Structural decomposition analysis of carbon footprint

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# Abstract

In the paper we perform a structural decomposition analysis of carbon footprint in selected countries. We decompose the change in carbon footprints into the factors: emission intensity, structural change, structure of consumption and total level of consumption. All these factors are also decomposed into domestic versus foreign effect. While the total amount of GHG emissions in european countries are stable or decreasing, the carbon footprint embodied in the european consumption is increasing. With the SDA we test the pollution haven hypothesis that greater trade openness of european countries that leads to replacing domestic goods with imports (both in final and intermediate consumption goods) leads to an increase in carbon footprint of european countries. That leads to an increase in global emissions compared to the situation if domestic goods are not replaced by imports. We carry out the analysis for period 1995 - 2009 using data from WIOD.

# Introduction

Structural decomposition analysis (SDA) is a useful technique to decompose changes in a given indicator into its driving determinants. Environmental studies quite often try to decompose changes in greenhouse gas emissions into its determinants. Most studies are oriented on individual countries and production-based emissions (De Haan, 2001; Seibel, 2003; Peters et al., 2007; Chang – Lewis – Lin, 2008; Stocker – Luptacik, 2009; Lim – Yoo – Kwak, 2009; Wood, 2009; Yamakawa – Peters, 2011; Su - Ang, 2012; Brizga - Feng - Hubacek, 2014). Production based emissions refer to territorial concept of emissions.

A consumption-based approach to generated emissions, sometimes referred as carbon footprint, is gaining attention in the literature. It is becoming increasingly relevant concept for policy making, as suggests Wiedman (2009). It provides better understanding of the responsibility for the global warming problem among countries and useful information for international policy discussion on climate change and countries’ competitiveness. Carbon footprint is based on the concept of ecological footprint (Lenzen and Murray, 2003), which began to be popular in environmental studies since the early 90’s (Rees, 1992; Wackernagel and Rees, 1996).

Most of the studies on carbon footprint concern to calculation of consumption-based emissions, which may be through a single-region input-output (SRIO) model or a multi-region input-output (MRIO) model. SRIO models use the assumption of identical direct emission intensity of imports and domestic production. MRIO models use a more sophisticated treatment of imports based on country specific direct emission intensity coefficients.

Although there are many structural decomposition studies on production-based emissions, only very few papers apply SDA on the consumption-based emissions. They apply structural decomposition on cabon footprint computed from SRIO model (Duarte - Mainar - Sánchez-Chóliz, 2013) or a non-standard MRIO model (Baiaiocchi – Minx, 2010). The latter improved the SRIO approach by imposing region-specific emission intensity coefficients on imports (the three regions are Europe-OECD, other OECD countries and non-OECD countries). Though that is a great improvement, those data are still very aggregated and most importantly, they do not account for multilateral trade among other countries. They use only bilateral trade which is insufficient in the face of production fragmentation processes in the world economy.

Recent developments in MRIO tables enable to use SDA on a carbon footprint computed from a true MRIO model. Namely WIOD tables were available also in previous year prices. The aim of this paper is therefore to apply SDA on carbon footprint computed from a true MRIO model.

# Methodology and data

For quantification of carbon footprint we use an environmentally extended multiregional input-output model (EE-MRIO). This model allows to account for emissions generated not only directly by producers delivering products to final demand (as the early ecological footprint studies used to do), but also for emissions generated indirectly by suppliers in the whole production chain. It accounts for emissions generated by suppliers in the domestic economy as well as by suppliers in importing countries and suppliers from third countries (which do not import directly into Slovakia but indirectly via other producers).

## The EE-MRIO model

The basis is the input-output model (1) which studies the impact of exogenous final demand on the production in the economy. The input-output model uses disaggregated industrial data about the use of energy, primary and material inputs. Therefore the model is absolutely suitable for quantifying indirect effects in the economy.

x = (I – A)-1 y (1)

where

 x - vector of production

 I - identity matrix

A - matrix of technical coefficients

y - vector of final demand

The matrix A is a “cookbook” of the economy. It represents the direct needs of industries in the columns for intermediate deliveries from industries in the rows. Different industries have different needs for the input structure.

