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Does consistency with detailed national data matter for calculating carbon footprints with global multi-regional input–output tables? A comparative analysis for Belgium based on a structural decomposition

Caroline Hambÿe[1], Bart Hertveldt[1] and Bernhard Michel[1,2*]

*Correspondence: bm@plan.be
[1] Federal Planning Bureau, Avenue des Arts 47-49, 1000 Brussels, Belgium
Full list of author information is available at the end of the article

Abstract

Consistency with detailed national data is an important challenge when using multi-regional input–output (MRIO) tables for carbon footprint analysis at the national level. This article presents carbon footprint calculations for Belgium with original and adapted MRIO tables from the World Input–Output Database (WIOD) project. For constructing the adapted tables, we have reproduced the MRIO construction process of WIOD replacing source data for Belgium by detailed supply-and-use table data from national sources and keeping these unchanged in the balancing phase. The novelty of our approach is that we investigate a time series and analyse the differences in results with respect to the original tables using structural decomposition analysis (SDA). According to our calculations, Belgium's carbon footprint is up to 15% lower than in calculations based on the original WIOD MRIO tables. The SDA reveals that this is largely due to differences in data on import uses and taxes and subsidies. Hence, consistency with detailed national data does indeed matter for MRIO-based carbon footprint calculations. Therefore, we advocate building global MRIO tables by incorporating a maximum of detailed national data in close cooperation with national statistical institutes before letting the balancing process work freely.

Keywords: Carbon footprint, Global multi-regional input–output tables, National accounts consistency, Consumption-based emission accounting, Structural decomposition analysis

1 Introduction

International climate negotiations have up to now been based on emission inventories for greenhouse gases (GHG), thereby attributing responsibility to the producing country. However, this attribution may be distorted by emissions embodied in international trade. Indeed, even with identical consumption levels and profiles, countries importing emission-intensive commodities will have lower production-related GHG emissions than countries exporting such commodities. This has motivated the development of consumption-based GHG emission accounting to calculate carbon footprints. But although the carbon footprint is advocated as a key indicator by international institutions (e.g. UNECE 2017) and considered as an official statistic in the UK (see Wiedmann and Barrett 2013; Defra 2017), the method and data for its calculation must be sufficiently robust if it is to be used as a tool for climate policy (Kanemoto et al. 2012).

Consumption-based GHG emission accounts are established using environmentally extended input–output (IO) models. Data availability has been the main issue faced by researchers when trying to establish robust consumption-based emission accounts (Wiedmann et al. 2007; Hoekstra 2010), conditioning the type of IO models that they have used. Early contributions to this literature were almost all restricted to national IO tables relying on a single country input–output (SRIO) model and the domestic technology assumption (DTA) for import flows (e.g. Kondo et al. 1998; Munksgaard and Pedersen 2001; Mäenpää and Siikavirta 2007). But this conveys an unrealistic picture of foreign emission intensities and production technology and excludes any trade links between other countries. A global multi-regional input–output (MRIO) model is to be preferred for calculating footprints (Turner et al. 2007) as emissions embodied in trade between other countries are adequately measured and feedback loops accounted for. Several global MRIO databases (Eora, EXIOBASE, WIOD, OECD ICIOs, GTAP-MRIOT, GRAM, IDE-JETRO's AIIOT) have been developed since the mid-2000s through the efforts of different consortia of academic researchers (see Tukker and Dietzenbacher 2013, for an overview). They have been used to calculate carbon footprints for large panels of countries (e.g. Peters et al. 2012; Arto et al. 2012; Tukker et al. 2014).

Even though the development of global MRIO databases constitutes a major step towards greater robustness of consumption-based GHG emission accounts, it has not settled all issues. The mere fact that several global MRIO databases have been created in parallel reflects differences in many aspects of the construction process, e.g. the degree of harmonisation of underlying data or the approach to reconciling conflicting data sources. As emphasised by Tukker and Dietzenbacher (2013), "[d]epending on choices, assumptions and perceptions of which data seem most reliable, one will arrive—with certain limits—at different but equally plausible 'mappings of the world economy'" (p. 14). As a consequence, carbon footprint results for individual countries vary between MRIO databases.[1] This constitutes a first potential hindrance for the adoption of MRIO-based carbon footprint calculations at the national level.

In this context, divergence with respect to published national data is another important challenge. In general, MRIO databases ensure consistency with national accounts aggregates, i.e. industry-level output and value added, and are based on national supply-and-use tables or IO tables as a starting point. Nonetheless, the reconciliation of conflicting data sources in MRIO construction entails the "need for significant transformation of data originally validated in national statistical systems" that "makes it difficult for the National Statistical Institutes to build [G]MRIO tables themselves or even participate in their building" (Tukker and Dietzenbacher 2013, p. 7). Therefore, to promote the acceptance of MRIO-based carbon footprints at the national level, there is the

[1] Hoekstra et al. (2014) provide a detailed account of potential sources of variation in MRIO-based carbon footprint calculations.

need to address the demand for consistency with more detailed national data within the MRIO framework.

Only very few MRIO-based footprint analyses focused on individual countries address the issue of consistency. For calculating the UK's carbon footprint, a specific UKMRIO is built, which combines national IO tables for the UK with data from the Eora MRIO tables (see Owen et al. 2017). The issue has been addressed most thoroughly for the Netherlands in Edens et al. (2015). They have reproduced World Input–Output Database (WIOD) MRIO tables for 2003 and 2009 that fully respect national accounts and trade data for the Netherlands and used them to calculate the country's carbon footprint, which turns out lower than in calculations based on the original WIOD MRIO tables.[2]

The aim of the work presented here is to provide further insights into the issue of the consistency of MRIO tables with detailed national accounts data in carbon footprint calculations. This should not be interpreted as a criticism of the work of the consortia that have constructed MRIO tables, but rather as an attempt to see whether including additional national data in the MRIO construction process can contribute to increasing the robustness of carbon footprint results for an individual country. We also want to analyse how footprint results are influenced by the transformation of national data in the course of the MRIO construction process. For this purpose, we estimate Belgium's carbon footprint with MRIO tables into which we have integrated detailed data from Belgian supply-and-use tables (including valuation tables and the import use table). As a first step, we rebuild WIOD MRIO tables for all years from 1995 to 2007 along the lines of what Edens et al. (2015) have done for the Netherlands, injecting data from a series of temporally consistent supply-and-use tables for Belgium (Avonds et al. 2012). We refer to these tables as WIODBEL MRIO tables. As a second step, we compare Belgium's carbon footprint based on the original WIOD MRIO tables with the country's carbon footprint based on WIODBEL MRIO tables for the years 1995–2007. Hence, compared to Edens et al. (2015) we observe not only differences in carbon footprint levels but also differences in the trend over time. Moreover, we analyse the difference between WIOD and WIODBEL carbon footprints for Belgium by means of structural decomposition analysis (SDA), identifying to what extent differences in emission intensities, input structure, and imports and exports contribute to differences in footprint results.

This article is organised as follows. We start off by comparing national data with WIOD data for Belgium in Sect. 2 and then describe in Sect. 3 how the WIODBEL MRIO tables are built with data for Belgium from national sources. Section 4 presents the carbon footprint calculations and results. The structural decomposition analysis comparing WIOD and WIODBEL carbon footprints for Belgium is developed in Sect. 5. Finally, Sect. 6 provides a discussion of results and conclusions.

[2] Although the OECD recommends implementing analyses according to the procedure of Edens et al. (2015) for the Netherlands (see OECD 2017), there is concern about the workload of this procedure. In particular, Moran et al. (2017) take a different perspective on the consistency issue. They show that feedback loops in MRIO-based footprint calculations are small and argue that it is therefore sufficient to combine national tables and MRIO-based multipliers to calculate a footprint for an individual country that is consistent with national data.

2 Comparing national data with WIOD data for Belgium

The main advantage of using an MRIO database rather than only national data for calculating a country's carbon footprint and emissions embodied in trade is that it allows to avoid unrealistic assumptions about foreign technology. However, data for individual countries in MRIO databases differ from (official) national data. This was first pointed out by Wilting (2012) and then analysed in detail in Edens et al. (2015). Discrepancies with respect to national data are due to differences in source data and adjustments made in the construction process of the multi-regional tables.

