinson et al., 2001) generally have the greatest theoretical relevance under no further information, as they effectively mean that in order to match a constraint, all values of **Z** will be scaled identically. Under a quadratic target function, the square of the scaling factor is taken such that larger values of **Z** get moved relatively more than smaller values of **Z** (as large values can be scaled less than small values would have to be in order to match the constraints **C**). Under a weighted quadratic target function (as with the weighting by size of **Z** here) (Morrison and Thumann, 1980), this is offset, with scaling relative to $\mathbf{Z}^0$.

An advantage of the quadratic target function is purely pragmatic, in that the solution can be reached much more simply in terms of computational effort than for a minimum entropy approach. A minimum entropy approach introduces nonlinearity into the target function which requires significantly more computational effort to solve.

The form of the target function becomes more important for

(1) large differences between $\mathbf{Z}^0$ and $\mathbf{Z}$ and
(2) fewer values of $\mathbf{c}$.

The first point should be self-explanatory – if $\mathbf{Z}^0$ matches $\mathbf{Z}$, then no scaling takes place, and the form of the target function is of no importance. The second point is perhaps less clear. If our problem was fully determined, we would have identical number of data points w of $\mathbf{c}$ as the number of elements in $\mathbf{Z}$. If this was the case, again, the target function would be of no importance, as the elements of $\mathbf{Z}$ would be fixed by Equation 1. The less data points w available, the more reliance is put on the target function to specify the changes in $\mathbf{Z}$ to match $\mathbf{c}$.

In order to reduce the effect of the first point, in this project, a pre-scaling algorithm is run on $\mathbf{Z}^0$ according to the list of constraint $\mathbf{c}$ (but without row column balances). As the pre-scaling is the most easily performed iteratively, the scaling is the best performed in the order of increased reliability of the constraints $\mathbf{c}$, so that the least reliable constraints are re-scaled to more reliable constraints (see below) throughout the iteration.

3.3.3. Conflicting Data

In the case of conflicting data sources, we will not be able to reach a solution. We then need to 'soften' constraints such that information on data reliability can be taken into account.

Hence Equation 1 becomes

$$c_w = \left(\sum_{i \in \mathbf{B}_i(w,i), j \in \mathbf{B}_j(w,j), k \in \mathbf{B}_k(w,k)} Z_{i,j,k} \right) + dc_w,$$

where dc_w is a measure of the error in c_w. We also introduce the weighting term sc_w (defined later) for each error term dc_w according to reliability of the constraint. And adjusting target function to include minimisation of a function f (defined later) of this error term:

$$\min(t(\mathbf{Z}, \mathbf{Z}^0) + f(dc_w)), \tag{2}$$

sc gives information about the reliability of the *data point* (i.e. if data within the set conflicts, how do we resolve the differences). This happens, for example, when data for the supply matrix do not match those for the use, and is evident, for example, in the IEA data after prices are applied, and also when source SUT has imbalances between supply and use, or negatives in the supply. If no additional data are available, only the largest element of c_w will be moved to resolve the discrepancy. This has no economic meaning; hence, under no further information, we assume that reliability is linked to the size of the constraint $|c_w|$, as larger elements are generally known more precisely, and hence we define

$$sc_w = m + \frac{1}{(|C_w + \delta|)},$$

δ, a small number, is introduced to compensate for $c_\mathrm{w} = 0$. m, is a large number to ensure changes in constraints, dc_w, are penalised more than changes in $\mathbf{S}$ (i.e. that the constraints are met as priority to the balance from the initial estimate). This approach follows that of similar work in Lenzen et al. (2009), but is implemented using a optimisation algorithm rather than an iterative method.

Our target functions then become

$$t(\mathbf{Z}, \mathbf{Z}^0) = \sum_{i,j,k} |Z_{i,j,k}| S_{i,j,k} \ln(S_{i,j,k}) + \sum_{w} sc_w{}^* (dC_w)^2$$

or

$$t(\mathbf{Z}, \mathbf{Z}^0) = \sum_{i,j,k} |Z_{i,j,k}| * (1 - S_{i,j,k})^2 + \sum_{w} sc_w{}^* (dC_w)^2.$$

Due to computational limitations, it is the second target function that is currently being used. As the target function of the disaggregation does not include extensions, and, in the case of electricity, may not adequately represent mixes of electricity consumption according to generation type, further post-processing was undertaken (see supplementary information, Appendix B).

