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METHODS, TOOLS, DATA, AND SOFTWARE

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Toward the development of subnational hybrid input–output tables in a multiregional framework

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Abstract

Environmental input–output analyses can be a useful decision support tool at the subnational level, because of its ability to capture economic and environmental impacts at other geographical levels. Yet, such analyses are hindered by the lack of subnational IO tables. Furthermore, the lack of physical product and waste flows in what is known as a "hybrid" table prevents a range of consumption-based and circular-economy-type analyses. We demonstrate the development of a multiregional hybrid IOT (MRHIOT) along with environmental extensions at the subnational level and exemplify it for the case of Belgium. The development procedure discloses a novel approach of combining national hybrid tables, subnational monetary tables, and physical survey-based data. Such a combination builds upon a partial-survey approach that includes a range of techniques for initial estimation and reconciliation within a balancing procedure. For the validation of the approaches, we assessed the magnitude of deviations between the initial and final estimates and analyzed the uncertainties inherent to each initial estimation procedure. Subsequently, we conducted a consumption-based analysis where we assessed the carbon footprint (CF) at the subnational level and highlighted the CF inherent to the interregional linkages. This study provides methodological and application-based contributions to the discussion on the relevance of hybrid subnational tables and analyses compared to national ones. The proposed approach could be replicable to some extent for further developing subnational MRHIOT. The study is expected to foster more research toward the development of further subnational MRHIOT as well as its associated wide-ranging applications.

KEYWORDS
carbon footprint, environmental accounting, hybrid input–output tables, industrial ecology, material balance, subnational analysis

1 | INTRODUCTION

Multiregional input–output tables (MRIOT) represent an important tool for environmental–economic analyses. Such analysis can be performed at product, sectoral, subnational, national, and global levels. National IOT as well as information on trade flows between countries have been constructed and progressively made available. This has triggered the development of global MRIO databases such as EXIOBASE (Merciai & Schmidt, 2017; Stadler et al., 2018; Wood et al., 2015), Eora (Lenzen, Kanemoto, Moran, & Geschke, 2012, 2013), and WIOD (Dietzenbacher, Los, Stehrer, Timmer, & Vries, 2013); but also, computational platforms for constructing Australian MRIOT such as the Industrial Ecology Virtual Laboratory (IELab) (Lenzen et al., 2014).

The importance of MRIOT in analyzing environmental aspects lies in their environmental extensions such as emissions, natural resources, waste, water, land use. However, except the hybrid (or mixed-unit) MRIOT of EXIOBASE, most databases account for intersectoral flows of products in monetary units and environmental extensions in physical units. The disconnection between the monetary values of intersectoral flows and the physical environmental extensions may hamper the capacity for policy support, for example, for waste management and circular economy (CE), since the definition and achievement of quantitative targets within these policies could be facilitated when adequately formulated in physical terms (Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, & Tukker, 2018; McCarthy, Dellink, & Bibas, 2018; Towa, Zeller, & Achten, 2020a).

In addition to the physical MRIOT, subnational MRIOT and related applications develop at slower pace than economic and national MRIOT. One major drawback is the lack of data (Malik, McBain, Wiedmann, Lenzen, & Murray, 2018; Minx et al., 2009; Towa et al., 2020a). Most physical data on production and consumption are accounted for at the national level. And, statistics on physical flows, and outflows such as waste and emissions, and international and interregional physical trade flows are hardly accessible at the subnational level (Boero, Edwards, & Rivera, 2018; Giljum & Hubacek, 2009).

Regions rely on natural resources and products from other regions within a country or from the rest of the world. Consequently, they unavoidably cause emissions, generate waste, use natural resources, and are thus responsible for environmental impacts caused beyond their geographical boundaries (Minx et al., 2009; Towa, Zeller, Merciai, & Achten,). In some countries, some environmental policies are of regional competence (e.g., waste management in Belgium). In other countries, national policies apply to all regions of the country. In either case, it is important to consider the reduction of environmental pressures within and outside regional boundaries. Therefore, knowledge on interregional trade flows at the subnational level is paramount in quantifying the impacts deriving from interregional linkages (Sargento, Ramos, & Hewings, 2012).

The lack of survey-based interregional data renders the development of MRIOT at subnational level a complex and time-consuming task, requiring adequate methods and high computational power. The lack of survey-based data has often induced the application of various non-survey methods such as location-quotient method, RAS, and entropy (Sargento et al., 2012; Szabó, 2015; Többen & Kronenberg, 2015). The general underlying principle of these methods lies in exploiting the data that are available to estimate the data that are missing. Considering the context where physical data at subnational level are missing, applying such methods can serve as a pathway toward the construction of MRIOT at the subnational level.

This paper aims to demonstrate the development of a multiregional hybrid IOT (MRHIOT) and environmental extensions at the subnational level. The demonstration is presented jointly with an example on Belgium. The Belgian regions considered are Brussels, Flanders, and Wallonia (NUTS 2 level). We develop subnational HIOT for Belgium that we link with IOT of 42 other countries and 5 rest of world (RoW) regions. We propose a top-down approach in which we regionalize the national hybrid supply and use table (SUT) to obtain subnational SUT (initial estimation). These are subsequently harmonized based on a non-survey method (final estimation). The final estimates are then analytically compared with the initial ones to quantify the uncertainties inherent to the estimation procedure. We also propose a consumption-based analysis as an analytical capability of the model. Here, "hybrid'' pertains to a mixed-unit framework in which in the SUT tangible products and energy products are given in physical unit, non-tangible energy products in energy units and services in monetary unit. The main environmental extensions developed include natural resources, emissions, and waste including the trade of waste.

2 | METHOD AND DATA

2.1 | The model framework

Figure 1 shows the subnational HSUT in a multiregional framework. The framework is applied to the three Belgian regions Brussels, Flanders, and Wallonia and includes both the supply and use sides.

The supply side includes the core supply table that shows the products and services produced by sectors in the economy. Furthermore, the supply table also includes the waste sectors providing waste treatment services for a certain flow of waste. The supply table is extended with environmental accounts namely emissions, supply of waste (or waste generation), and stock addition, all in mass units. The emission account shows the emission types generated by different sectors and final use categories. The supply of waste accounts for the waste generated, induced by the production and consumption of products and services purchased in the accounting period 2011. And the stock addition accounts for the products that join the in-use stocks and will become waste in the future years.

The use side includes the core intermediate and final use tables. These use tables describe the flows of products and services consumed by sectors and final users. Moreover, the use tables integrate the waste types that are generated by sectors and final users and their related waste treatment (e.g., wood waste recycling). Besides, for each use, we differentiate the intraregional, interregional, and international use. For instance, the use table of Brussels includes the use of domestic products (intraregional), use of Flemish products (interregional), use of Walloon products (interregional), and the use of RoW products (international). In addition, the use of Brussels' products in other regions, as well as in RoW is also illustrated (international). The RoW includes 42 countries and 5 RoW regions as available in EXIOBASE.

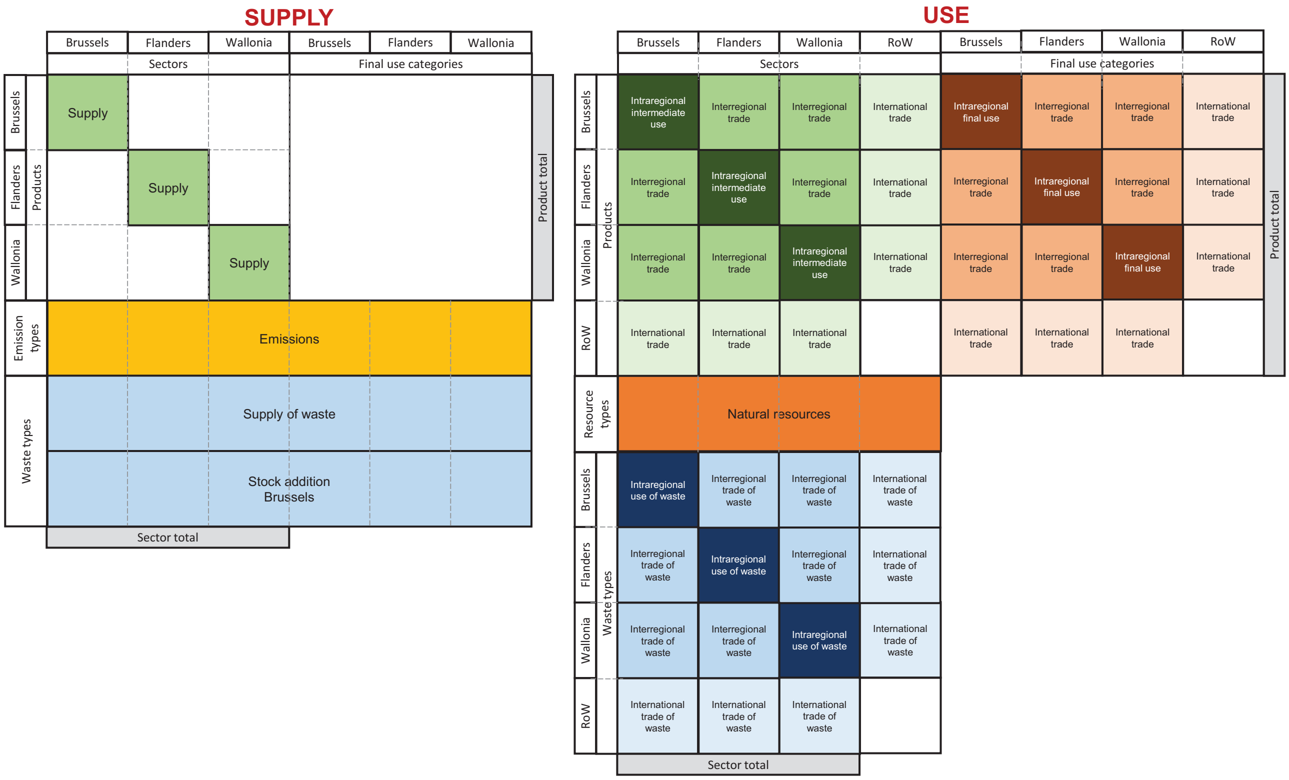

FIGURE 1 Framework of the multiregional hybrid supply and use tables at subnational for the case of Belgium. RoW = rest of world that includes 47 countries and regions. The list is provided inSupportingInformation S1