Here, we compare Belgian SUT from national sources with SUT for Belgium used in the construction of the World Input–Output Database (WIOD). On the one hand, we take data from the UpdateSUT project of the Belgian Federal Planning Bureau (FPB) as the national reference data (see Avonds et al. 2012, for the methodology). The project consisted in revising and updating Belgian SUT for the years 1995–2007 so as to produce a time series of SUT consistent with the then most recent national accounts (NA) vintage (November 2010). On the other hand, we have chosen WIOD among the available MRIO databases for the same reasons as Edens et al. (2015): because it largely respects countries' national accounts totals, because the WIOD MRIO tables are derived from supply-and-use tables (SUT), because of its open source character whereby the SUT and final result MRIO tables are freely available on the WIOD website, and because it contains a time series of MRIO tables. EXIOBASE2 also fulfils the first three criteria, but only contains data for 2007.[3] Dietzenbacher et al. (2013) provides a detailed description of the construction process of the first vintage of the WIOD MRIO tables released in 2012. They are industry-by-industry tables consistent with SNA93 for 1995–2009[4] covering 40 countries (among which Belgium) and a "rest of the world" (RoW) region, and 35 industries in a classification derived from Nace Rev. 1.1. The underlying product-by-industry SUT contain 59 product categories that correspond to the 2-digit CPA.[5]

The MRIO construction process in WIOD is summarised in flow chart form on the left-hand side of Fig. 1. Source data for Belgium comprise national SUT taken from Eurostat for the years 1995, 1997 and 1999–2007 as well as NA data (output and expenditure) from the OECD's STAN database (see Erumban et al. 2012, p. 6). While the NA data are available in a consistent time series, i.e. data for all years respecting the same and then most recent NA vintage, the SUT have not been revised. Dietzenbacher et al. (2013) describe the process of harmonising and subsequently benchmarking countries' SUT to the revised NA and of interpolation to complete the SUT time series for missing years. To obtain use tables in basic prices, valuation tables for trade and transport margins and taxes minus subsidies on products were estimated by the WIOD consortium. The distribution of margins and net taxes over use categories is largely proportional. As a further step, bilateral trade was derived from detailed product-level trade data from COMTRADE, and it was used to construct the import part of the use tables with a

[3] Note that the OECD ICIO's, which can be downloaded for free, respect national accounts totals and cover several years, were not available yet when we started this project.

[4] The time coverage of the first vintage of WIOD MRIO tables was subsequently extended to more recent years. Here, we restrict WIOD data to 1995–2007 to match the period covered by UpdateSUT.

[5] CPA stands for Statistical Classification of Products by Activity in the European Economic Community. Here, the CPA version of 2002 is used.

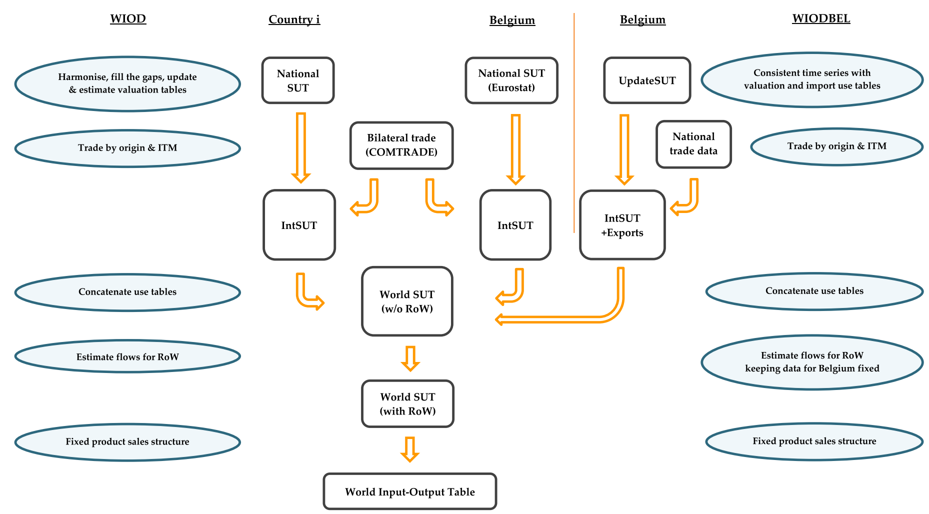

Fig. 1 Overview of the MRIO construction in WIOD and in WIODBEL

split by country of origin.[6] Therefore, the so-called international supply-and-use tables (IntSUT) were obtained. In parallel, the bilateral trade data also served to estimate international trade margins (ITM) based on the difference between "cost-insurance-freight" (cif) and "free on board" (fob) valuation of mirror import and export flows. In the next stage, the IntSUT were then combined for all countries in the database in a world SUT that was completed by the estimation of (trade and internal) flows for the RoW. The industry-by-industry MRIO table was then derived from this world SUT based on the fixed product sales structure assumption.[7]

The UpdateSUT project started from the original non-revised Belgian SUT published by the Belgian National Accounts Institute (NAI). Valuation tables for margins, taxes and subsidies as well as import use tables were available for the IO benchmark years, all estimated in the process of deriving IO tables. Avonds et al. (2007) provide detail on methods for constructing tables for missing years (1996 and 1998), revising tables so that they respect the common NA vintage and estimating the valuation and import use tables for non-benchmark years.

Regarding the source data, the Belgian SUT available from Eurostat are the same as those published by the Belgian NAI. The NA data underlying the first release of the WIOD MRIO tables (taken from the OECD's STAN database) are identical to the corresponding vintage of the NA published by the NAI. This facilitates the comparison between the Belgian SUT from UpdateSUT and the IntSUT from WIOD. However, for IO benchmark years, the construction of valuation tables for trade and transport margins, taxes and subsidies is based on firm-level data and detailed fiscal data in UpdateSUT (FPB 2010), i.e. the methodology for estimating those tables differs from what is done by the WIOD consortium. For trade, there is also a difference in source

[6] In this procedure, different use categories (intermediate inputs, final consumption and investment) were considered separately along the lines of the Broad Economic Categories (BEC) classification of trade.

[7] Dietzenbacher et al. (2013) provide a WIOD-specific explanation of this last step, while Eurostat (2008) is the standard methodological reference for this transformation.

data between UpdateSUT and WIOD. Merchandise trade statistics for Belgium are established according to two different concepts: the community concept and the national concept (see NAI 2010, for full detail on the two concepts). Data in community concept are internationally comparable and reported for international databases like COMTRADE, used for constructing WIOD MRIO tables. They comprise all cross-border transactions with a change in ownership as well as transactions for processing. Merchandise trade data in national concept are derived from those in community concept and are used in building the NA and balance of payments statistics. Compared to data in community concept, they do not comprise cross-border transactions of non-residents. In UpdateSUT, use tables are split into uses of domestic production and imports based on trade data in national concept at firm-level for IO benchmark years (Van den Cruyce 2004).[8] First, firm-level imports and exports are compared at the most detailed product-level (8-digit Combined Nomenclature) to identify re-exports. Then, remaining imports are matched to firm-level input use by product. Thus, methodological differences compared to WIOD are clearly driven by differences in the available data (firm-level data by product in national concept vs. product-level data in community concept). In particular, the identification of re-exports is different in WIOD: there are re-exports for a specific product when exports exceed domestic production. For services, the use table of imports is determined based on detailed service trade data by EBOPS[9] category according to the specific methodology described in Hambÿe (2001). Finally, WIOD also proceeds to necessary modifications of the data for Belgium in the process of constructing the IntSUT to align mirror export and import flows and, further down the line, in the process of constructing MRIO tables when it comes to balancing world-wide flows and estimating flows to the RoW.

These differences in source data with respect to what is available and done at the national level should not be considered as a shortcoming of the WIOD MRIO construction process. Access to national firm-level data is largely restricted due to confidentiality considerations. Hence, the pledge of the WIOD consortium to use only publicly available data (Dietzenbacher et al. 2013) seems sensible. Moreover, even if national firm-level data were available, it would not make sense for the construction of MRIO tables to redo work that has already been done at the national level. Closer cooperation between those who construct MRIO tables and national statistical institutes for the exchange of data could be a way forward in this context, in particular as regards import use tables and valuation tables. Eurostat has initiated such a process for the construction of its European MRIO tables (Figaro project).[10]

It is useful from a national perspective to examine differences between national data and MRIO data for Belgium to get a grasp of where discrepancies in the results of analytical applications, e.g. footprint calculations, come from. In Tables 1, 2, 3 and 4, we compare the Belgian IntSUT for 2005 from WIOD with the same year's SUT from

[8] IO benchmark years are 1995, 2000 and 2005. The use tables for imports are interpolated for all other years in UpdateSUT.

[9] EBOPS stands for Extended Balance Of Payments Services classification.

[10] Valuation tables (for margins and taxes and subsidies) as well as import use tables are publicly available for Belgium for input–output reference years. The Belgian Federal Planning Bureau has provided these tables for non-reference years to Eurostat for the needs of the Figaro project for constructing European MRIO tables.