3.3.4. Limitations

The disaggregation is limited by three main factors:

(1) The accuracy of the aggregate IO tables.
(2) The data available to the disaggregation routine.
(3) The interpretation of the classification of the aggregate IO table.

The effects of these three factors are

(1) Where aggregate IO tables contain inaccuracies (apart from illegal positive/negative data), they are preserved. Whilst IO tables are seemingly accurate at the aggregate level, at the disaggregate level, they may contain irregularities. For example, no use of nuclear fuel by the electricity industry, despite production of electricity by nuclear technology.
(2) Some coefficient data are disaggregated across all countries based on combining country-specific estimates of production volumes (see, e.g. Section 3.1) with the sales structure of only one country. For example, the only coefficient data on sales of refinery products at the EXIOBASE classification was available from Australia, and even this was incomplete at the level of detail desired in EXIOBASE, but was further split by Canadian data for diesel and heavy fuel oil.
(3) Standard global classifications are used from the energy and minerals data sets. These are respected unless the aggregate IO table has detail on the energy and mineral products. The classification of the aggregate IO table may not be in line with the global data sets. For example, the energy data set treats use of natural gas in a standard way, which may or may not be the same as the treatment of the IO data set. This makes the use of ‘Natural gas’ or ‘Town gas’ non-standard across countries. This can be circumvented to an extent by prior aggregation of individual country classifications to the least common level of detail. However, this can lead to significant loss of detail in the aggregate SUTs.

4. RESULTS OF DISAGGREGATION OF AGGREGATE SUTS

One of the major empirical outcomes of this work was the disaggregation of the SUTs to a standard classification using a variety of auxiliary information. Significant analysis can be done here, as the data set is so large. We take instead representative countries to show the impact of disaggregation on three indicators – an economic one – compensation of employees (CoE); social – labour; and environmental – carbon dioxide (CO_2). The disaggregation of CoE is implicit in the disaggregation of the SUTs, as an item of value added. The labour disaggregation is described in the supplementary information, Appendix B. The disaggregation of the emissions data set was based on detailed IEA energy balances (consistent with those used in the disaggregation of the MSUT), alongside supplementary LCA-based coefficient data and activity data. All energy flows and activity variables were used within the TEAM emissions model (Pulles et al., 2007) to generate emission values. The reader is referred to Tukker et al. (2013) for details of the methods employed.

We focus firstly on the multipliers – the impact per unit expenditure of each country; and secondly, we look at the implications of this for calculating trade-related effects – the total impact embodied in exports from a country. We use the standard SUT classification used at Eurostat as a reference point (59 sectors) compared to the EXIOBASE classification of 129 sectors. It should be noted that all results are domestic impact intensities and domestic multipliers.

4.1. Multipliers

4.1.1. Compensation of Employees

The results show the original country intensities as a black line, the disaggregated intensities as dots, and the unweighted lognormal ‘world’ average intensities across all EXIOBASE countries with plus or minus one standard deviation as dotted lines. All results are plotted on a logarithmic scale. Figure 1 presents intensities, whilst Figure 2 presents multipliers. The world average and standard deviations are shown for what could be the expected range of results – obviously, some countries will be outside this range, and they are not able to give an ‘exact’ or ‘correct’ value, but an indication of size.

The disaggregation occurs at the intensity (or flow) stage, but the impact of the disaggregation on embodied impact in products is shown through the values of the multipliers which include total upstream impact. What we find is that considerable scatter occurs for small industries at the intensity level, but because of their minor contribution to overall production chains, at the multiplier stage, we get much less scatter in results. This result is in line with various other research studies showing higher uncertainty for smaller flows (Lenzen et al., 2010). Results are shown for UK (GB) and Germany (DE). It is clear that particularly in the primary part of the economy, for example, for agriculture (industries 1–15), mining and quarrying (22–33), and food processing (33–44), there is a significant difference in both the intensity and multipliers for the GB from the final results (dots) to the aggregated table (black line). Note that a logarithmic scale is used. It is interesting to note that this has almost no impact on the total impact (multipliers) for services, which have relatively high direct labour costs. Hence, it could be argued that for labour costs, disaggregation is important for the consumption of goods at the primary end of the economy, but less so for tertiary goods, where average upstream production recipes

FIGURE 1. Results of disaggregation of CoE in terms of intensity, GB.