The matrix L = (I – A)-1 (Leontief inverse) is a geometric series expansion of matrix A and represents direct and indirect needs of industries in its columns for intermediate inputs from industries in the rows to satisfy the final demand for their production. An element of this matrix *lij* expreses the direct and indirect needs of intermediate inputs from industry i for one unit of industry j´s output to be delivered to final demand.

Pre-multiplying both sides of (1) by a diagonal matrix of emission intensity E (where ei = gi / xi) leads to a vector of total emissions g on the left-hand side. In (2) the emission vector g is a product of direct and indirect emission intensities (E\*L) and final demand (y).

$g=E\*L\*y $ (2)

Knowing the structure of imports (structured by both countries and industries) we can extend the above mentioned framework to an environmentally extended multiregional input-output model (EE-MRIO) (3):

$\overbar{g}=\overbar{E}\*\overbar{L}\*\overline{y} $ (3)

We use a vector of total country´s final demand if we are trying to determine the total domestic emissions generated by this final demand. However if we are interested in the country´s carbon footprint we account only for domestic final demand. That means we exclude exports and include imports which directly satisfy domestic final demand.

$\overbar{g }=\left(\begin{matrix}\hat{e}\_{1}&0&0\\0&\hat{e}\_{2}&0\\0&0&\hat{e}\_{3}\end{matrix}\right)\left(\begin{matrix}L\_{11}&L\_{12}&L\_{13}\\L\_{21}&L\_{22}&L\_{23}\\L\_{31}&L\_{32}&L\_{33}\end{matrix}\right)\left(\begin{matrix}y\_{11}\\y\_{21}\\y\_{31}\end{matrix}\right)=\left(\begin{matrix}g\_{1}\\g\_{2}\\g\_{3}\end{matrix}\right)=\left(\begin{matrix}\hat{e}\_{1}L\_{11}y\_{11}+\hat{e}\_{1}L\_{12}y\_{21}+\hat{e}\_{1}L\_{13}y\_{31}\\\hat{e}\_{2}L\_{21}y\_{11}+\hat{e}\_{2}L\_{22}y\_{21}+\hat{e}\_{2}L\_{23}y\_{31}\\\hat{e}\_{3}L\_{31}y\_{11}+\hat{e}\_{3}L\_{32}y\_{21}+\hat{e}\_{3}L\_{33}y\_{31}\end{matrix}\right)$ (4)

For the sake of simplicity we interpret the model (3) in a case of three countries (4). Let the domestic economy be the country 1. In that case the first partitioned matrix $\overbar{E}$ represents the coefficients of direct emission intensities. Each submatrix on the main diagonal consists of industry-specific coefficients for each country. The second partitioned matrix represents direct and indirect flows among industries inside a given country (submatrices on the main diagonal - **L11**, **L22**, **L33**) or direct and indirect industry-specific flows among countries. Final demand is represented by the demand of country 1 for its own production (**y11**) and by the demand for imported products (**y21***,* **y31**).

In this case the carbon footprint of country 1 consists of:

* ***emissions generated in the domestic economy -*** $g1$
	+ *induced by final demand for domestic products* - $e\_{1}L\_{11}y\_{11}$ ,
	+ *induced by final demand for imports* - $e\_{1}L\_{12}y\_{21}+ e\_{1}L\_{13}y\_{31}$
* ***emissions generated offshore -*** $g2 + g3$
	+ *induced by final demand for domestic products* - $e\_{2}L\_{21}y\_{11}+$$e\_{3}L\_{31}y\_{11}$
	+ *induced by final demand for imports*
		- resulting from bilateral flows - $e\_{2}L\_{22}y\_{21}+ e\_{3}L\_{33}y\_{31}$
		- resulting from multilateral flows - $e\_{3}L\_{32}y\_{21}+ e\_{2}L\_{23}y\_{31}$

## Structural decomposition

If we split vector of final demand into the factor of structure (product mix) of final demand and total level of final demand, the carbon footprint is then a product of four factors (5): total level of final demand (*f*), structure of final demand (B), structure of production (L) and direct emission intensity (E). For simplicity of marking we omit dashes above the matrices.