Table 1 WIOD supply Table (2 × 2), Belgium, 2005, basic prices, million USD

	Manufacturing	Services	Imports	Total
Manufacturing	295,368	11,381	230,025	536,773
Services	15,785	460,959	37,034	513,778
Total	311,153	472,340	267,059	1,050,552

Table 2 UpdateSUT supply Table (2 × 2), Belgium, 2005, basic prices, million USD

	Manufacturing	Services	Imports	Total
Manufacturing	295,561	11,520	236,162	543,243
Services	15,592	460,821	41,006	517,418
Total	311,153	472,340	277,168	1,060,661

Table 3 WIOD use Table (2 × 2), Belgium, 2005, basic prices, million USD

	Manufacturing	Services	Final demand	Exports (DO)	Re-exports	ITM	Total
Manufacturing	135,462	41,216	114,505	199,686	37,228	8678	536,773
Services	77,225	166,946	222,228	47,379	0	0	513,778
Total	212,686	208,162	336,733	247,066	37,228	8678	1,050,552
ITM	4091	1006	3581	–			
TXSP	10,764	11,077	19,222	–			
Value added	83,612	252,095	–	–			
Total	311,153	472,340	359,536	247,066			

ITM international trade and transport margins, *TXSP* other taxes minus subsidies on production, *DO* domestic origin

Table 4 UpdateSUT Use Table (2 × 2), Belgium, 2005, basic prices, million USD

	Manufacturing	Services	Final demand	Exports (DO)	Re-exports	ITM	Total
Manufacturing	159,647	45,096	106,037	144,039	80,812	7611	543,243
Services	62,160	165,600	220,548	68,759	351	0	517,418
Total	221,807	210,696	326,582	212,798	81,163	7611	1,060,661
ITM	4100	897	2614	–			
TXSP	1634	8652	30,336	441			
Value added	83,612	252,095	–	–			
Total	311,153	472,340	359,532	213,239			

ITM international trade and transport margins, *TXSP* other taxes minus subsidies on production, *DO* domestic origin

UpdateSUT. The values of the latter have been converted to USD at the rate used in WIOD. For ease of presentation, the tables are aggregated to a two-industry-two-product (manufacturing and services[11]) format. Use tables are in basic prices. The tables confirm that WIOD does indeed largely respect the NA totals. The values of total output and value added are identical in the WIOD IntSUT for Belgium and the UpdateSUT tables, and the difference in total domestic final demand is negligible. Total imports and

[11] In 2-digit NACE Rev. 1.1, 'manufacturing' as reported in Tables 1, 2, 3 and 4 corresponds to industries 01–45 and services to 50–95, i.e. construction is part of 'manufacturing'. The equivalent split-up in terms of the WIOD classification is AtB-F and 50-P.

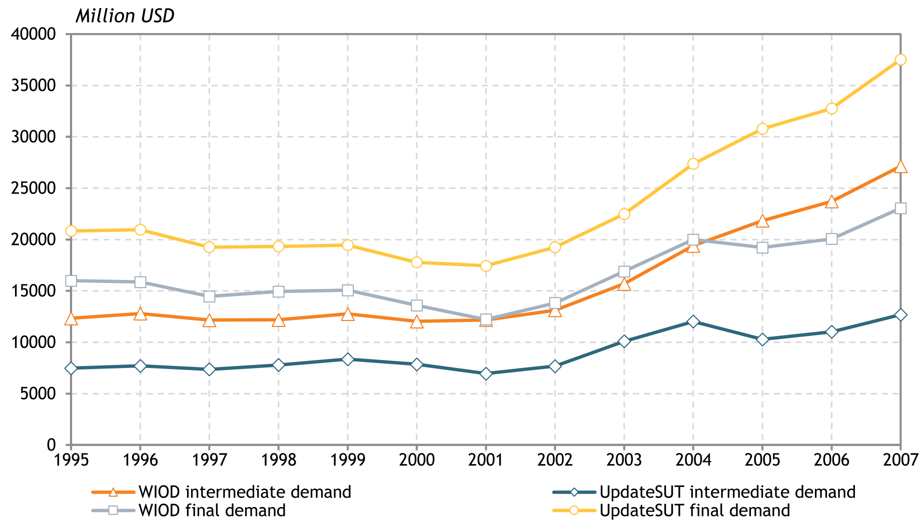

Fig. 2 Distribution of taxes and subsidies on production over intermediate and final demand, 1995–2007

exports are almost identical in purchasers' prices, but in basic prices both are lower in WIOD than in UpdateSUT. The difference is approximately 10 billion USD in both cases and originates from a valuation (c.i.f.–f.o.b.)[12] correction applied in WIOD. The NA consistency of WIOD also holds at a more detailed industry level (WIOD classification) and for all domestic final demand categories. The distribution of output over product categories is also very similar in the supply tables (Tables 1, 2).

There are larger discrepancies in the product distribution of intermediate and domestic final demand in the use tables in basic prices (Tables 3, 4). They are partly due to differences in the valuation tables for taxes and subsidies.[13] Although the totals are identical, there are large and from 2003 onwards growing differences in the distribution of other taxes and subsidies on production (TXSP) over industries and domestic final demand in the use tables (see Fig. 2). As they are subtracted from uses in purchaser prices for conversion to basic prices, they make for a large part of the differences in the product distribution of intermediate and final demand.

Another major difference between WIOD and UpdateSUT concerns re-exports. This difference matters because re-exports are excluded when deriving MRIO tables, i.e. only exports of domestic origin and imports that are not re-exported are taken into account. While values for total exports and imports (including re-exports) are relatively similar in the two datasets, the estimation of re-exports yields substantially different results due to differences in source data and methodology as explained above. For 2005, re-exports amount to 37 billion USD in WIOD, whereas in UpdateSUT they amount to 81 billion USD.[14] Figure 3 shows that there is indeed a sizeable difference in the estimation

[12] In the valuation of trade data, c.i.f. stands for cost, insurance and freight, and f.o.b. for free on board.

[13] Valuation tables for trade and transport margins are also likely to differ in the two databases, but as data on trade and transport margins other than international trade and transport margins (ITM) is not explicitly reported by WIOD, a comparison of these valuation tables with UpdateSUT was not possible.

[14] By definition, services cannot be re-exported. Hence, re-exports are only goods. The small amount of re-exports in the 'services' product category in Table 4 is due to certain goods that are part of merchandise trade statistics but classified in service categories in the CPA 2002 because they are closely linked to specific service categories, e.g., architectural plans and drawings, music (printed or in manuscript) and original works of art.

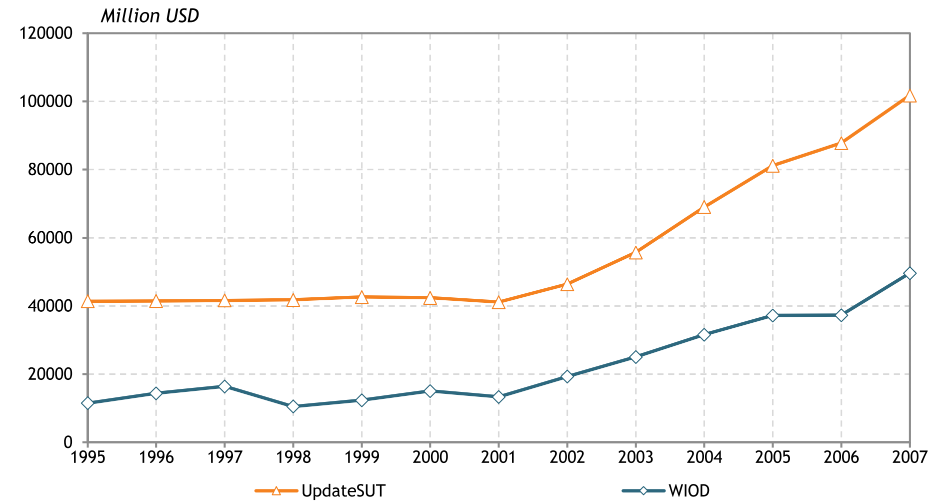

Fig. 3 Re-exports for Belgium in WIOD and UpdateSUT, 1995–2007

of re-exports for Belgium between WIOD and UpdateSUT for all years between 1995 and 2007. It amounts to almost 30 billion USD in 1995, is relatively stable at that level until 2003 and then grows to more than 50 billion USD in 2007.[15] As re-exports are subtracted from both exports and imports, the trade balance remains unchanged.