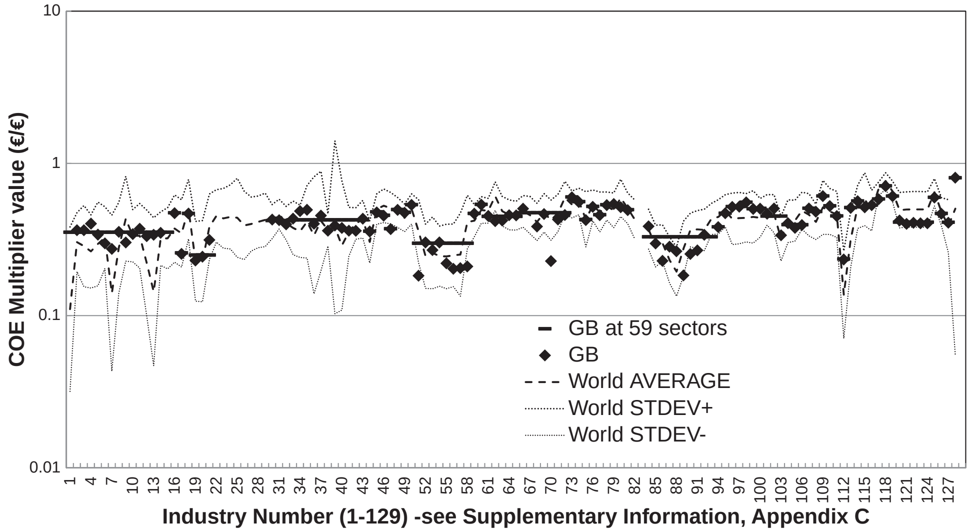
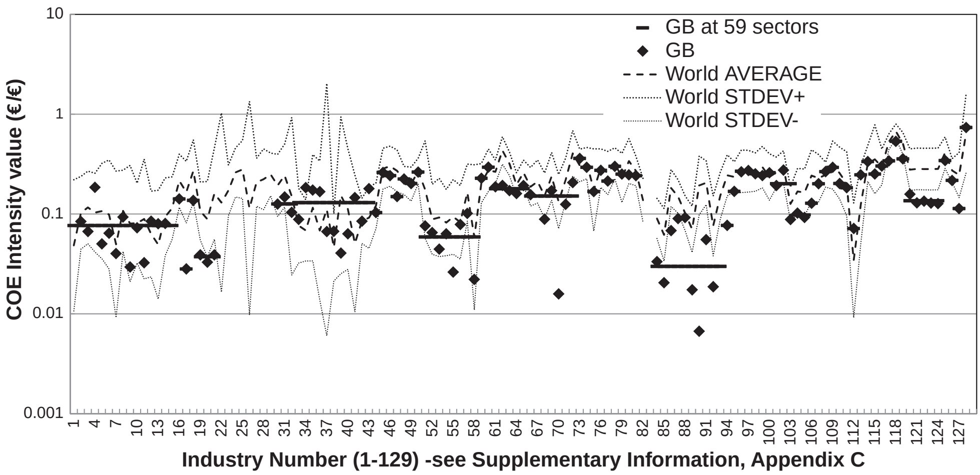


FIGURE 2. Results of disaggregation of CoE in terms of multipliers, GB.

