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A Structural Decomposition of Global Raw Material Consumption

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Abstract

Between 1995 and 2008, the global extraction of biomass, fossil fuels, and minerals grew from 48 to 69 billion metric tons. This study investigates how changing consumption and investment patterns affected the aforementioned increase. A series of Structural Decomposition Analyses at a global level as well as for 38 major economies is conducted. The analyses disentangle the drivers of Raw Material Consumption, which measures the extraction of materials necessary to produce a country's final demand. Data is taken from the World Input-Output Database. The results suggest that rising final demand is the predominant driver of growing Raw Material Consumption. Furthermore, final demand shifted into countries that consume material intensive goods. This shift was particularly pronounced for construction minerals and investment, indicating that infrastructure investment in industrialising nations was a key driver. The mix of goods in final demand slightly dematerialised. Falling material intensities in extractive industries as well as changes in production and trade patterns decelerated the growth of Raw Material Consumption. The country-level Structural Decomposition Analyses obtained qualitatively similar results.

JEL Classifications: Q2, Q3, C67

Keywords: Raw Material Consumption, Structural Decomposition Analysis, Input-Output Models

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1 Introduction

In 1995, 48 billion metric tons of fossil fuels, minerals, and biomass were extracted from nature. This number rose to 69 billion tons in 2008. 18 billion tons of materials were extracted solely in China, an increase of 129 per cent compared to 1995. Extracting and processing raw materials causes numerous environmental damages, including losses of biodiversity, acidification, and climate change (e.g. Dudka and Adriano, 1997). The utilisation of materials is often interpreted as, at least, a proxy for human pressure on ecosystems (Fischer-Kowalski and Hüttler, 1998).

Motivated by both environmental concerns and economic motives, policy makers have started to encourage a more efficient use of materials. The EU Commission has implemented a flagship initiative for a resource-efficient Europe as part of its Europe 2020 strategy (EU Commission, 2011). The German Federal Government has set the doubling of material efficiency until 2020, relative to 1994, as a goal for the German sustainability strategy already in 2002 (Bundesregierung, 2002).

A majority of policies focuses on the reduction of apparent consumption of materials. This approach neglects the indirect flows that are needed to produce a good but which become unobservable once goods cross a border. The mass of imported steel can be measured, for instance, but the coal used to reduce the iron ores is not observed. Indirect flows become increasingly important in a globalised world (Wiedmann et al., 2013).

Raw Material Consumption (RMC) is an indicator which avoids these shortcomings. It quantifies all materials extracted to produce a country's final demand, including indirect flows. Thus, it measures a country's material footprint. Data on RMC has been compiled at a national (Kovanda and Weinzettel, 2013; Schaffartzik et al., 2014), international (Schoer et al., 2012; Muñoz et al., 2009), and global level (Bruckner et al., 2012; Wiebe et al., 2012; Wiedmann et al., 2013, 2014).

The advantages of measuring material use as Raw Material Consumption are increasingly recognised by policy makers. The EU Commission identified GDP divided by RMC as a potential metric for resource productivity. In the European Union, official data on RMC is compiled by Eurostat (EU Commission, 2014) and, for the UK, by the Office for National Statistics (2013).

In this study, I disentangle the drivers of growing global Raw Material Consumption between 1995 and 2008. By conducting a series of Structural Decomposition Analyses (SDAs) at a global level and for 38 major economies, I decompose the change in RMC into a product of five drivers: the growth of final demand, the change in the mix of goods in final demand, the change of countries supplying final demand, the change in the input-output structure of the global economy, and the change in material intensity of extractive sectors. At a global level, regional shifts of final demand are considered as well.

Experiences from climate policy indicate the relevance of this study. Peters and Hertwich (2008), for instance, reveal that more than 5.3 Gt of CO_2 are embodied in international trade and that Annex B countries are net importers of greenhouse gas emissions. The latter is interpreted as carbon leakage. An improved understanding of the powers that drive RMC helps policy makers to design effective policies for the reduction of material use. Hence, it enables them to anticipate a potential "material leakage".

This study is the first to present a global Structural Decomposition Analysis of Raw Material Consumption. Weinzettel and Kovanda (2011) as well as Wood et al. (2009) conduct country-level SDAs of consumption-based indicators for material use. Weinzettel and Kovanda (2011) decompose the RMC of the Czech Republic from 2000 to 2007. They find that growing final demand is the most important driver of increased RMC. Dematerialising consumption patterns had a limited impact. Wiedmann et al. (2013) estimate the drivers of global RMC in 2008. They identify GDP per capita as the most important driver of RMC. A 10 per cent increase in GDP per capita leads to a 6 per cent increase in RMC.[1]

By conducting Structural Decomposition Analyses of greenhouse gas emissions using WIOD data, Arto and Dietzenbacher (2014) as well as Xu and Dietzenbacher (2014) present methodologically similar work. Arto and Dietzenbacher (2014) investigate the drivers of global greenhouse gas emissions, while Xu and Dietzenbacher (2014) decompose the emissions embodied in imports and exports.

The Logarithmic Mean Divisia Index (LMDI) method (Ang and Liu, 2001) is applied to decompose RMC growth into its drivers. The LMDI is an established method in the field of Index Decomposition Analyses (IDA, see e.g. Ang and Zhang, 2000) and gains

[1] Studies examining the drivers of apparent consumption of materials are more numerous. Methodologies applied include Index Decomposition Analyses (Hoffrén et al., 2000; Hashimoto et al., 2008; Pothen and Schymura, 2015), Structural Decomposition Analyses (Muñoz and Hubacek, 2008; Wood et al., 2009), and econometric methods (Steinberger et al., 2010; Steger and Bleischwitz, 2011; Steinberger et al., 2013).

importance in Structural Decomposition Analyses as well (Su and Ang, 2012).