**g** = **E L b** *f* (5)

Using a polar decomposition on (5) generates

$∆g=\frac{1}{2}\left[\left(∆E\right)L^{1} b^{1} f^{1}+\left(∆E\right)L^{0} b^{0} f^{0}\right]$

$ +\frac{1}{2}\left[E^{0}\left(∆L\right)b^{1} f^{1}+E^{1}\left(∆L\right)b^{0} f^{0}\right]$

$ +\frac{1}{2}\left[E^{0} L^{0}\left(∆b\right) f^{1}+E^{1} L^{1}\left(∆b\right)f^{0}\right]$

$ +\frac{1}{2}\left[E^{0} L^{0} b^{0}\left(∆f\right) +E^{1}L^{1} b^{1}\left(∆f\right)\right]$ (6)

Contribution of each factor in (6) can be further decomposed into a domestic and a foreign effect. For the domestic effect we pre-multiply the contribution of each factor with a row elementary vector $e\_{d}'$of dimension*n\*c x 1*, where n stands for the number of industries and c stands for the number of countries in the MRIO model. The vector has zeros on all the positions ( for *r* = *1,...c* and for *i* = *1,...n*) except those which correspond to domestic industries (for *r* = *s*) where we put ones. For the foreign effect we pre-multiply the contribution of each factor with a row elementary vector $e\_{f}'$, which is a complement of $e\_{d}'$. Addition of these vectors generates a vector of ones.

The expression (7) is the basic equation for decomposition of a carbon footprint calculated from a MRIO model.

$∆g=\frac{1}{2}e\_{d}^{'} \left[\left(∆E\right)L^{1} b^{1} f^{1}+\left(∆E\right)L^{0} b^{0} f^{0}\right]$

 + $\frac{1}{2}e\_{f}^{'} \left[\left(∆E\right)L^{1} b^{1} f^{1}+\left(∆E\right)L^{0} b^{0} f^{0}\right]$

$ +\frac{1}{2}e\_{d}^{'} \left[E^{0}\left(∆L\right)b^{1} f^{1}+E^{1}\left(∆L\right)b^{0} f^{0}\right]$

$ +\frac{1}{2}e\_{f}^{'} \left[E^{0}\left(∆L\right)b^{1} f^{1}+E^{1}\left(∆L\right)b^{0} f^{0}\right]$ $ $

$ +\frac{1}{2}e\_{d}^{'} \left[E^{0} L^{0}\left(∆b\right) f^{1}+E^{1} L^{1}\left(∆b\right)f^{0}\right]$

$ +\frac{1}{2}e\_{f}^{'} \left[E^{0} L^{0}\left(∆b\right) f^{1}+E^{1} L^{1}\left(∆b\right)f^{0}\right]$

$ +\frac{1}{2}e\_{d}^{'} \left[E^{0} L^{0} b^{0}\left(∆f\right) +E^{1}L^{1} b^{1}\left(∆f\right)\right] $

$ +\frac{1}{2}e\_{f}^{'} \left[E^{0} L^{0} b^{0}\left(∆f\right) +E^{1}L^{1} b^{1}\left(∆f\right)\right]$ (7)

## Data

For the analysis we use data from WIOD database (Timmer et al., 2012), which covers the period 1995 – 2009 and lists 40 countries + The Rest of World. Sector detail consists of 35 industries. We use the April 2012 version which contains also MRIO tables in previous year prices. This enables undertaking the structural decomposition.

Regarding the environmental data we use data from the WIOD project on three main greenhouse gases: CO2, CH4 and N2O. They are expressed in CO2-eq according to the global warming potential mentioned in the 2007 IPCC report (IPCC, 2007) so we value methane to have 24 times and nitrous oxide 298 times stronger greenhouse effect than carbon dioxide. For simplicity we use only emissions generated in the production process and omit the emissions generated by household heating activities and household transport.

# Results

The carbon footprints of individual countries vary significantly in the sample of countries. For 2008 it ranges from 1,75 tons p.c. in India to 24,85 tons p.c. in Australia.