The intermediate use table is extended with environmental accounts such as natural resources and use of waste (or waste treatment). The use of waste table differentiates the use of waste according to the origin of the waste generation. For instance, the use of waste table of Brussels includes the use of domestic waste, that is, waste generated in Brussels, the use of interregional waste, that is, waste generated in Flanders and Wallonia, and the use of international waste, that is, waste generated in the RoW. In addition, the use of Brussels' waste in the other Belgian regions and in the RoW is also included. Clearly, the framework presented in this study includes the trade of waste for treatment.

Table 1 provides further details.

2.2 | Data description

First, we used the subnational SUT in monetary units that were developed based on the (confidential) data provided by the Federal Bureau of Planning (Avonds et al., 2016). The monetary SUT (MSUT) is part of an environmentally extended interregional IO model for Belgium, for 2010. The developed model structures the Belgian economy into 81 products and sectors, plus 6 final use categories. It includes the SUT of Brussels, Flanders, and Wallonia, which also include the interregional trade. The methodology and data sources used to construct that model is detailed in (Avonds et al., 2016; Zeller, 2017).

Second, we used EXIOBASE v3.3.17 that provides the MRHSUT including national data on production and consumption in Belgium in 2011 in mass, energy, and monetary units (Merciai & Schmidt, 2017). The tables include 200 products and 164 sectors, plus 6 final uses categories. We used the tables in a 164 × 164 dimension. It includes the trade between Belgium and the RoW. EXIOBASE also contains country-wide environmental accounts, such as emissions, natural resources, and waste.

Third, we have collected physical survey-based data which are data that have not been used to construct national and subnational tables and that include information on subnational production and consumption. The survey-based data we have gathered include production volumes in tons,[1] energy production in energy units and waste collection and treatment in mass units, for each region. They have been all obtained from regional statistics.

[1] "Tons," as used in this paper refers to metric tons.

TABLE 1 Description of tables presented in the framework and used in this study

Indices			
Products	i	164	
Sectors	j	164	
Final use categories	y	6	
Waste types	w	19	See list in Supporting Information S2
Resources types	res	39	
Emission types	b	65	
Regions	r and r'	4	Includes Brussels, Flanders, Wallonia and RoW; $r = r' =$ RoW is not allowed
Tables			
Supply	V'^{r}_{ij}	Products i by sectors j	Shows the supply of products and services in region r
Use	$U^{rr'}_{ij}$	Products i by sectors j	Shows the products and services produced in region r' and used in region r • $r =$ Brussels and $r' =$ Flanders→ use of Flanders' products in Brussels, or imports from Flanders to Brussels (i.e., interregional imports) • $r =$ Brussels and $r' =$ RoW→ use of RoW products in Brussels, or imports from RoW to Brussels (i.e., international imports) • $r =$ RoW and $r' =$ Brussels→ use of Brussels products in RoW, or exports to RoW from Brussels (i.e., international exports)
Final use	$Y^{rr'}_{iy}$	Products i by final use categories y	
Resource	$R^{r}_{\text{res}\,j}$	Resources res by sectors j	Shows the natural resources extracted in region r
Use of waste	$W_{\text{use}\,wj}^{\;rr'}$	Waste types w by sectors j	Shows the waste generated in region r and used in region r' • $r =$ Brussels and $r' =$ Flanders→ use of Brussels waste in Flanders, or imports of waste treatment services from Flanders to Brussels (i.e., interregional trade of waste) • $r =$ Brussels and $r' =$ RoW→ use of Brussels waste in RoW, or imports of waste treatment services from RoW to Brussels (i.e., international trade of waste)
Supply of waste	$W_{\text{sup}}^{\;r}$		Shows the waste generated in region r
Stock addition	ΔS^{r}		It shows the stock addition produced in region r in the accounting period and assumed to become waste in period the future
Emissions	B^{r}	Emission types b by sectors j	Shows the emissions released in region r

The classification of products and sectors in the subnational monetary tables and EXIOBASE are both based on the NACE system. This facilitates the establishment of correspondence between the two classifications. The subnational MSUT have 81 products and sectors, whereas EXIOBASE SUT have 164. While some products and sectors have the same resolution, for example, the forestry sector, it is not the case for sectors such as the agriculture sector. The 164 products include 37 services, 92 physical products, and 35 waste types. We provide the correspondence between the two classifications in Supporting Information S1.

2.3 | Initial estimation of regional hybrid SUT

2.3.1 | The monetary part of the regional hybrid SUT

The monetary part of the subnational hybrid SUT covers 37 services and is built upon data on the subnational MSUT from Zeller (2017) and national MSUT from EXIOBASE. First, the subnational monetary use table follows the same framework as illustrated in Figure 1, that is, they distinguish the intraregional, interregional, and international products. Second, the subnational monetary table and EXIOBASE have the same product resolution especially for services. These points provided the advantage to directly exploit the monetary data on final use. To exploit data on the intermediate use tables, the second point only did not hold. In the supply and use tables, services are distributed over 81 sectors instead of 164 sectors as targeted. In order to obtain this sector resolution, we have disaggregated the 81 sectors of the regional monetary tables into 164 sectors. This disaggregation procedure was based on a proration technique that extracts the shares of products in the MSUT of EXIOBASE and applies them to the subnational MSUT.

2.3.2 | The physical part of the regional hybrid SUT

The physical part of the subnational hybrid tables covers 92 products and is built on a regionalization of the physical SUT (PSUT) of EXIOBASE. To calculate the regionalization keys, we exploited in first order the physical survey-based data, when available. Whenever physical survey-based data were not available, and whenever the product resolution between EXIOBASE and the subnational MSUT matched, we applied the subnational MSUT in second order. As last resort we used the disaggregated MSUT when the product resolution between EXIOBASE and the subnational MSUT was different.

(a) Supply tables

To develop subnational supply tables we developed regionalization keys in accordance to the procedure previously presented. The first-order regionalization keys (i.e., for 51 products) were calculated from physical survey-based data, mainly related to subnational production volumes. These keys correspond to the share of regional physical production in the national one. The second-order keys were obtained from the subnational MSUT (i.e., for 35 products) as the share of regional monetary production in the national one. Lastly, the regionalization keys for the nine remaining products were obtained from the disaggregated monetary supply table the share of regional monetary production in the national one.

(b) Intermediate and final use tables

The use table comprises three main pieces: intraregional use, interregional use, and international use. We first estimated the subnational physical intraregional intermediate use. To do so, the supply and use tables of EXIOBASE were used to determine the Belgian physical production function. The latter is the technical coefficients matrix where each element represents the direct inputs of product *i* produced in Belgium that are required to produce one unit of output of sector *j*. To obtain a first estimation of subnational intraregional use, these coefficients were applied to regions according to their respective productions. Second, to estimate the intermediate use of interregional imports, we converted the interregional part of the disaggregated MSUT in physical units. To do so, we applied the price (€) per unit of physical unit of products. Lastly, to estimate the intermediate use of international imports and exports, we derived regionalization keys from the disaggregated monetary intermediate use of international imports and exports. For example, the keys express the shares of imports to each region from RoW in the total imports to Belgium. Then, the regionalization keys were applied to the national physical use of international imports of EXIOBASE.

The same latter approach was performed to estimate the final use of international imports and exports: extract regionalization keys from the disaggregated monetary final use of international imports/exports and apply them to the national physical final use of international imports/exports of EXIOBASE. The remaining part of the final use is the intraregional and interregional use. To estimate these pieces, we isolate the monetary tables of final use of intraregional and interregional products, from which we extracted regionalization keys. The latter were subsequently applied to the national physical intra-country final use of EXIOBASE.

Before closing this section, we provide few comments on the steps performed so far.

The initial estimation of subnational PSUT was based on the development of regionalization keys that were applied to the PSUT of EXIOBASE. First, we share the concern that this initial estimation may possibly come with unavoidable inaccuracies or discrepancies inherent to our regionalization procedure. We attempt to treat most of them in Section 2.5, and empirically illustrate and discuss them in Section 3.1.