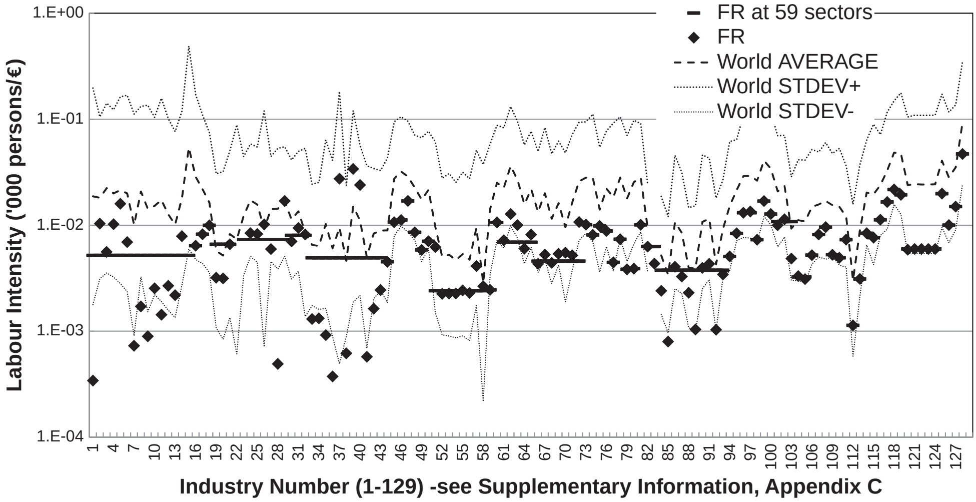


would suffice. The economy-wide unweighted average difference in intensities from the aggregate to the disaggregate model is 21%, whilst the average difference in multipliers is 7%.

4.1.2. Labour

Labour presents a similar picture to the CoE. Whilst on the one hand, this should be expected, it is also interesting to note that CoE is a constrained component of value added

FIGURE 3. Results of disaggregation of labour in terms of intensities, France.



(and hence should generally have intensities less than 1 and usually in the order of 0.1–0.2 €/€). Labour, on the other hand, represents an input to production that is not bound by value added, and from different data sources to the SUT. We show results for France and see a significant variation, both across the aggregate data and introduced in the disaggregation stage in the intensities (Figure 3), which is somewhat less pronounced for manufactured goods and services when looking at multipliers (Figure 4). Of note are the differences in the agricultural sector. Labour here only includes paid employment, and not self-employees (included in mixed income), something which is common in farmer-owned establishments in the agricultural sector. On average, there is a 37% and 18% difference between intensities and multipliers, respectively, from the disaggregate level to the aggregate level.

4.1.3. Carbon Dioxide Emissions

Whilst the composition of the greenhouse gas data is not a focus of this study, it is of interest to see what the implications are of using a disaggregated MRIO model versus an aggregate MRIO model. It complements the work of Su and Ang (2010), Su et al. (2010) and Bouwmeester and Oosterhaven (2013) who take a look at the differences between spatial and sectoral aggregation. For CO_2, shown here for Germany (DE), the greatest differences in the intensities (Figure 5) occur in the manufacturing sector and the electricity sector (as to be expected). We see spikes for coke-oven products, as well as considerable differences in intensities for different types of metal production (sectors 60–70). Of note are the four order of magnitude differences for some sectors such as the renewable electricity generators and the coal-fired generators. Some outliers on the intensity figure represent industries such as uranium processing (58) – which is poorly represented in SIOTs.

Comparing to global average intensities and multipliers (Figure 6), we see that the disaggregation brings us much closer to the distribution of the expected value. Whilst it is not known if the global average is representative of reality, it would be expected that it is more

FIGURE 4. Results of disaggregation of labour in terms of multipliers, France.