Figure 1 Carbon footprint of individual countries, 2008, tons of CO2-eq per capita

Source: Own computations

The largest increases in the carbon footprint are observed in fast-growing emerging economies such as China, Turkey, Mexico, India or Indonesia, but also European peripheral economies Ireland, Cyprus, Lithuania, Spain or Greece. It suggests that these economies did very little in cutting emissions as did for example new member states which also faced fast economic growth but with limited impact on emissions (Slovakia, Czech republic, Hungary, Estonia, Poland, Romania, Bulgaria).

Figure 2 Change in total carbon footprint of individual countries, 1995 - 2008

Source: Own computations

There may be many factors determining the change in carbon footprint, both of domestic and foreign origin. We decompose the change in carbon footprint into factors of emission intensity, Leontief structural change, final demand product mix and total level of consumption, all the factors consisting of domestic and foreign effect.

The results show an overall pattern of increasing the carbon footprints. The exceptions are Bulgaria, Japan and Germany. In Bulgaria it is mainly due to a sharp decrease in direct emission intensity of domestic production. In Japan and Germany it is due to very low growth of domestic demand which was surpassed by factors decreasing emissions.

The factor of domestic direct emission intensity decreased carbon footprint in all of the countries except of Estonia (where the direct emission intensity eventually increased in the period 1995 – 2003). Most notable decreases in carbon footprint due to a decrease in direct emission intensities are observed in China, Bulgaria, Turkey, Taiwan, Poland and Romania. Very low decreases are observed in Japan, Australia and Slovenia.

Change in foreign direct emission intensity decreased carbon footprints in all of the countries, most significantly in small open and very developed economies relying heavily on imports (Austria, Belgium, Ireland, Luxembourg, Netherlands and Sweden). Lowest contributions are observed in large economies producing mainly raw resources (with limited needs of imports).

Regarding the Leontief structural change, we do not observe a clear tendency. Although the footprints increased due to foreign effect (using more imported inputs, possibly also with higher emission intensity) in all countries, the results for domestic effect are at least “strange”. Approximately half of the countries decreased its carbon footprint due to domestic structural change but another half has even increased the emissions. This suggests shifting from emission less intensive towards emission more intensive inputs (“technological regress”). Only a small group of countries (Czech Republic, Poland, Slovakia, Romania, Estonia, India and Russia) observed a significantly stronger decrease of domestic emissions than increase of foreign emissions due to structural changes.

The changes in product mix show that decreases in domestic emissions were roughly offset by increased emissions abroad with some exceptions listing fast growing economies (converging CEE economies and China, Russia and India) where the consumption is probably shifting from goods to services.

The change in total level of consumption was the main source of growing carbon footprint except of Japan which faced near-zero growth of consumption. Large and relatively closed economies faced most of the increase domestically while in small open economies the increase was often embodied more in imports than in domestic production.