Second, the underlying reason of this regionalization approach is data oriented. We tried to use as much as possible physical-based regionalization keys to develop the subnational physical tables. This was especially the case for the estimation of the supply table. Monetary-based regionalization keys were involved when physical-based ones cannot be calculated, due to the lack of physical data. And this was the case for the other pieces of the subnational tables. As the low availability of subnational physical data may hamper the construction of subnational PSUT from a bottom-up perspective, we stress that subnational physical data can be a starting point for the construction of subnational PSUT from a top-down perspective; for example, by applying a regionalization procedure as attempted in this study.

Lastly, further details on the approach presented in this section including the mathematics behind each calculation step are provided in Supporting Information S2. In addition, Supporting Information S1 provides further details on the regionalization of the supply tables.

2.4 | Estimation of the regional environmental extensions on the use side

2.4.1 | Natural resources tables

The subnational natural resources table shows the materials extracted in Belgium and are built on the Belgian table of EXIOBASE. The calculation of such table for the concerned extracted materials was implemented as follows: In EXIOBASE the natural resource table of extracted materials is constructed in accordance with the columns of the supply table involved in resource extracting activities, such as mining and quarrying sectors. The subnational resource tables were thus derived from the national resource table using the regionalization keys of supply tables (calculated in Section 2.3.2) for these specific sectors.

2.4.2 | Use of waste tables

The use of waste table shows the amount of waste that is handled by waste treatment activities. To construct subnational table of use of waste we gathered information on collection and treatment per type of waste, with a distinction between waste from household and economic sectors. Information on waste collected in a region and treated out of that region, that is, the destination of waste for their treatment was available. Such information served to develop the tables of trade of waste for treatment. Hence, the regional use of waste includes distinctly (a) the waste collected and treated in that region and (b) the waste collected in another region but treated in that region (i.e., imports of waste). Information on the imports of waste from the RoW to Belgium was unavailable. Consequently, the tables of trade of waste include the interregional trade of waste and the waste generated in each region and exported out of Belgium for treatment.

The obtained tables show the amount of waste generated by economic activities and households and the amount collected per region. Moreover, we developed three-dimension subnational waste treatment allocation share matrices per region *r*, linking waste treatment sectors (included in *j*), waste types (*w*), and the region where the treatment occurs *r*'. The subnational use of waste matrices ${W_{\mathrm{use}}}_{wj}^{rr'}$ were thus calculated multiplying the amount of waste generated by the waste treatment allocation shares.

2.5 | Reconciling the different estimations

So far, different datasets data have been used. And several estimates have been done mostly independently from one another. The estimated tables are surely inconsistent with one another. This is why the next step toward the development of the subnational hybrid SUT of Belgium is to reconcile and harmonize all initial estimates. In other words, the different subnational tables must be balanced. The balance was kept when constructing the monetary part of the subnational HSUT. The balancing procedure conducted here is implemented for the physical part.

To do so, we created a constrained optimization problem using the cross-entropy method for balancing estimated tables. The cross-entropy method is recognized in adjusting and balancing SUT and IOT as it allows a wide range of prior information of various nature to be used efficiently in estimation (Canning & Wang, 2005; Golan, Judge, & Robinson, 1994; Merciai & Schmidt, 2017; Robinson, Cattaneo, & El-Said, 2001).

The balancing procedure lies upon solving an optimization problem (Equation 1) framed by a set of constraints (Equations 2–6). The equations apply for any physical product *i*, regions *r* and r'. Waste types per waste treatment i_w are not considered in these equations. They are calculated further in the procedure (see Sections 2.6.1 and 2.6.2). The subscript *j* stands for any sector except in Equation (6), where *j* includes only sectors where the main product is in physical units. This means that physical balance for service sectors was not performed. With Equation (1), we set up an optimization function (OF) for the balancing procedure (Merciai & Schmidt, 2017).

$$\mathrm{OF} = \min\left\{\sum_{r}\sum_{r'}\sum_{i}\sum_{j}\left(U_{ij}^{rr'}\cdot\log\left(\frac{U_{ij}^{rr'}}{\widetilde{U_{ij}^{rr'}}}\right)\right)\right\} \tag{1}$$

The OF is a cross-entropy function that aims to redistribute the elements of the subnational use tables while minimizing the entropy distance between the "optimized" ($U_{ij}^{rr'}$) and the initially estimated ($\breve{U}_{ij}^{rr'}$) subnational use tables. The OF is framed by a set of constraints explained in the following equations. Equations (2)–(4) refer to trade balance. Equations (5) and (6) refer to the product and sector balances, respectively, based on

(Merciai & Schmidt, 2017)

$$\sum_{\substack{r \\ \text{with } r \neq \text{RoW}}} \left(\sum_j U_{ij}^{r\text{RoW}} + \sum_y Y_{iy}^{r\text{RoW}} \right) = m_i, \tag{2}$$

$$\sum_{\substack{r \\ \text{with } r \neq \text{RoW}}} \left(\sum_j U_{ij}^{\text{RoW}r} + \sum_y Y_{iy}^{\text{RoW}r} \right) = e_i, \tag{3}$$

$$\sum_{\substack{r \\ \text{with } r \neq r' \\ r \neq \text{RoW} \\ r' \neq \text{RoW}}} \left(\sum_j U_{ij}^{rr'} + \sum_y Y_{iy}^{rr'} \right) < \sum_j V'^{r'}_{ij}, \tag{4}$$

$$\sum_j V_{ij}^r + \sum_{\substack{r' \\ \text{with } r \neq r' \\ r \neq \text{RoW} \\ r' \neq \text{RoW}}} \left(\sum_j U_{ij}^{rr'} + \sum_y Y_{iy}^{rr'} \right) = \sum_{\substack{r' \\ \text{with } r \neq \text{RoW}}} \left(\sum_j U_{ij}^{rr'} + \sum_y Y_{iy}^{rr'} \right) + \sum_{\substack{r \\ \text{with } r \neq r' \\ r \neq \text{RoW} \\ r' \neq \text{RoW}}} \left(\sum_j U_{ij}^{rr'} + \sum_y Y_{iy}^{rr'} \right), \tag{5}$$

$$\sum_i \left[\left(\sum_{\substack{r' \\ \text{with } r \neq \text{RoW}}} dm' \cdot \left(U_{ij}^{rr'} - U_{c_{ij}}^{rr'} \right) \right) * D_{ij}^r \right] + \sum_{\text{res}} \left(dm_R' \cdot \left(R_{\text{res}j}^r * F_{\text{res}j} \right) \right) + \sum_{i_w} dm_W' \cdot \left(W_{\text{use}_{i_w j}}^r * T_{i_w j} \right) = \sum_i \left(dm' \cdot V'^r_{ij} \right). \tag{6}$$

Equation (2) indicates that for any product i the imports to each region r from RoW must equal the imports to Belgium (m_i) from EXIOBASE. Equation (3) indicates that the exports to RoW from each region r must equal the exports from Belgium (e_i) from EXIOBASE. With Equation (4), for any product, we do not allow a region to export more than it produces. Equation (5) aims to satisfy the product balance. It states that for any product, the sum of the supply, plus the imports from the RoW and from other regions must equal the use plus the exports to the RoW and to other regions. It also assures that for a product i, the total imports from region r to region r' must equal the total exports from region r' to region r. Equation (6) aims to satisfy the sector balance. It determines that only feedstock materials from products, resources, and waste can be part of the produced output. ($U_{ij}^{rr'} - U_{c_{ij}}^{rr'}$) indicates that only materials that can be embodied in the produced output are considered. For instance, we make sure that energy products that are combusted during the production process cannot be part of the produced output but instead is part of the discharged emissions.

The tables of dry matter coefficients of different inputs (dm), the transformation coefficients D_{ij}^r, $F_{\text{res}j}$, and $T_{i_w j}$ for products, resources, and waste, respectively, were all sourced from Merciai et al. (2014). The allowed values for transformation coefficients ϵ were [0;1]. They indicate the proportion of each of these inputs that is present in the product supplied by a sector. 0 indicates that the product, resource, or waste is not present in the produced output. A value ϵ]0;1] signifies that the product, resource, or waste is present in the produced output in the specified proportion (Merciai et al., 2014; Schmidt et al., 2014).

The coefficients D_{ij}^r are provided with upper and lower limits. They have been set as variables allowing them to optimally move within these limits with respect to the OF. Moreover, we set as variables the subnational use tables ($U_{ij}^{rr'}$) that include the intraregional, interregional, and international use. This implies that each piece of the use table is endogenously and optimally determined within the balancing procedure. The involvement of these pieces in the balancing procedure is expressed in all the constraint-based equations (Equations 2–6). The reason for setting them as variables is to attempt to cope with the discrepancies inherent to the initial estimation procedure, consistently with other tables. All these variables must remain non-negative. And, the remaining tables in the procedure are all kept constant.

2.6 | Regional environmental extensions on the supply side

2.6.1 | Waste accounts and stock addition

As shown in Equation (6), a proportion of inputs of products, resources, and waste is embodied in the produced output. The proportion that is not embodied in the produced output, nor emitted to air soil or water represents the potential waste generation.