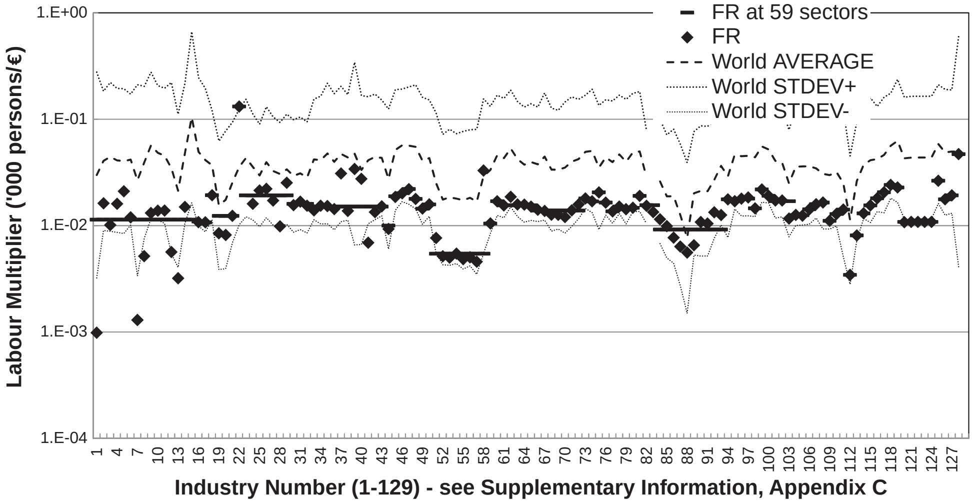
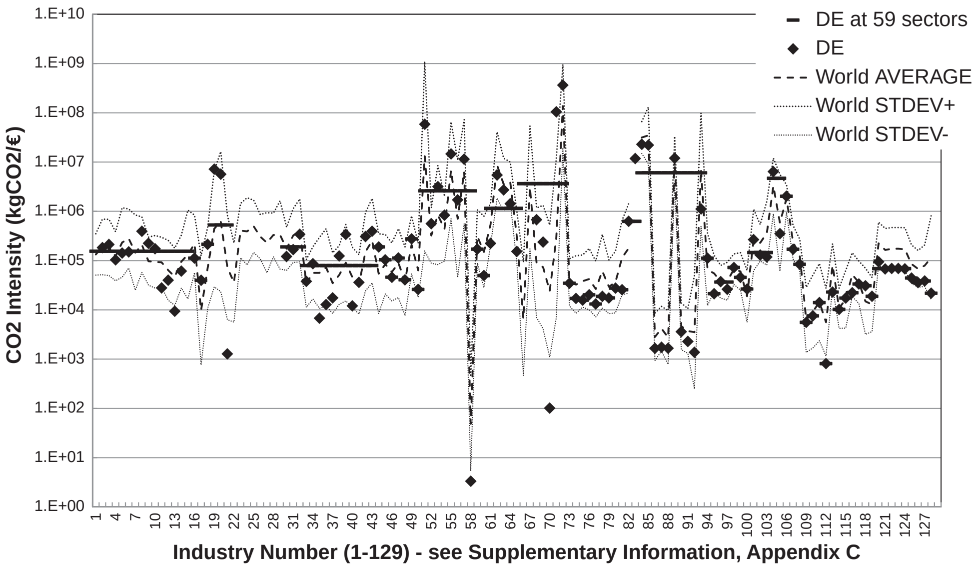


FIGURE 5. Results of disaggregation of CO_2 in terms of intensities, Germany.



representative than the aggregated intensities/multipliers. This is because for many of the key materials, they are already disaggregated in required detail in key exporting countries (e.g. agriculturally strong countries have multiple agriculture industries in their original SUTs, countries with a strong mining sector already have detailed sub-industries in their original SUTs). On average, there is a 217% and 170% difference between intensities and multipliers, respectively, from the disaggregate level to the aggregate level.

FIGURE 6. Results of disaggregation of CO_2 in terms of multipliers, Germany.