Table 1 Structural decomposition of carbon footprints

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Carbon footprint** | **E\_dom** | **E\_imp** | **L\_dom** | **L\_imp** | **b\_dom** | **b\_imp** | ***f*\_dom** | ***f*\_imp** |
| **AUS**  | 42,9% | -1,1% | -15,6% | -13,3% | 14,4% | -13,9% | 11,4% | 45,3% | 15,6% |
|  **AUT**  | 7,3% | -10,1% | -30,1% | 1,1% | 16,6% | -5,6% | 12,8% | 7,1% | 15,5% |
|  **BEL**  | 20,1% | -7,6% | -35,3% | -3,9% | 27,6% | -6,2% | 14,1% | 9,1% | 22,3% |
|  **BGR**  | -0,3% | -54,0% | -8,5% | 16,8% | 8,3% | -18,5% | 3,4% | 36,6% | 15,6% |
|  **BRA**  | 28,8% | -13,9% | -6,4% | 2,0% | 10,2% | -4,8% | 3,0% | 33,4% | 5,3% |
|  **CAN**  | 35,8% | -22,1% | -16,8% | 0,5% | 13,6% | -7,7% | 12,2% | 35,5% | 20,7% |
|  **CHN**  | 68,0% | -82,5% | -4,8% | 8,1% | 8,2% | -16,0% | 2,0% | 141,3% | 11,7% |
|  **CYP**  | 65,9% | -16,9% | -22,1% | 15,1% | 26,0% | -10,3% | 5,3% | 34,4% | 34,4% |
|  **CZE**  | 10,4% | -16,1% | -15,6% | -22,0% | 10,9% | -5,9% | 8,1% | 32,4% | 18,5% |
|  **DEU**  | -9,7% | -17,8% | -20,0% | -0,1% | 10,7% | -4,2% | 10,2% | 5,8% | 5,9% |
|  **DNK**  | 4,6% | -13,7% | -24,3% | -3,5% | 17,4% | -10,5% | 12,9% | 11,9% | 14,3% |
|  **ESP**  | 53,6% | -25,8% | -28,9% | 8,7% | 28,5% | -7,0% | 16,8% | 33,3% | 28,2% |
|  **EST**  | 18,7% | 5,4% | -16,0% | -38,5% | 6,9% | -45,1% | 4,8% | 69,1% | 32,1% |
|  **FIN**  | 18,9% | -18,9% | -20,7% | -3,6% | 15,1% | -2,8% | 6,1% | 22,3% | 21,4% |
|  **FRA**  | 14,7% | -17,9% | -25,1% | 0,0% | 13,8% | -3,3% | 14,6% | 15,2% | 17,3% |
|  **GBR**  | 15,6% | -18,4% | -24,6% | -6,0% | 17,2% | -8,7% | 12,3% | 23,8% | 20,0% |
|  **GRC**  | 49,8% | -23,7% | -21,0% | -7,2% | 21,9% | 4,7% | 11,5% | 40,5% | 23,0% |
|  **HUN**  | 8,6% | -12,8% | -19,3% | -5,4% | 15,7% | -23,0% | 4,6% | 27,6% | 21,3% |
|  **IDN**  | 47,4% | -25,6% | -9,2% | 6,1% | 10,1% | 7,9% | 4,0% | 44,3% | 9,9% |
|  **IND**  | 55,3% | -21,2% | -6,8% | -17,6% | 7,5% | -17,0% | 4,4% | 96,3% | 9,7% |
|  **IRL**  | 82,6% | -31,8% | -30,5% | 2,5% | 30,4% | -9,2% | 25,3% | 49,1% | 46,9% |
|  **ITA**  | 14,0% | -10,0% | -25,7% | 1,7% | 21,9% | -5,7% | 9,4% | 11,9% | 10,5% |
|  **JPN**  | -7,3% | -0,4% | -18,8% | -4,3% | 15,1% | -4,8% | 3,6% | 1,5% | 0,9% |
|  **KOR**  | 32,3% | -22,0% | -20,5% | 3,8% | 20,2% | -6,8% | 3,9% | 34,7% | 19,0% |
|  **LTU**  | 55,2% | -26,3% | -21,4% | -17,0% | 14,4% | -17,2% | 5,6% | 56,6% | 60,6% |
|  **LUX**  | 23,8% | -14,7% | -43,2% | 0,5% | 28,9% | -0,8% | -1,9% | 9,1% | 46,0% |
|  **LVA**  | 41,3% | -33,6% | -19,9% | -2,6% | 15,1% | -23,2% | 4,2% | 53,8% | 47,4% |
|  **MEX**  | 56,9% | -18,3% | -13,0% | -4,3% | 16,1% | -11,1% | 12,0% | 57,4% | 18,1% |
|  **MLT**  | 19,4% | -29,3% | -26,8% | 10,3% | 19,9% | 2,6% | 6,9% | 14,5% | 21,2% |
|  **NLD**  | 13,4% | -8,5% | -33,5% | -1,2% | 19,8% | -4,7% | 6,0% | 12,7% | 22,8% |
|  **POL**  | 11,6% | -37,0% | -9,0% | -18,8% | 10,0% | -15,1% | 8,6% | 57,5% | 15,4% |
|  **PRT**  | 21,9% | -21,1% | -22,2% | 7,0% | 21,8% | -4,5% | 6,1% | 20,3% | 14,6% |
|  **ROU**  | 1,7% | -37,5% | -8,1% | -23,2% | 6,9% | -16,7% | 5,0% | 56,7% | 18,7% |
|  **RUS**  | 5,5% | -14,2% | -3,9% | -25,6% | 3,0% | -25,5% | 4,5% | 60,9% | 6,4% |
|  **SVK**  | 33,0% | -15,6% | -21,4% | -21,1% | 11,1% | -17,4% | 7,4% | 44,7% | 45,3% |
|  **SVN**  | 40,9% | -3,8% | -26,5% | -5,3% | 19,1% | -17,3% | 14,7% | 27,9% | 32,1% |
|  **SWE**  | 24,8% | -11,6% | -31,7% | -1,5% | 25,8% | -5,5% | 17,6% | 10,9% | 20,8% |
|  **TUR**  | 66,1% | -41,3% | -18,1% | 14,4% | 20,4% | -4,7% | 5,1% | 62,6% | 27,7% |
|  **TWN**  | 15,3% | -42,2% | -20,5% | 15,2% | 0,9% | 10,9% | 0,7% | 29,2% | 21,1% |
|  **USA**  | 14,5% | -11,2% | -13,7% | -10,1% | 12,9% | -10,9% | 5,8% | 33,1% | 8,6% |
|  **RoW**  | 39,1% | -53,2% | -7,0% | 11,9% | 5,5% | -1,5% | 5,5% | 60,5% | 17,4% |