The calculated potential waste from sectors and final use includes (a) the initial supply of waste referring to all the materials that become waste in the same accounting period of the purchase (i.e., 2011); and (b) the stock addition that joins the in-use stocks and refers to materials that will become waste in the future. In order to differentiate these two components, we applied lifetime functions that were developed in the FORWAST project (Schmidt, 2010; Schmidt, Weidema, & Suh, 2010). The lifetime functions are triangular functions illustrating the period when a material becomes waste. For instance, for food and textile products the average lifetime are assumed to be <1 year and 10 years, respectively (Merciai & Schmidt, 2016). This assumes that theoretically almost 100% of food products become waste in 2011; while 1% of the total purchased textiles become waste in 2011, and the remainder being stock addition (Merciai & Schmidt, 2016).

The obtained initial supply of waste and stock addition tables are in the format products by sectors. We subsequently converted them in a format where products becomes waste types with respect to the framework (see Figure 1). The conversion is performed by applying the three-dimensional transformation matrices linking (a) each product *i* of (b) a sector *j* or a final demand category *y* with (c) waste types *w*.

Furthermore, it has to be determined how each waste fraction supplied by sectors and final demand is treated. To do this, we first assume (as in Merciai & Schmidt, 2016) that the waste treatment scenario is the same for all activities generating that waste. This means that if 1% of wood is landfilled in a region, 1% of wood waste generated by each sector in that region will be assigned to the landfill treatment. The use of waste that is exogenous (built from regional waste statistics) and the supply of waste that is endogenous (calculated within the balancing procedure) can barely be equal. We secondly assume, that if the supply of waste is higher than the use of waste, there might be unregistered waste which should thus be included in the waste accounts; and if the initial supply of waste is lower, there might be materials accumulated in previous years that are collected and treated in 2011, and these thus need to be included in the waste account. The two assumptions are adapted from Merciai and Schmidt (2016) due to lack of data for instance on how waste supplied by sector is treated in each region; on time series data on the amount of in-use stocks and of stock depletion for each region and per material. Applying these assumed conditions allows to calculate the final tables of supply of waste and stock addition from sectors and final use.

2.6.2 | Integrating waste in the SUT and ensuring the waste balance

It is in this section that we complete the supply, intermediate, and final use tables and integrate information on waste, that is, i_w, as mentioned in Section 2.5. At the same time, we ensure a waste balance among the tables.

Waste treatment sectors produce the service of treating waste. With respect to the MRHSUT of EXIOBASE, we also account for that service in mass flow corresponding to the amount of waste that is treated by the sector. From the subnational tables of use of waste (see Section 2.4.2), the amount of waste that is treated in each region is known. It is this information that is adequately integrated in the supply tables.

Sectors and final users demand for the treatment service of their waste generated. We account for that service in mass flow corresponding to the amount of waste for treatment generated by each sector and final user. From the supply of waste table (see Section 2.6.1), this information is known. Yet, as the use table is differentiated into intraregional and trade, so do the waste flows generated for treatment. To do so, we multiplied the amount of waste generated by the waste treatment allocation shares. The latter includes for a region, waste types generated by sector and final users, waste treatment types and the region where the treatment occurs. The result is the waste generation differentiated per location of treatment. And it is this information that is adequately integrated in the intermediate and final use tables.

At this stage, the supply, intermediate, and final use tables are finally completed. The waste balance needs to be ensured. The waste balance pertains to product balance, as performed in Equation (5), but at the level of waste type per treatment i_w. Clearly, it refers to Supply + Imports = Use + Exports + Stock depletion. In other words, it can be expressed as: Use of waste + Imports of waste treatment services = Waste generation + Exports of waste treatment services + Stock depletion. The last piece of information that is necessary to ensure the waste balance is the stock depletion, that is, waste from the degradation of previous in-use stocks. The stock depletion was thus calculated as the waste collected (obtained from regional waste statistics, from Section 2.4.2) minus the supply of waste (from Section 2.6.1). It is noteworthy that the supply of waste calculated here corresponds to the waste generated from the production and consumption of products purchased in 2011.

2.6.3 | Emissions

The subnational emissions tables include substances that have been emitted in the environment due to the: (a) combustion of fossil fuels and biomass, (b) supply of products, (c) use of products, (d) treatment of waste, and (e) activities in agriculture. The emission tables are calculated within the balancing procedure by applying emission factors (Stadler et al., 2015) to materials that were not embodied in the produced good and that did not end up as waste. Specifically, the materials include combusted materials (a), supplied products (b), used products (c), and treated waste (d). As for the emissions from agricultural activities, we simply use the national emissions from agricultural activities for Belgium as calculated in Merciai and Schmidt (2016, 2017) and we split them into regional ones according to the supply of each sector in each region. We provide further details on the procedure in Supporting Information S1 and the list of emissions in Supporting Information S2.

2.7 | Integrating subnational Belgian tables in the multiregional framework

In this section, we describe how we integrate these subnational tables into the multiregional (MR) framework of EXIOBASE. The aim is to interconnect each of the Belgian regions with the other 42 countries and the 5 RoW regions. To do so, the subnational supply, intraregional, and interregional use tables were integrated as such in the MR framework without any adjustments. Subsequently, the table of imports from RoW to each Belgian region were disaggregated into the 47 countries and regions. The same applied for exports to RoW from each Belgian region. The disaggregation procedure assumes that a country importing to Belgium, imports to Brussels, Flanders, and Wallonia according to its respective import share. The same applies for exports.

It is noteworthy that the assumption based on an average import share taken within this integration procedure could be a source of uncertainties that are not estimated here. For example, due to the assumption, we could miss the information that a certain sector has chosen a specific supplier at international level. In other words, that sector has made an import choice that could deviate from the average distribution. However, they come at the cost of lack of detailed information on trade at product level and in physical unit and will be further updated when new data is available. Besides, as first step, we took the decision to work with one table as the sum of all imports to/exports from Belgium. Part of the solution to cope with the average import share assumption could be found in a balancing procedure as conducted in this study, in which the 47 countries and regions are distinguished from one another.

2.8 | Estimates evaluation—method

It is meaningful to know how much each set of estimates deviates from the initial estimates. The assessment of these deviations is conducted on the subnational use tables, as they were set as variables. We applied estimates evaluation statistics that are recognized for providing insights on the deviations (Canning & Wang, 2005; Miller & Blair, 2009; Watson & Teelucksingh, 2010). Several measures exist to compare the estimates ranging from basics to sophisticated statistics. Although most of them have attractive analytical properties, we focus here on basics statistics as they have sufficient information to impart. More specifically, we exploit the mean deviation (MD), the mean percentage deviation (MPD), and the Theil's U_1 coefficient to analyze the estimates. The analysis is extended with several other statistics which we provide in Supporting Information S1. They include for instance the (root) mean square deviation, the mean absolute (percentage) deviation, the Theil decomposition. We concentrate on the MD, MPD, and U_1 as they allow to gain sufficiently insights on the estimates. The MD indicates the average deviation between the final and initial estimates. This information is subsequently accompanied with details on the average proportionate deviations, provided by the MPD. U_1 provides a supplementary information on the distance between final and initial estimates. In fact, U_1 is generally bounded between 0 and 1. The closer U_1 is to 0, the closer the final estimates are from the initial estimates. For further details on these statistics refer, for example, to Miller and Blair (2009), Theil (1966), and Watson and Teelucksingh (2010).

The indicators are computed following Equations (7)–(9), where $U_{ij}^{rr'}$ and $\breve{U}_{ij}^{rr'}$ represent the final and the initial estimates, respectively. N denotes the number of estimates.

$$\mathrm{ME} = \frac{\sum_i \sum_j \left(U_{ij}^{rr'} - \breve{U}_{ij}^{rr'} \right)}{N}, \tag{7}$$

$$\mathrm{MPD} = 100 \frac{\sum_i \sum_j \left(U_{ij}^{rr'} - \breve{U}_{ij}^{rr'} \right)}{\sum_i \sum_j \breve{U}_{ij}^{rr'}}, \tag{8}$$

$$U_1 = 100 \frac{\sqrt{\sum_i \sum_j \left(U_{ij}^{rr'} - \breve{U}_{ij}^{rr'} \right)^2}}{\sqrt{\sum_i \sum_j U_{ij}^{rr'\,2}} + \sqrt{\sum_i \sum_j \breve{U}_{ij}^{rr'\,2}}}. \tag{9}$$

2.9 | Constructing multiregional input–output tables

The MRHIOT are derived from the constructed MRHSUT with the purpose of environmental IO analysis. There exist several approaches to build IOT from SUT (Eurostat, 2008; Miller & Blair, 2009; Suh, Weidema, Schmidt, & Heijungs, 2010). In this study, we used the by-product technology assumption, also known as the Stone's method (Stone, 1961). We chose this approach as it performs better than the others especially when by-products are at stake. The by-product technology model assumes that production of by-products is fully dependent on the production of the principal product and treats by-products as negative inputs (Miller & Blair, 2009; Suh et al., 2010). The developed subnational HSUT include waste treatment sectors, next to other economic sectors. The waste treatment sectors have as principal production the service of treating waste and as by-products recycled materials (in case of recycling) and electricity (in case of incineration with energy recovery). The by-product technology model is pertinent when the effects of mechanisms between principal and by-products on the environmental pressures need to be captured.