3 WIODBEL methodology and results

The results of the comparison of the WIOD IntSUT for Belgium with national data (UpdateSUT tables) have prompted us to produce alternative WIOD MRIO tables that are consistent with national data for Belgium and which we refer to as WIODBEL. For this purpose, we proceed in two steps (see right-hand side of Fig. 1). First, we replace the WIOD IntSUT for Belgium by tables in the same format based on data from UpdateSUT and a specifically computed distribution of imports over countries of origin. Moreover, we also distribute Belgian exports from UpdateSUT over destination countries. Second, we estimate flows for the RoW and build world SUT from the IntSUT keeping data for Belgium unchanged. The industry-by-industry WIODBEL MRIO tables are then derived from the world SUT following the standard method (fixed product sales structure assumption).

Before injecting UpdateSUT-based Belgian national data (IntSUT and exports) into WIOD, some preliminary work on the UpdateSUT data was required:

- Supply-and-use tables from the UpdateSUT project in EUR were converted to USD at the exchange rates used by WIOD.
- Imports and exports from the UpdateSUT project's supply-and-use tables were distributed over countries of origin and destination. To determine the distributions, we

[15] The increase in re-exports is likely to be related to several of the main drivers of the growth in trade flows in the early 2000s. The rise of global value chains and China's WTO accession in 2001 (see Los et al. 2015) has probably contributed to increasing the amount of goods dispatched to other European countries through Belgium, in particular the port of Antwerp. The introduction of the euro has probably acted as a facilitator for re-exports.

rely on 8-digit Combined Nomenclature merchandise trade data in national concept for goods and on service trade data by EBOPS category matched to the CPA-based WIOD product categories.[16]

- Supply-and-use tables from the UpdateSUT project were aggregated from a work format breakdown (approximately 120 industries and 320 product categories) to the level of 2-digit Nace Rev.1.1 and CPA, i.e. 59 industries and product categories. Data for Belgium are thus slightly more disaggregated at the industry level than in the original WIOD IntSUT (35 industries).

To make sure that we obtain results comparable to the original WIOD MRIO tables, we first implemented the construction procedure with the original WIOD IntSUT for Belgium and all other countries. Data for Belgium were allowed to change in this procedure (see Fig. 1). Just like Edens et al. (2015) for the Netherlands, we tried to match the WIOD construction procedure as described in Timmer et al. (2012) as closely as possible.[17] We refer to this as WIOD redone. Our results are reasonably close to the original WIOD MRIO tables. Row and column totals are identical and the mean cell-wise absolute difference over all years amounts to 0.6 million USD with the main differences occurring in domestic flows for the RoW region.[18] In what follows, WIOD redone (rather than the original WIOD) will be used as basis for comparing results so as to maintain a methodological consistency.

For deriving the WIODBEL MRIO tables, we then injected Belgian national data and re-implemented the construction procedure keeping data for Belgium unchanged. This yields results that are relatively close to WIOD redone. While there are only minor discrepancies in the row totals and none in the column totals, the internal structure of the tables for Belgium is different. The overall mean cell-wise absolute difference between the WIODBEL and WIOD redone MRIO tables amounts to 0.2 million USD over all years, and for all flows involving Belgium it stands at 3.7 million USD.

4 Carbon footprint calculations

For calculating carbon footprints and emissions embodied in trade for Belgium, we use a multi-regional input–output (MRIO) model with data from WIOD and WIODBEL MRIO tables. The tables provide information for all countries on how exports are used in the destination country. In what follows, we briefly derive and explain formulas for these calculations and then report results for Belgium.

[16] We distribute Belgian exports over use categories in the country of destination according to the countries' imports from Belgium reported in WIOD.

[17] All these calculations were done in LArray, a Python module developed at the FPB. The module and code can be made available upon request.

[18] An exact replication of the construction procedure is not possible just based on descriptive sources without getting a view of the original code. Even though the description in Timmer et al. (2012) is fairly detailed, it does not shed light upon all problems that come up in the course of the construction process. For sure, there are some methodological differences in our estimation of flows for the RoW compared to the original, e.g., the treatment of negative exports that are the counterpart of changes in inventories and the treatment of product flow imbalances for uranium and thorium ores. These differences have repercussions for domestic flows of the RoW.

4.1 The model

Although in practice there are many countries in an MRIO model, it can be conveniently illustrated for two countries (see Serrano and Dietzenbacher 2010): the focal country, which is Belgium in our case, and the RoW region. There are $i = 1,\ldots, n$ industries in Belgium. The RoW encompasses all other countries in the WIOD MRIO tables (including the WIOD RoW). There are n industries in each of these countries, so the RoW contains (m-1)n industries where m is the number of countries in WIOD. The standard input–output demand equation indicating output delivered to intermediate and final demand can be written in partitioned form. In all submatrices and subvectors with two superscript indices, the first one stands for the country of origin and the second one for the country of destination.

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} = \begin{bmatrix} \mathbf{Z}^{11} & \mathbf{Z}^{12} \\ \mathbf{Z}^{21} & \mathbf{Z}^{22} \end{bmatrix} \boldsymbol{\iota} + \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \tag{1}$$

Here, $\mathbf{x}^1$ is the $(n \times 1)$ output vector for Belgium, $\mathbf{x}^2$ is the $((m-1)n \times 1)$ output vector of the RoW, $\mathbf{Z}^{11}$ and $\mathbf{Z}^{22}$ are the $(n \times n)$ and $((m-1)n \times (m-1)n)$ domestic intermediate demand matrices of the two countries, $\mathbf{Z}^{12}$ and $\mathbf{Z}^{21}$ are the $(n \times (m-1)n)$ and $((m-1)n \times n)$ imported intermediate demand matrices, $\boldsymbol{\iota}$ is a $(mn \times 1)$ vector of 1's for summation, $\mathbf{y}^{11} + \mathbf{y}^{12}$ is the $(n \times 1)$ final demand vector for Belgian output[19] and $\mathbf{y}^{21} + \mathbf{y}^{22}$ is the $((m-1)n \times 1)$ final demand vector for RoW output.[20] Defining partitioned input requirement matrices as $\begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} \\ \mathbf{A}^{21} & \mathbf{A}^{22} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}^{11} & \mathbf{Z}^{12} \\ \mathbf{Z}^{21} & \mathbf{Z}^{22} \end{bmatrix} \begin{pmatrix} (\hat{\mathbf{x}}^1)^{-1} & \\ & (\hat{\mathbf{x}}^2)^{-1} \end{pmatrix}$, this can be rewritten as:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} \\ \mathbf{A}^{21} & \mathbf{A}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} + \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \tag{2}$$

and transformed into (with $\mathbf{I}$ representing an identity matrix of appropriate size):

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} = \begin{bmatrix} \mathbf{L}^{11} & \mathbf{L}^{12} \\ \mathbf{L}^{21} & \mathbf{L}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \quad \text{with} \quad \begin{bmatrix} \mathbf{L}^{11} & \mathbf{L}^{12} \\ \mathbf{L}^{21} & \mathbf{L}^{22} \end{bmatrix} = \left(\begin{bmatrix} \mathbf{I} & 0 \\ 0 & \mathbf{I} \end{bmatrix} - \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} \\ \mathbf{A}^{21} & \mathbf{A}^{22} \end{bmatrix} \right)^{-1} \tag{3}$$

where the $\mathbf{L}$-matrices are the partitioned Leontief inverse matrices. This equation links output to final demand. An industry's output (one element of vector $\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix}$) is generated to serve (domestic or foreign) final demand either directly or indirectly through intermediate input deliveries to other industries at home or abroad.

At this stage, we introduce greenhouse gas emissions into the model defining the vectors $\mathbf{p}^1$ and $\mathbf{p}^2$ as production-related emissions by industry, respectively, in Belgium and the RoW, and the scalars p^1 and p^2 as country-wide production-related emissions, which correspond to the sum of all elements of, respectively, vectors $\mathbf{p}^1$ and $\mathbf{p}^2$. At the industry

[19] We do not consider the individual final demand categories (household consumption, government consumption) separately but only total final demand.

[20] Bold capital letters are used for matrices, bold lowercase letters for column vectors and letters in italics for scalars. A prime indicates transposition and a circumflex diagonalization of a vector.

level, emission intensities are described by the vectors $\mathbf{w}^1 = \mathbf{p}^1\left(\hat{\mathbf{x}}^1\right)^{-1}$ and $\mathbf{w}^2 = \mathbf{p}^2\left(\hat{\mathbf{x}}^2\right)^{-1}$. Then, the Leontief inverse matrices premultiplied by the diagonalised emission intensity vectors yield the emission multiplier matrices. Take for example $\hat{\mathbf{w}}^1\mathbf{L}^{12}$. Any element $\left(\hat{\mathbf{w}}^1\mathbf{L}^{12}\right)_{\mathbf{ij}}$ represents (direct and indirect) emissions by industry i in Belgium for satisfying final demand for output of industry j in another country (RoW). The full production chain is taken into account: final demand for output of industry j in RoW leads, in a first step, to industry j sourcing intermediate inputs from its suppliers, among which industry i in Belgium. In a second step, all the industries supplying j will require, for their extra output, intermediate inputs from their supplying industries among which i. And so on. This gives rise to emissions: direct emissions in the production for final demand and indirect emissions in the different stages of intermediate input production.