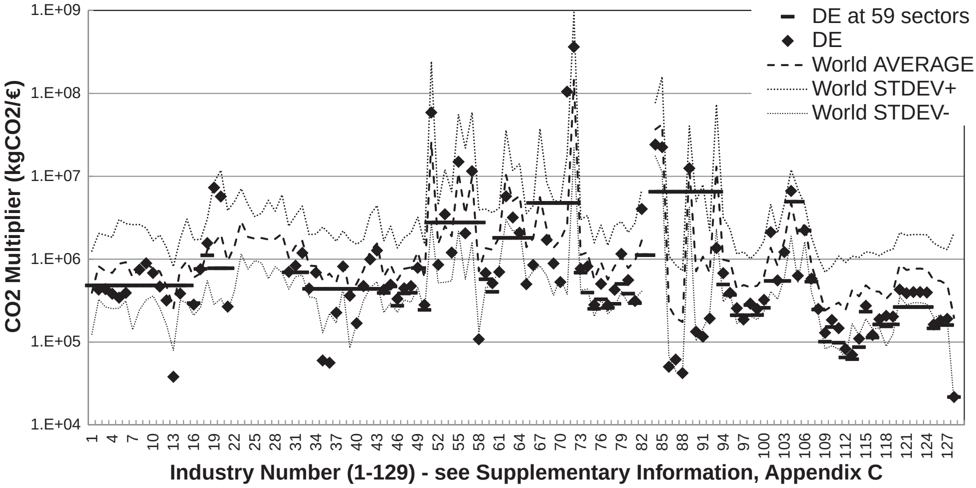
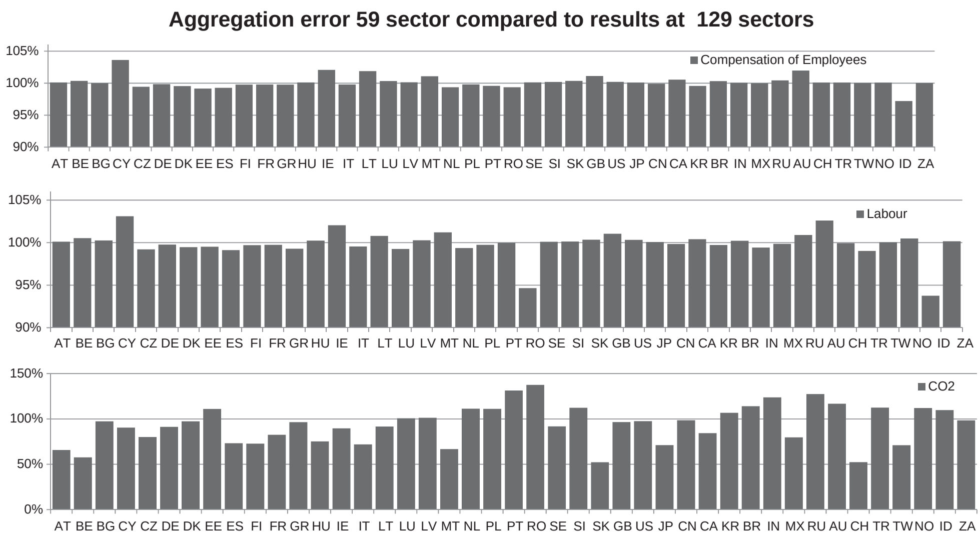


FIGURE 7. Results of disaggregation of impacts embodied in exports by indicator for each country, relative to calculation at the 129 sector level.



4.2. Implications for Impact Embodied in Trade

Input–output modelling is essentially an exercise in allocation – allocating a primary input such as CO_2 to its consumers, meaning that domestic impacts should be wholly distributed to final goods and services. As trade of goods and services complicates the matter, and is the reason why multi-regional data sets are needed, it is then interesting to note what the effect of disaggregation has for accounting for impacts embodied in trade. If goods and services were exported in the same proportion as they are consumed domestically, we should see no impact, but when we get large exports of, for example, high value goods, it can affect results considerably.

The magnitude of the impact of disaggregation on the three indicators used above (CoE, labour and CO_2, respectively) is presented in Figure 7. The figure shows the difference in impacts embodied in exports of results calculated with a 59 sector model versus the 129 sectors used in EXIOBASE. Of note, whilst all original European tables were disaggregated from the 59 sectors, non-European tables often had higher levels of disaggregation before harmonisation.

There is a reasonable level of agreement for CoE at the aggregate and disaggregate levels. Only some countries differ in the range of 5%. Findings are similar for labour, although there is somewhat more variation. Finally, for CO_2, we are confronted with large errors for an aggregated model. Given that the benefits of disaggregation for environmentally important indicators are shown elsewhere (Lenzen, 2011), it is clear that more attention needs to be paid to the representation of detailed product groups while looking at this issue for traded goods.

5. CONCLUSION

This paper details the construction of SUT for EXIOBASE. It concentrates on the creation of basic price SUTs including the harmonisation of source data and the disaggregation of environmentally important sectors. We focus on methodological challenges, as well as implications of various approaches for demand-side modelling.

We find that reverse engineering SUTs is not a fruitful way forward, that optimisation procedures can help handle large discrepancies in data, but that care is required in interpreting the disagreements from different data sources. Finally, adding detail to MRIO analysis by disaggregating tables can have a large impact on product-specific multipliers, with obvious implications for capturing environmental impacts, such as greenhouse gas emissions embodied in traded products.

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SUPPLEMENTAL DATA

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