If by-products or off-diagonals V′ are treated as negative inputs, then the matrix of intersectoral transactions Z, that is, IOT is expressed as in Equation (10). Z includes 50 countries and regions of 164 × 164 dimension, that is, 8200 × 8200.

$$Z = U - \breve{V}'. \tag{10}$$

From this, the technical coefficient matrix Z, where each element represents the direct inputs of product that are required to produce one unit of output of sector is expressed in Equation (11).

$$A = Z\left(\widehat{V'}\right)^{-1}, \tag{11}$$

$\widehat{V'}r$ represents the principal products or diagonals of the subnational supply tables.

Then, with Equation (12), we calculate the environmental pressures p as a result of the final demand Y (Leontief, 1970; Miller & Blair, 2009; Suh et al., 2010).

$$p = E(I - A)^{-1} Y + E_y. \tag{12}$$

The first term $(E(I - A)^{-1} Y)$ quantifies the environmental pressures caused in the supply chain and induced by the final demand Y. The second term E_y refers to the environmental pressures directly caused by households. E denotes the environmental intensities indicating the environmental pressures (e.g., emissions, waste, resource use), per unit of the principal production of a sector $(\widehat{V'})$. I stands for the identity matrix.

3 | RESULTS

This section is structured into two main parts. Section 3.1 presents the results of the estimates evaluation and Section 3.2 shows the results of the consumption-based analysis, for the case of carbon footprint at the subnational level. We also provide, in Supporting Information S1, the outcome of the development procedure, that is, the different tables and in Supporting Information S2, a detailed analysis of the subnational waste, stock addition, and stock depletion accounts (developed in Section 2.6.1).

3.1 | Estimates evaluation—results

Table 2 presents the results of the MD, MPD, and U_1 to assess the deviations between the final estimates (see Section 2.5) and initial ones (see Section 2.3.2) of the subnational use tables.

We highlight three main trends from Table 2. First, analyzing the values of MD informs that in general, the initially calculated use tables were on average overestimated. But, (secondly), for most pieces of use tables, the values of MPD express that the final estimates are on average

TABLE 2 Deviations of final estimates from initial estimates of the use tables

Region	Pieces of use table	Description	MD	MPD	U_1
Brussels	Intraregional use	Intraregional use	−460.93	13.31	32.52
	Interregional trade	Imports from Flanders	−114,128.41	22.61	68.64
		Imports from Wallonia	−4,162.84	−16.00	46.66
	International trade	Imports from RoW	−0.57	2.65	0.10
		Exports to RoW	−2,840.95	−31.39	38.74
Flanders	Intraregional use	Intraregional use	−4,258.21	66.73	33.35
	Interregional trade	Imports from Brussels	−60,569.83	−84.93	99.45
		Imports from Wallonia	23,530.67	12.74	63.05
	International trade	Imports from RoW	−2.90	1.06	0.01
		Exports to RoW	39,311.83	2.82	5.48
Wallonia	Intraregional use	Intraregional use	4,257.69	66.16	43.84
	Interregional trade	Imports from Brussels	−27,200.01	−79.43	75.82
		Imports from Flanders	−152,341.01	−11.68	38.57
	International trade	Imports from RoW	3.63	1.33	0.18
		Exports to RoW	−37,053.99	−15.67	23.62

proportionally higher. Lastly, examining the values of U_1 reveals that the distance between the final and the initial estimates varies from one piece of use table to another.

A hotspots analysis discloses three main insights of these trends.

First, for all statistics, the highest deviations are observed for the interregional trade estimations. For instance, the initial estimates of the use of Flanders products in Wallonia were on average 152,341 higher than the final estimates. Another example is that on average, each initial estimate of the use of Brussels products in Flanders is on average 85% higher than each corresponding final estimate; and according to U_1, the distance between the estimates for this piece of use is the highest (99.45). Such significant deviations are a reflect of the "uncertainties" or "errors" inherent to the initial estimation of interregional trade that is based on price conversion, assuming fixed price of products over sectors.

Second, the lowest deviations are observed especially for the estimates of imports from RoW. All statistics display values that tend to zero. One plausible explanation for this case is that, the monetary information on international imports from the subnational MSUT reflects well the physical reality. This is less the case for the exports to RoW.

Lastly, the deviations on estimates of the intraregional use depict non-negligible values. On average, the initial estimates were higher for Brussels and Flanders, and the lower for Wallonia. Despite this negativity of the MD values for Brussels and Flanders, each final estimate of the intraregional use of Brussels and Flanders is on average 13% and 67% higher than each corresponding final estimate, respectively. And according to U_1, the distances between the estimates for this piece of use for each region are relatively similar, especially for Brussels and Flanders (32 and 33 for Brussels and Flanders, respectively, and 44 for Wallonia). The magnitude of these deviations describes the "uncertainties" intrinsic to the estimation procedure based on the application of the national production function on regions. See Supporting Information S1 for further results.

3.2 | Consumption-based analysis

3.2.1 | Subnational carbon footprint

In this section, we perform a consumption-based analysis at subnational level. We apply Equation (12) considering emissions as environmental pressures in order to assess the global warming potential or carbon footprint (CF) at the subnational level for Belgium.

From Figure 2, the Belgian CF amounted 169 $MtCO_2eq$[2] in 2011, with 17% of direct impacts, that is, emissions from household, and 83% of indirect impacts, that is, throughout the supply chain. In the national CF, Flanders contributed the most with 61% (103 $MtCO_2eq$), followed by Wallonia 31% (53 $MtCO_2eq$) and Brussels 8% (13 $MtCO_2eq$). While noticing a clear regional variation in the CF in absolute terms, we observe low variation of the footprint in ton CO_2eq per capita (tCO_2eq/cap). Figure 2 indicates 12, 16, and 15 tCO_2eq/cap for the CF of Brussels, Flanders, and Wallonia, respectively.

[2] In line with global warming potential (100 years) reported in (Houghton et al., 1996, p. 22) CO_2 equivalent (CO_2eq) is computed as $CO_2 + 310 \times N_2O + 25CH_4$ considering the data available.

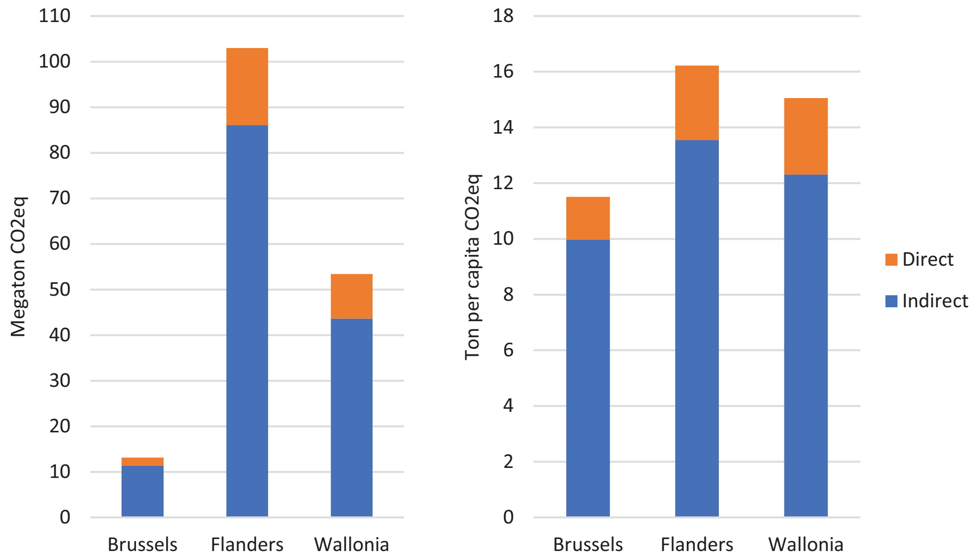

FIGURE 2 Carbon footprint of Brussels, Flanders, and Wallonia in 2011. Underlying data used to create this figure can be found in Supporting Information S3

3.2.2 | Analytical comparison with other studies

Table 3 presents the CF-related studies for Belgium (BE). It allows to perform an analytical comparison between the results in this study and the ones in other studies. The analysis includes for each study, specificities such as the year of data, the unit of IOT, the database used, the country and sector resolutions and the approach used.

First of all, we observe a certain disparity in the CF at the national and subnational levels, in this study and in other studies. In general, the disparities between the CF could be explained by the specificities intrinsic to each database and CF calculation process. We do not assess the contribution of each specificity nor calculation process to the differences in the CF here, but we instead discuss them, *ceteris paribus*.