Source: Author´s computations

A regional comparison shows that the sharpest decrease in carbon footprint due to a change in domestic direct emission intensity is observed in Central Europe new member states[[2]](#footnote-2) and in other emerging markets[[3]](#footnote-3) around the world. On the other hand very little progress is observed in the group of very developed non-european countries JACU[[4]](#footnote-4). Though Core-EU[[5]](#footnote-5) and Medi-EU[[6]](#footnote-6) countries showed a small decrease in domestic emission intensity, they profited significantly from a decrease in foreign emission intensity, specifically from Central Europe and emerging countries.

Figure 3 Relative contribution of direct emission intensity change to a change in carbon footprint, domestic (left) and foreign (right) effect

Source: Author´s computations

Carbon footprint changes due to structural changes show a diversified picture. Only regions of JACU and especially Central Europe show a decrease in emissions which is very surprising. A decrease may signal two things: Either positive true structural changes leading to a shift from emission intensive inputs to less intensive inputs or a shift from domestic to foreign inputs. In fact, the Central Europe region is the only region where a decrease observed domestically was not fully offset by the increase abroad. All other region´s results suggest that substitution of domestic inputs with foreign inputs leads to an increase in their carbon footprints.

Figure 4 Relative contribution of structural change to a change in carbon footprint, domestic (left) and foreign (right) effect

Source: Author´s computations

Similar picture can be seen also in the case of changes in the structure of final demand. Region of Central Europe was the only one where the changes in consumption positively contributed to a decrease in carbon footprint. The decrease in domestic emissions was not offset by emissions embodied in imports. In the EU Core as well as Mediterranean a shift towards imports lead even to an increase in carbon footprints.

Figure 5 Relative contribution of change in the structure of final demand to a change in carbon footprint, domestic (left) and foreign (right) effect

Source: Author´s computations

# Conclusions

In this paper we showed that SDA can be used also on the carbon footprint calculated from an MRIO model. For this we used WIOD data which provide also MRIO tables in previous year prices. The empirical results show that all the surveyed countries increased their carbon footprints in the period 1995 – 2008 except of Bulgaria, Japan and Germany. While Bulgaria reached this result mainly via decreasing the direct emission intensity of their domestic production, Japan and Germany did so because of slow growth of consumption.

The sharpest decrease in carbon footprint due to a decrease in emission intensity is observed in the regions of Central Europe and global Emerging countries. Structural changes in the production as well as changes in the structure of final demand lead to an increase in overall emissions. The substitution of domestic production by imports leads to a decrease in the emission generated domestically but increase emissions generated abroad by even more. The only exception is the region of Central Europe where structural changes and changes in final consumption mix which lead to a decrease in domestic emissions were not offset by emissions embodied in imports.

Unfortunately the approach in this paper is unable to accurately distinguish between the effect of substituting domestic production by imports and the effect of true structural changes in intermediate and final consumption.

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