For Belgium, production-based emissions are then:

$$p^1 = \mathbf{w}^{1'}\mathbf{L}^{11}\mathbf{y}^{11} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{21} + \mathbf{w}^{1'}\mathbf{L}^{11}\mathbf{y}^{12} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{22} \tag{4}$$

Belgium's consumption-based emissions, i.e. its carbon footprint c^1, emissions embodied in exports and imports (eex^1 and eem^1), and balance of emissions embodied in trade ($beet^1$) are:

$$\begin{aligned}
c^1 &= \mathbf{w}^{1'}\mathbf{L}^{11}\mathbf{y}^{11} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{21} + \mathbf{w}^{2'}\mathbf{L}^{21}\mathbf{y}^{11} + \mathbf{w}^{2'}\mathbf{L}^{22}\mathbf{y}^{21} \\
eex^1 &= \mathbf{w}^{1'}\mathbf{L}^{11}\mathbf{y}^{12} + \mathbf{w}^{2'}\mathbf{L}^{21}\mathbf{y}^{12} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{21} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{22} \\
eem^1 &= \mathbf{w}^{2'}\mathbf{L}^{22}\mathbf{y}^{21} + \mathbf{w}^{1'}\mathbf{L}^{12}\mathbf{y}^{21} + \mathbf{w}^{2'}\mathbf{L}^{21}\mathbf{y}^{11} + \mathbf{w}^{2'}\mathbf{L}^{21}\mathbf{y}^{12} \\
beet^1 &= \mathbf{w}^{1'}\left\{\mathbf{L}^{11}\mathbf{y}^{12} + \mathbf{L}^{12}\mathbf{y}^{22}\right\} - \mathbf{w}^{2'}\left\{\mathbf{L}^{21}\mathbf{y}^{11} + \mathbf{L}^{22}\mathbf{y}^{21}\right\}
\end{aligned} \tag{5}$$

Belgium's footprint comprises all (direct and indirect) domestic and foreign emissions for satisfying Belgian final demand. Emissions embodied in Belgian exports can be domestic emissions and also foreign emissions. They comprise three elements: domestic direct and indirect emissions for satisfying the RoW's final demand for Belgian output (exports for final demand), foreign indirect emissions for satisfying this same final demand (exports for final demand), and domestic indirect emissions for satisfying (all) final demand for the RoW's output (exports for intermediate demand). It is easy to verify that the difference between production-based and consumption-based emissions corresponds to the balance of emissions embodied in trade for Belgium.

4.2 Results for Belgium

There are few prior calculations of the CO_2 or GHG footprint (c) and the balance of CO_2 or GHG emissions embodied in trade (*beet*) for Belgium in the literature. Sissoko and Vandille (2008) have calculated CO_2-emissions embodied in Belgian trade over 1995–2004 based on a single-region input–output model. According to their results, Belgium is a net exporter of CO_2-emissions over this entire period. This strongly contrasts with Belgium's consumption-based CO_2-emissions calculated with MRIO tables, which always

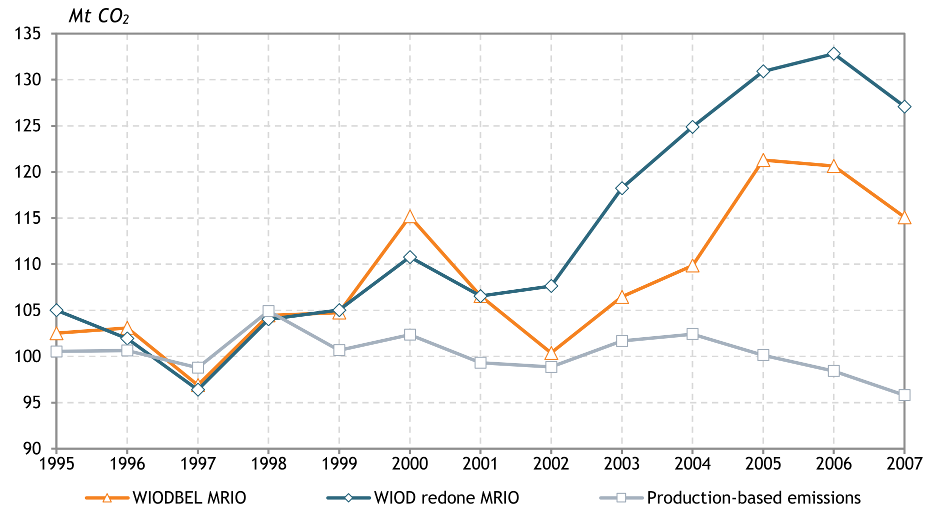

Fig. 4 Belgium's carbon footprint and production-based emissions, 1995–2007

largely exceed production-based emissions. Peters and Hertwich (2008) find a carbon footprint of 181.9 Mt CO_2 in 2001 for Belgium based on data from the GTAP-MRIO database. According to calculations by Tukker et al. (2014) with EXIOBASE, Belgium's carbon footprint amounted to 174.9 Mt CO_2 in 2007. Finally, Arto et al. (2012) report a GHG footprint of 184 Mt CO_2-eq. in 2007 for Belgium based on data from WIOD.[21]

Here, we first look at CO_2 footprints and emissions embodied in trade for Belgium and then add CH_4 and N_2O later for results in terms of a GHG index. For WIODBEL, we take national data on CO_2-emissions for Belgium from the country's air emission accounts (AEA).[22] The emission levels are actually very close to those published by WIOD for Belgium, both overall and at the industry level. We exclude direct emissions of households, which amount to approximately 30 Mt CO_2 and are relatively stable over the entire period.

Figure 4 provides an overview of Belgium's carbon footprint calculated with different MRIO tables. All results cover the years 1995–2007. Belgium's carbon footprint based on the original WIOD MRIO tables is very close to the one based on the WIOD redone MRIO tables. Therefore, we only report the latter.[23] Total production-based emissions (p) from the national AEA excluding direct household emissions are also shown. They amount to 100 Mt CO_2 in 1995 and remain relatively stable over the entire period with a slight downturn at the end. Based on the WIOD redone MRIO tables, we find a carbon footprint that stands at 105 Mt CO_2 in 1995 and remains relatively stable until 2002. It starts to grow fast from 2003 onwards reaching a peak of 133 Mt CO_2 in 2006. The results based on the WIODBEL MRIO tables are relatively similar until 2000 both in levels and in the trend over time. From 2002 onwards, the WIODBEL carbon footprint

[21] Note that all these results include direct emissions by households, which amount to approximately 30 Mt CO_2. As a reference, production-based CO_2-emissions for Belgium (including direct emissions by households) amount to 131 Mt in 2001 and 124 Mt in 2007, and production-based GHG emissions stand at 141 Mt CO_2-eq. in 2007 in the Belgian AEA.

[22] See Vandille and Janssen (2012) for a methodological description.

[23] Results based on the original WIOD MRIO tables are available upon request.

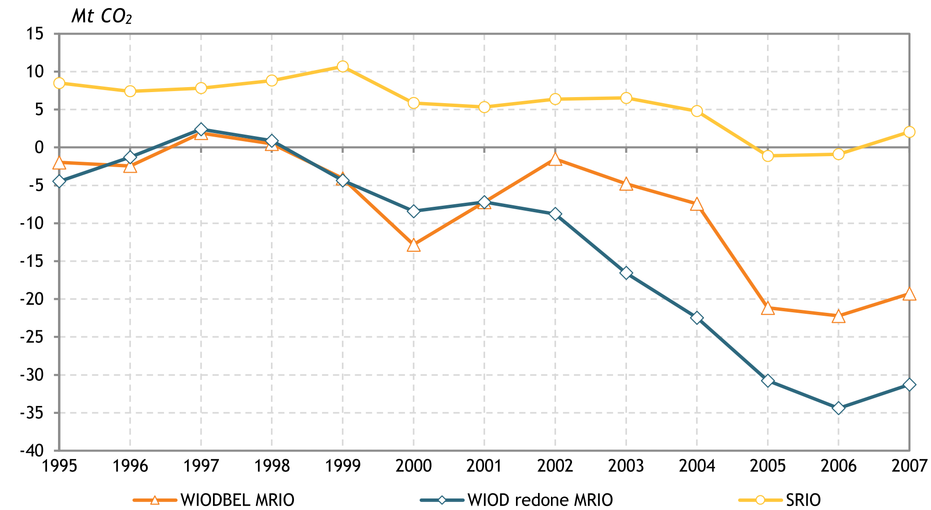

Fig. 5 Belgium's balance of CO_2-emissions embodied in trade, 1995–2007

rises just like the WIOD redone carbon footprint but at a slower pace. It reaches its peak at 121 Mt CO_2 in 2005. Hence, there is a gap between the WIODBEL and the WIOD redone footprint from 2001 onwards, the WIOD redone footprint being higher than the WIODBEL footprint.