At the national level, we observe that the CF in this study is 17% higher than the CF in Arto, Rueda-Cantuche, and Peters (2014) and Hambÿe, Hertveldt, and Michel (2017) both using WIOD[3]; and 4% lower than the CF in Arto et al. (2014) and Tukker et al. (2014) that used GTAP[4] and EXIOBASE, respectively. At the subnational level, we observe that the CF in this study are higher than the ones in other studies. Summing-up the subnational CFs of Ivanova et al. (2017) and Zeller (2017) yields 138.9 (22% lower than the one in this study) and 123.3 (37% lower) $MtCO_2eq$ in 2007, respectively. Moreover, for 2010, Zeller (2017) accounted for 132.7 (27% lower) $MtCO_2eq$. Besides, Moran et al. (2018) have accounted for 10.2 $MtCO_2eq$ for Brussels, that is 29% lower than the Brussels' CF in this study and Christis, Athanassiadis, and Vercalsteren (2019) have found 14.4 $MtCO_2eq$ for Brussels, that is 8% higher.

Analyzing the specificities presented for each study can provide qualitative elements of the differences between the subnational CF. First, the differences may be explained by the year of data. Most of them are from 2007, 2010, and 2015 while in this study, the base year is 2011. Second, the differences may be caused by the unit of IOT used. All studies used monetary IOT, and this study uses hybrid IOT. From this point of view, the monetary perspective could underestimate the subnational CF (or the physical perspective could overestimate the subnational CF). Third, the particularities of each database could also be reflected in the differences. For example, the level of (dis)aggregation of the countries and regions or of products and sectors have surely played a considerable role in the differences between the subnational CF of this study and the others (see, e.g., Andrew, Peters, & Lennox, 2009; Bjelle et al., 2020; Fry et al., 2018; Lenzen, 2011). Fourth, the approach used for CF calculation is also another relevant aspect that can influence the differences in the subnational CF. Ivanova et al. (2017) and Moran et al. (2018) estimated the subnational CF based on a regionalization of the national CF using auxiliary subnational data. Although Zeller (2017) applied a MR perspective, that is, considering the country- and region-specific technologies, the country resolution was reduced to 3 Belgian NUTS2 + 2 RoW regions (EU and non-EU) and the sector resolution to 81. In this study, we did not regionalize the national CF nor aggregated the number of sectors. Instead, we considered the 164 sectors and the country- and region-specific technologies for 3 Belgian NUTS2 regions, 42 countries, and 5 RoW regions. This has been possible with the integration of the subnational SUT in a MR framework (see Section 2.7).

[3] World IO database.
[4] Global trade analysis project.

TABLE 3 Analytical comparison of carbon footprint-related studies at national and subnational levels for Belgium

	Carbon footprint (CF) ($MtCO_2eq$)									
Reference	Brussels	Flanders	Wallonia	Belgium	Base year	Unit of IOT	Database	Geographical resolution	Sector resolution	Approach
Arto et al. (2014)	n.a.	n.a.	n.a.	175.3	2007	Monetary	GTAP	128 countries + 1 RoW	57	MRIO
Arto et al. (2014)	n.a.	n.a.	n.a.	148.0	2007	Monetary	WIOD	40 countries + 1 RoW	35	MRIO
Christis et al. (2019)	14.4	n.a	n.a.	n.a.	2010	Monetary	EXIOBASE	43 countries + 5 RoW	200	MRIO
Hambÿe et al. (2017)	n.a.	n.a.	n.a.	145.0	2007	Monetary	WIODBEL	40 countries + 1 RoW	35	MRIO
Ivanova et al. (2017)	12.8	81.5	44.6	n.a.	2007	Monetary	EXIOBASE	178 NUTS2 regions	200	Regionalization of national CF
Moran et al. (2018)	10.2	n.a.	n.a.	n.a.	2015	Monetary	GGMCF	13,000 cities	n.a.	Regionalization of national CF
Tukker et al. (2014)	n.a.	n.a.	n.a.	174.9	2007	Monetary	EXIOBASE	43 countries + 5 RoW	200	MRIO
Zeller (2017)	10.2	78.3	34.8	n.a.	2007	Monetary	EXIOBASE	3 Belgian NUTS2 regions + 2 RoW	81	MRIO
Zeller (2017)	12.5	78.0	42.2	n.a.	2010	Monetary	EXIOBASE	3 Belgian NUTS2 regions + 2 RoW	81	MRIO
In this study	13.1	103.0	53.4	169.5	2011	Hybrid	EXIOBASE	3 Belgian regions + 42 countries + 5 RoW	164	MRIO

GTAP, global trade analysis project; WIOD, world IO database; WIODBEL, WIOD MRIOT updated with national data for Belgium; GGMCF, gridded global model of city footprints based on Eora and other databases. RoW, rest of world; NUTS2, nomenclature of territorial units for statistics level 2; n.a., not applicable; MRIO, country- and region-specific technology considered; DTA, domestic technology assumption.

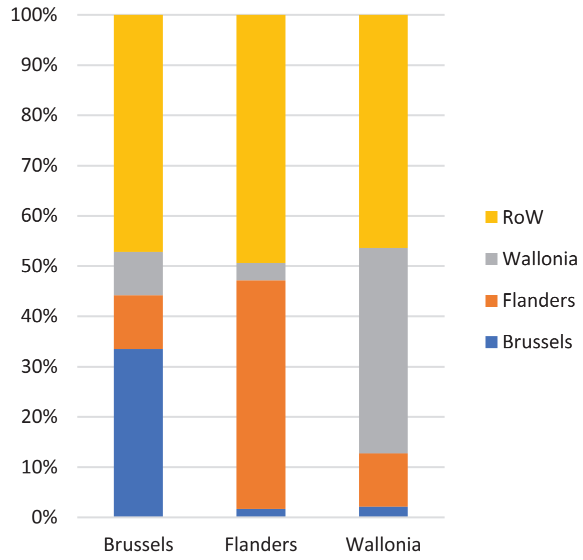

FIGURE 3 Region contribution to the indirect part of the carbon footprint of Brussels, Flanders, and Wallonia in 2011. Underlying data used to create this figure can be found in Supporting InformationS3

3.2.3 | Contribution analysis of regions

The CF of each region includes direct impacts from households and indirect impacts, occurring within and outside each region's boundaries, from the supply chain induced by households. Figure 3 depicts the contribution of each region to the subnational CF.

Figure 3 shows that 23%, 35%, and 28% of the CF of Brussels, Flanders, and Wallonia occurred within each respective territory. It also shows that 54%, 59%, and 57% of the CF of Brussels, Flanders, and Wallonia, respectively, occurred out of these regions' boundaries. This means in that Flanders and Wallonia contribute 12% and 10% to the Brussels' CF, respectively; Brussels and Wallonia contribute 2% and 4% to the Flanders' CF, respectively; and Brussels and Flanders contribute 3% and 13% to the Wallonia's CF. While this study unveils the impacts induced by the regional household consumption in 2011, Christis et al. (2019) focused on Brussels and found that on the total CF induced by the Brussels' final demands,[5] 17% occurred in the Brussels' territory, 12% in Belgium, and 71% outside Belgium in 2010. The differences between these figures and the ones of this study can be qualitatively explained by the specificities highlighted in Table 3.

We further provide in Supporting Information S1 the contribution of the other 42 countries and 5 RoW regions to the CF of Brussels, Flanders, and Wallonia. Such results highlight the usefulness and insights that the knowledge on interregional and international flows provides.

4 | DISCUSSION

4.1 | Why MRHIOT at subnational level are important?

We have presented how the subnational MRHIOT for Belgium have been constructed. The general contributions of this study are multiple. Comparing to the subnational monetary tables, we increased the product and sector resolution and developed a mixed-unit framework. Compared to EXIOBASE, we increased the geographical resolution. We developed subnational environmental extensions that were inexistent before namely natural resources, emissions,[6] and waste. In addition, we augmented the classical table of use of waste with the trade of waste, which is also a novelty. Lastly, we nested the subnational HIOT with 47 countries and regions worldwide. To the best of our knowledge, these are the first MRHIOT at the subnational level ever developed and published.

We believe such a study is pertinent as it addresses the research questions that . First, an analysis at the national level may describe an ''average'' situation at the regional level, as the regional specificities are hidden (Szabó, 2015). While it is possible that a regional structure is identical to the national one, they can also be completely different; and this is the case for Belgian regions (see Section 3.2). In such case, the regional specificities should be highlighted. Second, the smaller a territory unit (region, city, etc.) the higher its dependence on external territories through trade (Fischer

[5] The final demand categories studied include households, non-profit organizations, government, gross capital formation, and household buildings.
[6] Air emissions accounts exist from Belgian regions, but at a low sector resolution and are confidential.

& Nijkamp, 2014). Indeed, a region is barely independent in producing all the goods and services it needs. This is why a region often trades with its national hinterland and with other countries/regions. Thus, by consuming resources, goods, and services from other regions/countries, regions cause environmental pressures beyond their boundaries. Considering that, the path toward the mitigation of environmental impacts of a region should integrate, not only measures to mitigate impacts locally, but also measures that cope with issues occurring out of the region's boundaries. The measures should more specifically integrate the impacts of interregional linkage (i.e., between regions within the country) and the impacts of the connection between that region and other countries/regions (i.e., out of the country), on the impact mitigation of that region.

This study has contributed, to some extent, in coping with such a research problematic (mitigating impacts of a region) thanks to the subnational data. Indeed, results in Section 3.2 have clearly illustrated the contribution of each region in the CF of other regions in Belgium. This provides an overview on the state of the environmental pressures associated with the interregional linkages. A subsequent step could be to analyze how to vary the pressures when the interregional linkages are modified, with political relevance. We leave such analysis for future research.

4.2 | Data and method implications

We conducted an integrated approach built upon a regionalization of national tables followed by a reconciliation of estimates in a balancing procedure. The adoption of the approach in this study was purely data oriented. The availability of MSUT and some survey-based data (e.g., production volumes, waste collection, and treatment) at the subnational level, enabled to perform this research. The survey data contributed to developing regionalization keys and parameterizing the balancing procedure. We could recommend applying this approach only if a practitioner has a similar state/nature of data as the one in this study.

If the data used here are unlikely to be available for other regions, nor to be re-used by international/non-Belgian practitioners, the approach could be replicable to some extent. From our approach, we consider the regionalization of the national hybrid supply table (e.g., national supply table from EXIOBASE) as the bare minimum for building subnational IOT. If data on physical production volumes at the subnational level are unavailable, one can use alternative data. For example, data on monetary output of sectors could be used as a proxy to infer subnational supply tables. Other data types such as employment could also be valuable in regionalizing national hybrid supply tables. Furthermore, combining different datasets to extract regionalization keys per sector could also be an alternative (e.g., production volumes for primary sectors, monetary output for secondary sectors, employment for tertiary sectors). However, we recommend that the more subnational physical tables are obtained from physical-based regionalization keys, the better, as economic information may not always well reflect the physical reality.

In general, the methods for constructing subnational IOT can be divided into three fundamental groups: survey, non-survey, and partial survey (Greenstreet, 1989). The lower the availability of subnational survey data, the higher propensity of using non-survey methods. In this study, we applied a partial survey-based approach, that is a non-survey model augmented in prior estimation steps with subnational survey data and information from other databases. In a less ‘‘ideal'' situation where subnational survey data are lacking, techniques for constructing subnational HIOT should tend toward non-survey methods. As for partial-survey methods, non-survey ones include different estimation methods to generate subnational tables using national ones as a starting point. This can be facilitated as global hybrid IO database such as EXIOBASE provides hybrid SUT plus environmental extensions for 42 countries.

Moreover, applying non-survey approaches for building subnational IOT is not new. Mostly, they have been well applied on monetary IOT and there is a wide literature on the evidence on the performance of non-survey approaches in constructing subnational IOT (e.g., Fujimoto, 2019; Kowalewksi, 2015; Zhao & Choi, 2015). To date, there is still no consensus about the "most ideal" procedure. This is partially the result of the questionable performance of different non-survey techniques; and considering that the precision/performance of techniques is enhanced by using additional subnational survey data (Lahr, 1993; Szabó, 2015). Acknowledging that, plus the fact that scant attention has been accorded to applying non-survey methods in a physical context (i.e., on physical/hybrid IOT), we cannot yet provide concise information on which estimation technique is suitable for which availability degree of subnational survey data for building subnational HIOT. Nevertheless, we would like the approach conducted in this study to inspire and foster increasing attention of researchers toward more applications of partial- or non-survey methods for further developing subnational HIOT.

4.3 | Future research

Due to space and scoping reasons, the present work focuses purely on (a) the methodological aspects of the construction of a subnational hybrid model, (b) the validation aspects relative to objectives measures for the balancing, and (c) subnational consumption-based analysis and comparative measures for the well-studied phenomena of carbon footprints. Future research could be dedicated not only to perform diverse applications of the model but also to provide data and methodological improvements. Some applications are thrashed out in subsequent works that we performed.

First, the mass-balanced framework inherent to the model presents a strong potential for assessing the material circularity of regions and goes further than what is done in the following previous papers: Haas, Krausmann, Wiedenhofer, and Heinz (2015), Mayer et al. (2019), and

Aguilar-Hernandez et al. (2019). This potential has been fully exploited in another paper, that is, Towa, Zeller, and Achten (2020c). The latter not only analyses the material circularity at the subnational level, contrary to the previous papers that scoped the global and national levels. Furthermore, that paper showcases the usefulness of the knowledge on the interregional linkages by examining the effects of trade of waste in the material circularity of regions through a novel indicator the authors developed.

Moreover, the model has high analytical capabilities in terms of quantifying different environmental pressures at the subnational level. One of them, greenhouse gas emissions, has been quantified in this study. In the future, waste and resource footprints can also be assessed at the subnational level, unveiling the pressures related to interregional linkages. One example is Towa et al. () for the case of regional waste footprint analysis for Brussels, Flanders, and Wallonia. In addition, involving all these environmental extensions in tandem would also allow analyzing trade-offs between the different footprints.

The potential to extend footprints quantification, to deepen the pressures related to interregional linkages, and detail material circularity assessment toward scenario analyses is undoubtedly present. Clearly, designing and assessing different scenarios of consumption, waste treatments, and CE strategies would allow uncovering important spillover and feedback effects (in terms of environmental pressures) deriving from interregional linkages.

We strongly believe such analyses would yield to new types of results that offer more insights in the environmental pressures understanding and thus further feed the decision-making process.

On the other hand, next to further development of MRHIOT at the subnational level, there is still a wide room for improvement in terms of data and method.

First, there may be a possibility to use different initial estimation procedures (than regionalization keys) and different optimization techniques (than cross-entropy). The different scenarios of procedures and techniques could then be evaluated on the basis of their performances (i.e., deviations from initial estimation). Such analyses would allow extracting data- and method-based lessons and contribute to the discussion on the suitability between non-survey techniques and subnational survey data.

Besides, we have nested the subnational HIOT into a multiregional framework based on the average import share assumption (see Section 2.7). Yet, future research could attempt to integrate that task into the multiregional balancing procedure to improve that proportional distribution of imports/exports. Such a task is not free of high computational power requirements.

Moreover, the model in its current state does not provide information on the total stock from previous years that has been accumulated until 2011 nor obviously the proportion of the stock depleted in 2011 over that total. This will indeed require implementing region-specific dynamic aspects into the model.

Lastly, future research can also include the development of other types of extensions at the subnational level, such as land use, water use, employment, value added. Such development would increase the spectrum of analyses (as presented earlier in this section) and could be a path toward IO sustainability assessment.

5 | CONCLUSION

Environmental input–output analyses (EIOA) is relevant for supporting the decision-making process at the subnational level. Yet, such analyses develop at a low pace due to lack of subnational IOT. With this paper, we demonstrate the development of MRHIOT and environmental extensions at subnational level and exemplify it for the case of Belgium. To the best of our knowledge, these are the first MRHIOT at the subnational level ever developed and published. The development procedure discloses a novel approach of combining national hybrid tables, subnational monetary tables, and physical survey-based data. Such combination builds upon different simple techniques of data processing (initial estimation) and reconciliation (final estimation), embodied in a balancing procedure. The implementation of an automated procedure within the model facilitates further improvements and updates when new data becomes available.

The magnitude of the deviations between the initial and final estimates revealed insights on the "uncertainties" inherent to each initial estimation procedure. It also indicated how "*the monetary information mirrors the physical reality*," as most initial estimations were sourced from monetary information. This study confirms that deriving physical tables from price conversion of monetary ones is barely recommendable. The results have also depicted the CF including the impacts intrinsic to the interregional linkages. Moreover, the analytical comparison with results from other studies disclosed insights regarding the effects of some specificities on CF. The specificities include the year of data, the unit of IOT, the database used, the country and sector resolutions, and the approach used (e.g., DTA, regionalization of national CF).

This study provides methodological and application-based contributions to the discussion on the relevance of subnational tables and analyses compared to national ones. The proposed approach could be replicable to some extent for further developing subnational MRHIOT: for example, using EXIOBASE (i.e., national HIOT) as starting point, augmented with some available subnational survey data, all implemented in a non-survey estimation procedure. This study is expected to foster more research toward the development of further subnational MRHIOT as well as its associated wide-ranging applications. Some applications are already conducted in other papers. For example, a subsequent research has assessed the material circularity of regions considering the trade of waste for treatment, through a novel indicator (Towa et al., 2020c); and analyzed the regional waste footprint and waste treatments (Towa et al., 2020b).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions: A review of EEIOA-based studies. *Journal of Economic Structures*, *7*, 14.

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Merciai, S., Schmidt, J., Rodrigues, J. F. D., & Tukker, A. (2019). The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011. *Resources, Conservation and Recycling*, *151*, 104452.

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

Arto, I., Rueda-Cantuche, J. M., & Peters, G. P. (2014). Comparing the Gtap-Mrio and Wiod databases for carbon footprint analysis. *Economic Systems Research*, *26*, 327–353.

Avonds, L., Hambÿe, C., Hertveldt, B., & Michel, B. (2016). Analyse du tableau input-output interrégional pour l'année 2010. https://ibsa.brussels/sites/default/files/publication/documents/BFP_WP_1605_F.pdf

Bjelle, E. L., Többen, J., Stadler, K., Kastner, T., Theurl, M. C., Erb, K.-H., … Wood, R. (2020). Adding country resolution to EXIOBASE: Impacts on land use embodied in trade. *Journal of Economic Structures*, *9*, 14.