The results can also be presented in terms of the balance of emissions embodied in trade (*beet*). A positive balance means that Belgium is a net exporter of emissions and a negative balance means that Belgium is a net importer of emissions. Recall that the *beet* is equal to the difference between production-based emissions and consumption-based emissions. The carbon footprints calculated with both WIODBEL and WIOD redone data exceed production-based emissions for all years except 1997 and 1998. Hence, these results suggest that Belgium has a negative balance of CO_2-emissions embodied in trade over almost the entire period (see Fig. 5), i.e. is mostly a net importer of CO_2. The negative *beet* increases in absolute value in the early 2000s amounting to 20–30% of production-based emissions. Figure 5 also shows results for the *beet* calculated with national IO tables in a single-region IO model (SRIO), which are equivalent to those reported in Sissoko and Vandille (2008).[24] According to these results, Belgium is a net exporter of emissions in all years except 2005 and 2006.

Furthermore, we can test for aggregation bias in the footprint results given that compared to WIOD we have a more detailed industry breakdown for Belgium in the WIODBEL MRIO tables. Carbon footprints calculated with data from aggregated tables are always higher. The aggregation bias is between 2 and 3% (of results for disaggregated tables) in all sample years.

Finally, we have also computed GHG footprints and GHG emissions embodied in trade. Expressed in CO_2-equivalents (CO_2-eq.), the GHG index we use here is based on the global warming potential of CO_2, CH_4 (methane) and N2O (nitrous oxide).[25] The

[24] The small differences in results come from differences in the data due to NA revisions.

[25] Due to a lack of emission data in WIOD, we restrict our GHG index to these three standard gases. In line with global warming potentials reported in IPCC (1995, p. 22), it is computed as GHG index $= CO_2 + 21 \times CH_4 + 310 \times N_2O$.

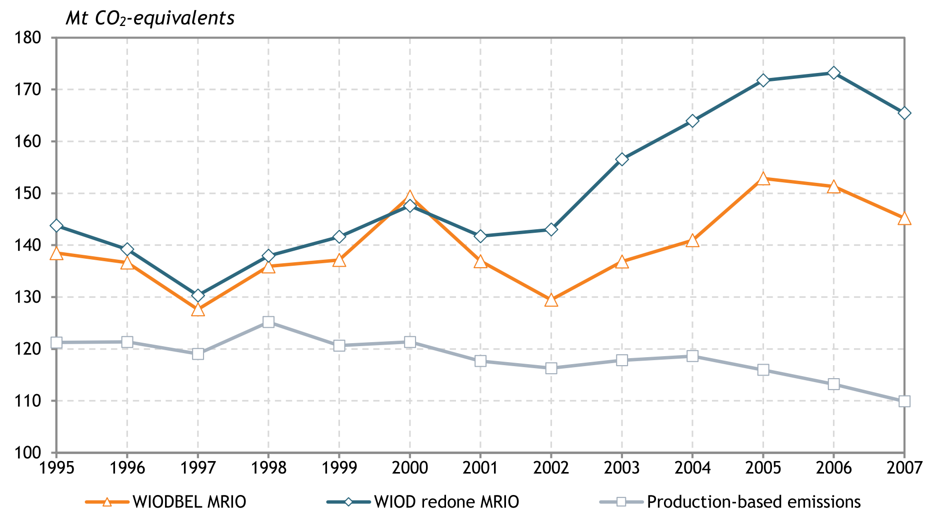

Fig. 6 Belgium's GHG footprint and production-based emissions, 1995–2007

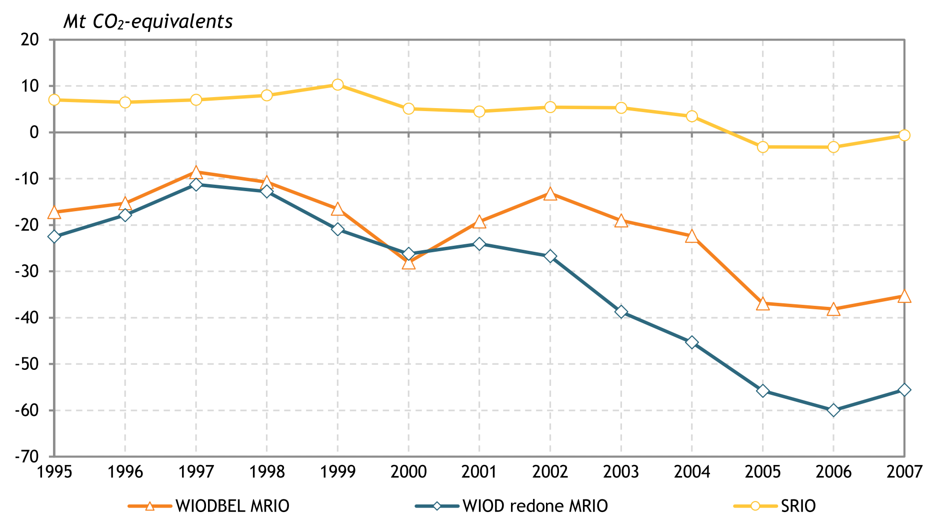

Fig. 7 Belgium's balance of GHG emissions embodied in trade, 1995–2007

results are reported in Figs. 6 and 7. As before, Belgian production-based GHG emissions come from the country's AEA. Again they are very close in levels to WIOD emission data. The results on GHG footprints and emissions embodied in trade for Belgium are very similar to the results with CO_2-emissions only. MRIO-based GHG footprints exceed production-based GHG emissions for all sample years without any exception.

5 Structural decomposition analysis of WIOD and WIODBEL footprints

In order to shed more light on the difference in footprint results for Belgium based on WIODBEL MRIO tables and on WIOD redone MRIO tables, we compare the two by means of a structural decomposition analysis (SDA). From a methodological point of view, this is an SDA to compare two different databases, which makes it different from a standard intertemporal SDA.[26] Our approach is comparable to prior use of SDA for comparing carbon footprints calculated with different MRIO databases. Owen et al. (2014) do so for GTAP, WIOD and Eora and Arto et al. (2014) for WIOD and GTAP. These authors compare carbon footprints for all countries in the global MRIO tables, while we specifically focus on Belgium. It is noteworthy that Owen et al. (2014) find that the differences in footprint results between MRIO databases are biggest for Belgium. In our SDA formulation, we look at the effects of differences in emission intensities, input structures and final demand to get an idea of how the consistency with Belgian national data in WIODBEL influences footprint results with respect to WIOD redone. We specifically isolate differences for Belgium. Note that in this SDA, contributions of particular differences between WIODBEL and WIOD redone, e.g. in re-exports and valuation tables, to footprint results are only identified indirectly through the effects of differences in input structures, final demand and emission intensities.

We start from the expression for calculating the carbon footprint for Belgium (c^1 in Eq. (5)). We add subscript index s for the dataset used in the calculation—either WIODBEL or WIOD redone—and rewrite it as follows:

$$c_s^1 = \mathbf{w}_\mathbf{s}^{'}\mathbf{L}_\mathbf{s}\mathbf{y}_\mathbf{s}^{\cdot 1} = \begin{pmatrix} \mathbf{w}_\mathbf{s}^1 \\ \mathbf{w}_\mathbf{s}^2 \end{pmatrix}^{'} \begin{bmatrix} \mathbf{L}_\mathbf{s}^{11} & \mathbf{L}_\mathbf{s}^{12} \\ \mathbf{L}_\mathbf{s}^{21} & \mathbf{L}_\mathbf{s}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}_\mathbf{s}^{11} \\ \mathbf{y}_\mathbf{s}^{21} \end{pmatrix} \tag{6}$$

This is the footprint calculation for 1 year. We compare the WIODBEL footprint ($s = b$) and the WIOD redone footprint ($s = r$) for Belgium for each sample year.

$$\Delta c^1 = c_b^1 - c_r^1 = \mathbf{w}_\mathbf{b}^{'}\mathbf{L}_\mathbf{b}\mathbf{y}_\mathbf{b}^{\cdot 1} - \mathbf{w}_\mathbf{r}^{'}\mathbf{L}_\mathbf{r}\mathbf{y}_\mathbf{r}^{\cdot 1} \tag{7}$$

To determine contributions of differences in the three terms on the right-hand side ($\Delta\mathbf{w}^{'}$, $\Delta\mathbf{L}$, $\Delta\mathbf{y}^{\cdot 1}$) to the difference in footprints (Δc^1), we apply the Sun (1998) decomposition formula, which is based on a linear interpolation of a Paasche and a Laspeyres index.[27] There are three effects:

$$\Delta c^1 = d_w + d_L + d_y \tag{8}$$

Here, d_w is the contribution of differences in emission intensities to the difference in footprints between WIODBEL and WIOD redone, d_L is the contribution of differences in the Leontief inverse matrix, and d_y the contribution of differences in Belgian final demand.

$$\begin{aligned} d_w &= \Delta\mathbf{w}^{'}\mathbf{L}_\mathbf{r}\mathbf{y}_\mathbf{r}^{\cdot 1} + \frac{1}{2}\Delta\mathbf{w}^{'}\Delta\mathbf{L}\mathbf{y}_\mathbf{r}^{\cdot 1} + \frac{1}{2}\Delta\mathbf{w}^{'}\mathbf{L}_\mathbf{r}\Delta\mathbf{y}^{\cdot 1} + \frac{1}{3}\Delta\mathbf{w}^{'}\Delta\mathbf{L}\Delta\mathbf{y}^{\cdot 1} \\ d_L &= \mathbf{w}_\mathbf{r}^{'}\Delta\mathbf{L}\mathbf{y}_\mathbf{r}^{\cdot 1} + \frac{1}{2}\Delta\mathbf{w}^{'}\Delta\mathbf{L}\mathbf{y}_\mathbf{r}^{\cdot 1} + \frac{1}{2}\mathbf{w}_\mathbf{r}^{'}\Delta\mathbf{L}\Delta\mathbf{y}^{\cdot 1} + \frac{1}{3}\Delta\mathbf{w}^{'}\Delta\mathbf{L}\Delta\mathbf{y}^{\cdot 1} \\ d_y &= \mathbf{w}_\mathbf{r}^{'}\mathbf{L}_\mathbf{r}\Delta\mathbf{y}^{\cdot 1} + \frac{1}{2}\Delta\mathbf{w}^{'}\mathbf{L}_\mathbf{r}\Delta\mathbf{y}^{\cdot 1} + \frac{1}{2}\mathbf{w}_\mathbf{r}^{'}\Delta\mathbf{L}\Delta\mathbf{y}^{\cdot 1} + \frac{1}{3}\Delta\mathbf{w}^{'}\Delta\mathbf{L}\Delta\mathbf{y}^{\cdot 1} \end{aligned} \tag{9}$$

[26] Note that we do not require constant price data for this SDA because we compare databases and we do not analyse changes over time.

[27] As noted in Hoekstra et al. (2016), this is equivalent to the widely used approach of computing the average of the k! complete weight decompositions where k is the number of terms in the expression to be decomposed (Dietzenbacher and Los 1998).

We further decompose these effects to isolate changes in data for Belgium. For d_w, this is not necessary as the only difference in emission intensities between WIODBEL and WIOD redone is in the data for Belgium. For d_y, we split Belgian final demand into final demand for domestic output and imported final demand, i.e. Belgian final demand for foreign output. This comes down to additively splitting the variation in Belgian final demand into two terms:

$$\Delta \mathbf{y}^{\cdot 1} = \begin{pmatrix} \Delta \mathbf{y}^{11} \\ \Delta \mathbf{y}^{21} \end{pmatrix} = \begin{pmatrix} \Delta \mathbf{y}^{11} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ \Delta \mathbf{y}^{21} \end{pmatrix} = \Delta \mathbf{y}^{\cdot 1}_{\mathbf{d}} + \Delta \mathbf{y}^{\cdot 1}_{\mathbf{m}} \tag{10}$$

and deriving two final demand effects: d_{y_d} and d_{y_m}. They measure the contributions of differences in Belgian final demand for domestic and foreign output.

For splitting d_L, we rely on the standard formula that links differences in the Leontief inverse to differences in the input requirement matrices (see Miller and Blair 2009, pp. 602–603): $\Delta \mathbf{L} = \mathbf{L_r} \Delta \mathbf{A} \mathbf{L_b}$ with $\Delta \mathbf{A} = \mathbf{A_b} - \mathbf{A_r}$. We specifically isolate terms for Belgium in $\Delta \mathbf{A}$:

$$\begin{aligned} \Delta \mathbf{A} &= \Delta \mathbf{A}_{\mathbf{bel\_d}} + \Delta \mathbf{A}_{\mathbf{bel\_m}} + \Delta \mathbf{A}_{\mathbf{bel\_x}} + \Delta \mathbf{A}_{\mathbf{nbel}} \\ &= \begin{bmatrix} \Delta \mathbf{A}^{11} & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \Delta \mathbf{A}^{21} & 0 \end{bmatrix} + \begin{bmatrix} 0 & \Delta \mathbf{A}^{12} \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \Delta \mathbf{A}^{22} \end{bmatrix} \end{aligned} \tag{11}$$

This yields four effects: $d_{L\_bel\_d}$, $d_{L\_bel\_m}$, $d_{L\_bel\_x}$ and d_{L_nbel}. They measure contributions of differences in input requirements to differences in the carbon footprint via the Leontief effect: the first one measures contributions of differences in Belgian domestic input requirements, the second one of differences in Belgian imported input requirements, the third one of differences in foreign input requirements for Belgian output, and the last one of differences in foreign input requirements for output of all other countries. The latter two only have an indirect effect on the Belgian carbon footprint.

Thus, expanding (8) we have the following effects in our SDA:

$$\Delta c^1 = \underbrace{d_w}_{(1)} + \underbrace{d_{L\_bel\_d}}_{(2)} + \underbrace{d_{L\_bel\_m}}_{(3)} + \underbrace{d_{L\_bel\_x}}_{(4)} + \underbrace{d_{L\_nbel}}_{(5)} + \underbrace{d_{y\_d}}_{(6)} + \underbrace{d_{y\_m}}_{(7)} \tag{12}$$

1. Emission intensity effect
2. Belgian domestic input requirements effect
3. Belgian imported input requirements effect
4. Foreign input requirements effect for Belgian output (exports)
5. Foreign input requirements effect for all other output
6. Belgian domestic final demand effect
7. Belgian imported final demand effect.

The difference between the carbon footprint for Belgium based on WIODBEL and on WIOD redone is reported as a line in Fig. 8. It is relatively small during the first half of the sample period, never exceeding 5 Mt CO_2 in absolute value or 5% of production-based CO_2–emissions. From 2002 onwards, it becomes negative and sizeable, i.e. the

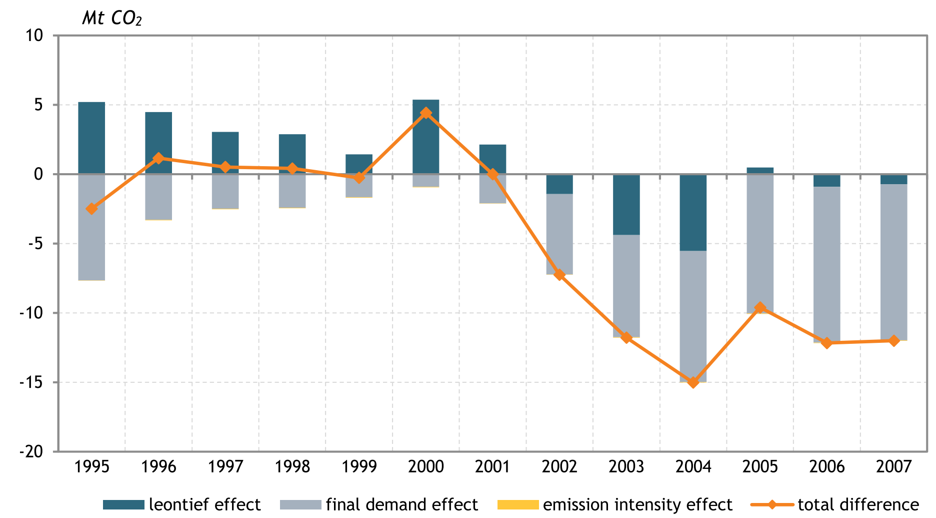

Fig. 8 SDA of the difference between the WIODBEL and WIOD redone carbon footprint—3 effects

WIOD redone footprint largely exceeds the WIODBEL footprint. The difference is largest in absolute value in 2004 when it amounts to 15 Mt CO_2 or 15% of Belgium's production-based emissions.