Boero, R., Edwards, B. K., & Rivera, M. K. (2018). Regional input–output tables and trade flows: An integrated and interregional non-survey approach. *Regional Studies*, *52*, 225–238.

Canning, P., & Wang, Z. (2005). A Flexible Mathematical programming model to estimate interregional input–output accounts. *Journal of Regional Science*, *45*, 539–563.

Christis, M., Athanassiadis, A., & Vercalsteren, A. (2019). Implementation at a city level of circular economy strategies and climate change mitigation – The case of Brussels. *Journal of Cleaner Production*, *218*, 511–520.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., & de Vries, G. (2013). The construction of world input–output tables in the Wiod project. *Economic Systems Research*, *25*, 71–98.

Eurostat (2008). *Eurostat manual of supply, use and input-output tables*. Luxembourg: Amt für amtliche Veröffentlichungen der Europäischen Gemeinschaften.

Fischer, M. M., & Nijkamp, P. (2014). *Handbook of regional science*. Berlin, Heidelberg: Springer Berlin Heidelberg.

Fry, J., Lenzen, M., Jin, Y., Wakiyama, T., Baynes, T., Wiedmann, T., … Schandl, H. (2018). Assessing carbon footprints of cities under limited information. *Journal of Cleaner Production*, *176*, 1254–1270.

Fujimoto, T. (2019). Appropriate assumption on cross-hauling national input–output table regionalization. *Spatial Economic Analysis*, *14*, 106–128.

Giljum, S., & Hubacek, K. (2009). Conceptual foundations and applications of physical in put-output tables. In *Handbook of input-output economics in industrial ecology* (pp. 61–75). Dordrecht, The Netherlands: Springer.

Golan, A., Judge, G., & Robinson, S. (1994). Recovering information from incomplete or partial multisectoral economic data. *Review of Economics and Statistics*, *76*, 541–549.

Greenstreet, D. (1989). A conceptual framework for construction of hybrid regional input-output models. *Socio-Economic Planning Sciences*, *23*, 283–289.

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology*, *19*, 765–777.

Hambÿe, C., Hertveldt, B., & Michel, B. (2017). Belgium's Carbon Footprint - Calculations based on a national accounts consistent global multi-regional input-output table. 37. https://www.plan.be/publications/publication-1712-en-belgium_s_carbon_footprint_calculations_based_on_a_national_accounts_consistent_global_multi_regional_input_output_table

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., & Maskell, K. (1996). Climate Change 1995 The Science of Climate Change.Contribution of working group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (J. A. Lakeman, Ed.; Vol. 2). Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_sar_wg_I_full_report.pdf

IPCC (1995). Climate Change 1995 The Science of Climate Change - Contribution of WG I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.

Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P. C., Wood, R., & Hertwich, E. G. (2017). Mapping the carbon footprint of EU regions. *Environmental Research Letters*, *12*, 054013.

Kowalewksi, J. (2015). Regionalization of national input–output tables: Empirical evidence on the use of the FLQ formula. *Regional Studies*, *49*, 240–250.

Lahr, M. L. (1993). A review of the literature supporting the hybrid approach to constructing regional input–output models. *Economic Systems Research*, *5*, 277–293.

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

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science & Technology*, *46*, 8374–8381.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input–output database at high country and sector resolution. *Economic Systems Research*, *25*, 20–49.

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., … West, J. (2014). Compiling and using input–output frameworks through collaborative virtual laboratories. *The Science of the Total Environment*, *485–486*, 241–251.

Leontief, W. (1970). Environmental repercussions and the economic structure: An input-output approach. *Review of Economics and Statistics*, *52*, 262.

Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M., & Murray, J. (2018). Advancements in input-output models and indicators for consumption-based accounting. *Journal of Industrial Ecology*, *23*, 300–312.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. *Journal of Industrial Ecology*, *23*, 62–76.

McCarthy, A., Dellink, R., & Bibas, R. (2018). The macroeconomics of the circular economy transition: A critical review of modelling approaches. (OECD Environment Working Papers No 130). OECD Publishing. https://doi.org/10.1787/af983f9a-en

Merciai, S., & Schmidt, J. (2016). Physical/hybrid supply and use tables - methodological report (EU FP7 DESIRE project; p. 91). http://fp7desire.eu/documents/category/3-public-deliverables?download=29:physical-hybrid-supply-and-use-tables-methodological-report

Merciai, S., & Schmidt, J. (2017). Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. *Journal of Industrial Ecology*, *22*, 516–531.

Merciai, S., Schmidt, J., Dalgaard, R., Giljum, S., Lutter, S., Usubiaga, A., … Delahaye, R. (2014). CREEA - Report and data Task 4.2: P-SUT (EU FP7 CREEA project). http://creea.eu/index.php/documents2/cat_view/9-public-deliverables

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: Foundations and extensions*. Cambridge: Cambridge University Press.

Minx, J. C., Wiedmann, T., Wood, R., Peters, G. P., Lenzen, M., Owen, A., … Ackerman, F. (2009). Input–output analysis and carbon footprinting: An overview of applications. *Economic Systems Research*, *21*, 187–216.

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., & Seto, K. C. (2018). Carbon footprints of 13 000 cities. *Environmental Research Letters*, *13*, 064041.

Robinson, S., Cattaneo, A., & El-Said, M. (2001). Updating and estimating a social accounting matrix using cross entropy methods. *Economic Systems Research*, *13*, 47–64.

Sargento, A. L. M., Ramos, P. N., & Hewings, G. J. D. (2012). Inter-regional trade flow estimation through non-survey models: An empirical assessment. *Economic Systems Research*, *24*, 173–193.

Schmidt, J. (2010). Documentation of the data consolidation and calibration exercise, and the scenario parameterisation (EU FP6 FORWAST project; Deliverable N° 6-1, p. 31). http://forwast.brgm.fr/Documents/Deliverables/Forwast_D61.pdf

Schmidt, J., Merciai, S., Delahaye, R., Vuik, J., Heijungs, R., de Koning, A., & Sahoo, A. (2012). CREEA - Compiling and Refining Environmental and Economic Accounts Recommendation of terminology, classification, framework of waste accounts and MFA, and data collection guideline.

Schmidt, J. H., Weidema, B. P., & Suh, S. (2010). Documentation of the final model used for the scenario analyses (EU FP6 FORWAST project; Deliverable N° 6-4). http://forwast.brgm.fr/Documents/Deliverables/Forwast_D64.pdf

Stadler, K., Wood, R., Simas, M., Bulavskaya, T., Kuenen, J., Fernandez, J. A., … Tukker, A. (2015). D5.3 Integrated report on EE IO related macro resource indicator time series (EU FP7 DESIRE project; Deliverable N° 5.3). http://fp7desire.eu/documents/category/3-public-deliverables?download=24:d5-3-integrated-report-on-ee-io-related-macro-resource-indicator-time-series

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., … Tukker, A. (2018). EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. *Journal of Industrial Ecology*, *22*, 502–515.

Stone, R. (1961). Input-output and national accounts. Organisation for European Economic Co-operation and Development.

Suh, S., Weidema, B., Schmidt, J. H., & Heijungs, R. (2010). Generalized make and use framework for allocation in life cycle assessment. *Journal of Industrial Ecology*, *14*, 335–353.

Szabó, N. (2015). Methods for regionalizing input-output tables. *Regional Statistics*, *5*, 44–65.

Theil, H. (1966). *Applied economic forecasting*. Amsterdam: North-Holland PubCo.

Többen, J., & Kronenberg, T. H. (2015). Construction of multi-regional input–output tables using the Charm method. *Economic Systems Research*, *27*, 487–507.

Towa, E., Zeller, V., & Achten, W. M. J. (2020a). Input-output models and waste management analysis: A critical review. *Journal of Cleaner Production*, *249*, 119359.

Towa, E., Zeller, V., Merciai, S., & Achten, W. M. J. (2020b). Regional waste footprints and waste treatment analyses. Submiss. Waste Manag.

Towa, E., Zeller, V., & Achten, W. M. J. (2020c). A circularity footprint analysis of regions. Submiss. *Journal of Industrial Ecology*.

Tukker, A., Bulavskaya, T., Giljum, S., Koning, A. de, Lutter, S., Simas, M., … Wood, R. (2014). The Global Resource Footprint of Nations. Carbon, water, land and materials embodied in trade and final consumption, calculated with EXIOBASE 2.1 (TNO). https://www.truthstudio.com/content/CREEA_Global_Resource_Footprint_of_Nations.pdf

Watson, P. K., & Teelucksingh, S. S. (2010). *A practical introduction to econometric methods: Classical and modern*. Jamaica: University of the West Indies Press.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., De Koning, A., … Tukker, A. (2015). Global sustainability accounting—Developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, *7*, 138–163.

Zeller, V. (2017). Evaluating environmental impacts from production and consumption at regional level with input-output life cycle assessment (PhD thesis). Université libre de Bruxelles, Belgium.

Zhao, X., & Choi, S.-G. (2015). On the regionalization of input–output tables with an industry-specific location quotient. *Annals of Regional Science*, *54*, 901–926.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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