The bar chart part of Fig. 8 shows the decomposition results for the three effects of Eq. (8) for each year.[28] The emission intensity effect is very small and its influence on the overall difference between the two footprints can be neglected. Between 1995 and 2001, the Leontief effect is positive, i.e. the differences in intermediate input requirements between WIODBEL and WIOD redone lead to a higher carbon footprint for WIODBEL. The opposite holds for differences in final demand, i.e. the final demand effect is negative over the period 1995–2001. Overall, the two effects compensate more or less so that the difference between the WIODBEL footprint and the WIOD redone footprint remains small. From 2002 onwards, the Leontief effect becomes negative in all years except for 2005. The final demand effect is negative over the entire period 2002–2007 and increases in absolute value. Thus, differences in intermediate input requirements and, in particular, differences in final demand contribute to our finding that the WIODBEL-based carbon footprint for Belgium is lower between 2002 and 2007.

The compensation between the final demand effect and the Leontief effect between 1995 and 2001 can be partly attributed to differences in the distribution of taxes and subsidies on production over intermediate and final demand: a larger share of taxes and subsidies on production is subtracted from final demand in WIODBEL than in WIOD redone (see Fig. 2). Hence, Belgian final demand in basic prices is globally higher in WIOD redone, which leads to a negative final demand effect, and Belgian intermediate demand is globally higher in WIODBEL, which leads to a positive Leontief effect.

The extra decomposition terms in Eq. (12), which are specifically focused on differences in data for Belgium, provide further insights into where the difference between

[28] The decomposition results for GHG footprint differences are not reported but can be made available upon request. They are qualitatively equivalent to the decomposition results for the CO_2 footprint.

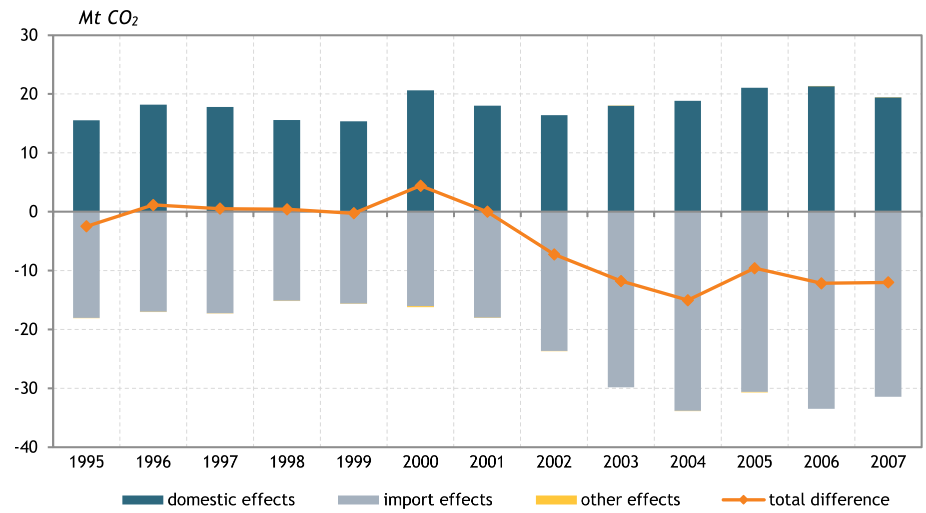

Fig. 9 SDA of the difference between the WIODBEL and WIOD redone carbon footprint—7 effects aggregated

WIODBEL and WIOD redone carbon footprints comes from. In Fig. 9, we have summed effects so as to highlight how much of the difference in Belgium's footprints is due to differences in Belgian domestic demand (domestic effect) and to differences in Belgian imports (import effect). The domestic effect is the sum of the Belgian domestic input requirements effect ($d_{L\_bel\_d}$) and the Belgian domestic final demand effect (d_{y_d}), and the import effect is the sum of the Belgian imported input requirements effect ($d_{L\_bel\_m}$) and the Belgian domestic final demand effect (d_{y_m}). The other three effects (d_w, $d_{L\_bel\_x}$ and d_{L_nbel}), which all turn out to be small, are aggregated into one term ("other effects").

The domestic effect is positive (higher WIODBEL carbon footprint) and relatively stable at 15–20 Mt CO_2 over the entire period. The import effect is negative and amounts to approximately 15–20 Mt CO_2 in absolute value between 1995 and 2001 leading to a rather small overall difference in footprints for those years. From 2002 onwards, the import effect grows in absolute value to reach 34 Mt CO_2 in 2004. Hence, for the years 2002–2007, it more than compensates the positive domestic effect so that the difference between the WIODBEL and the WIOD redone footprint is negative. This is related to the increase in the difference in Belgian re-exports between WIODBEL and WIOD redone from 2002 onwards (see Fig. 3).

6 Discussion and conclusions

In this article, we have compared carbon footprint results for Belgium for the years 1995–2007 calculated with original WIOD MRIO tables and modified WIODBEL MRIO tables. We have built the latter by reproducing the construction process of MRIO tables in the WIOD project replacing source data for Belgium used by the WIOD consortium by data from detailed supply-and-use tables from national sources. Subsequently, we keep data for Belgium unchanged in the construction process.

Belgium's carbon footprint based on WIODBEL tables amounts to 138 Mt CO_2-eq. in 1995 and 145 Mt CO_2-eq. in 2007 (total GHG emissions excluding direct emissions of households[29]). This is substantially higher than production-based GHG emissions which stand at 121 Mt CO_2-eq. in 1995 and 110 Mt CO_2-eq. in 2007. Hence, according to our calculations with WIODBEL tables, Belgium is a net importer of GHG emissions over the entire period.[30] From 2002 onwards, the original WIOD-based footprint is systematically higher than the WIODBEL-based footprint. The difference quickly becomes sizeable: it amounts to 14% on average between 2003 and 2007. The original WIOD footprint increased by 15% between 1995 and 2007, whereas the WIODBEL footprint only grew by 5% over the same period. According to the results of our decomposition analysis, this difference in footprint results can be attributed to a large extent to the growing difference in the estimated magnitude of Belgium's re-exports, which are higher in WIODBEL than in the original WIOD tables. Since re-exports are subtracted from imports in the MRIO construction process, Belgium's imports are globally lower in WIODBEL, which leads to a lower carbon footprint. Hence, original WIOD tables tend to overestimate the Belgium's carbon footprint, confirming prior findings for the Netherlands for 2003 and 2009 (Edens et al. 2015).

Although calculations of carbon footprints and emissions embodied in international trade based on MRIO tables are mainly used in analyses that take a global perspective, the adoption of MRIO tables for footprint analysis at the national level should not be neglected with a view to promoting carbon footprints as a climate policy tool. In this context, our work with WIOD tables shows that the consistency of MRIO tables with detailed data from national sources is an issue, in particular for a small open economy like Belgium. To foster the acceptance of footprint results at the national level, we believe that it would be beneficial for such an MRIO construction process to accommodate the desire to respect detailed data from national sources while limiting the workload of the process and avoiding hindrances to global balancing of the tables. With regard to an MRIO construction process based on supply-and-use tables for individual countries like in WIOD, it would, in our view, be worthwhile considering the integration of as much detailed material from national statistical offices (NSIs) as possible for all countries up to valuation tables and import use tables. Indeed, our work for Belgium with WIOD tables has shown that differences in valuation tables and import use tables make for differences in footprint results. If these tables are not publicly available, then NSIs should make them available to those who construct MRIO tables. Finally, keeping data fixed for an individual country in the subsequent balancing stage of the MRIO construction process is not feasible when it comes to building tables for more than just one country. In summary, we suggest building global MRIO tables by incorporating a maximum of detailed data from national sources in close cooperation with NSIs before letting the balancing process work freely.

[29] Direct emissions of households amount to approximately 30 Mt CO_2 and are relatively stable over the entire period.

[30] This confirms prior results based on global MRIO tables that are not consistent with the Belgium's detailed national accounts (Peters and Hertwich 2008; Arto et al. 2012; Tukker et al. 2014). Moreover, it allows to revise the—counterintuitive—finding based on national IO tables that Belgium is a net exporter of emissions (Sissoko and Vandille 2008).

7 Availability of data and materials

All data from the WIOD project that have been used in our calculations are publicly available on the projects website (www.wiod.org). The detailed Belgian supply-and-use tables from the UpdateSUT project are confidential at the workformat level of disaggregation. The WIODBEL tables that we have used for the footprint calculations (same industry breakdown as the original WIOD MRIO tables) can be obtained upon request from the authors.

Authors' contributions

CH, BH and BM carried out the data treatment and footprint calculations. BM drafted the manuscript. All authors read and approved the final manuscript.

Author details

[1] Federal Planning Bureau, Avenue des Arts 47-49, 1000 Brussels, Belgium. [2] Department of Economics, Ghent University, Ghent, Belgium.

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Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

Not applicable.

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