Data is taken from the World Input-Output Database (WIOD; Timmer, 2012; Timmer et al., 2015). It provides a time series of harmonised global multi-regional input-output (GMRIO) tables that differentiate between 34 sectors in 40 countries and a rest of the world (RoW) region (Dietzenbacher et al., 2013). WIOD contains the GMRIO tables in current and in previous years' prices (Los et al., 2014) from 1995 to 2009.[2] Thus, WIOD data allows a year-by-year decomposition conducted in constant prices. Furthermore, WIOD contains data on material extraction for all countries and the RoW.

The results suggest that RMC in the sample countries grew by 44 per cent from 1995 to 2008. Rising final demand was the predominant driver of RMC growth. If all other effects had remained at the levels of 1995, global RMC would have increased by 48 per cent. Furthermore, final demand shifted into countries consuming more material intensive goods. The shift increased global RMC by another 25 per cent, ceteris paribus. This development was particularly pronounced for construction minerals and for investment, implying that infrastructure investment in industrialising countries was a major driver of RMC growth. The mix of goods in final demand mildly dematerialised from 1995 to 2008. Material efficiency improvement in extractive industries as well as changes in the production and trade of intermediate goods decelerated the rising RMC. At the national level, I obtain qualitatively similar results. RMC decreased only in three countries between 1995 and 2008. Increasing final demand was the impelling force behind growing RMC in almost all nations. The majority of countries experienced that the goods mix of final demand slightly dematerialised.

2 Methodology

2.1 Raw Material Consumption

Let $\mathbf{rmc}$ denote the vector of Raw Material Consumption. Each element rmc_s records the material extraction implied by final demand in country s. Countries are indexed $r, rr, s \in R$, and sectors $i, j \in I$.

$\mathbf{ex}^\intercal$ is the transposed vector of material intensities, the amount of materials that

[2]The year 2009 is not included in the analysis because it appears severely biased by the financial crisis.

sector i in r extracts per unit of monetary output. $\mathbf{L}$ is the Leontief inverse. Its elements $L_{i,r,j,rr}$ record the input of sector i in r used to produce one dollar of output in sector j of country rr.[3] $\mathbf{F}$ is the matrix of final demand. Each element $F_{j,rr,s}$ records the value of goods that country s purchases from sector j in country rr due to final demand. Final demand encompasses consumption by households and governments as well as investment and changes in inventories.

rmc can be computed according to equation (1). Note that monetary input-output data is used to derive physical material flows. Equation (1) implicitly assumes unique prices in all sectors. This assumption is likely to be violated in practice (Weisz and Duchin, 2006), for example due to sectors exerting market power. The lack of physical input-output tables necessitates the use of data in monetary terms.

$$\mathbf{rmc} = \mathbf{ex}^{\intercal} \cdot \mathbf{L} \cdot \mathbf{F} \tag{1}$$

Reflecting the study's focus on final demand as a driver of RMC, I decompose the matrix $\mathbf{F}$ into three parts as follows. The first part is the the level of final demand in country s (f_s^{lev}). The share of sector j in s's final demand ($f_{j,s}^{str}$) builds the second part. The third and final part is the share of country s's final demand of good j which is supplied by country rr ($f_{j,rr,s}^{sup}$). Appendix A shows that Raw Material Consumption in country s can be computed as:

$$rmc_s = \sum_{i,r,j,rr} rmc_{i,r,j,rr,s} = \sum_{i,r,j,rr} ex_{i,r} l_{i,r,j,rr} f_{j,rr,s}^{sup} f_{j,s}^{str} f_s^{lev} \tag{2}$$

Equation (2) illustrates that RMC is a sum of all material extractions that country s's final demand implies. Each summand is a product of five factors. f_s^{lev} is the level of final demand. $f_{j,s}^{str}$ captures which goods are consumed by country s and $f_{j,rr,s}^{sup}$ records where they are bought from. $l_{i,r,j,rr}$ quantifies the inputs from sector i in r that are needed to produce the goods of sector j in rr. $ex_{i,r}$ is the amount of material extraction associated with the output of sector i in r.

[3] The Leontief inverse is defined as $\mathbf{L} = (\mathbf{E} - \mathbf{A})^{-1}$. $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$ is the matrix of direct input coefficients. $\hat{\mathbf{x}}^{-1}$ denotes the diagonalised vector of outputs. $\mathbf{Z} = (Z_{i,r,j,rr})$ is the matrix of intermediate flows from sector i in country r to sector j in country rr. $\mathbf{E}$ is the identity matrix.

2.2 Country-Level Structural Decomposition

Let $D_{s,t}^{tot}$ denote the change of RMC in country s from year $t-1$ to year t. $D_{s,t}^{tot}$ is also called *total effect*. The country-level SDA decomposes the total effect into a product of five effects (equation 3):

$$D_{s,t}^{tot} = \frac{rmc_{s,t}}{rmc_{s,t-1}} = D_{s,t}^{int} D_{s,t}^{leo} D_{s,t}^{sup} D_{s,t}^{str} D_{s,t}^{lev} \tag{3}$$

The effect exerted by falling or rising material intensities of extractive industries is denoted as *intensity effect* ($D_{s,t}^{int}$). $D_{s,t}^{leo}$ is the *Leontief effect*. It measures the impact that changes in production processes and trade structures of intermediate goods have on Raw Material Consumption. The *supplier effect* $D_{s,t}^{sup}$ reflects how the countries that supply final demand goods to country s change. The altering sectoral composition of final demand is captured by the *structure effect* $D_{s,t}^{str}$. It measures whether the bundle of goods consumed in country s dematerialises. The impacts of increasing or decreasing levels of final demand are captured by the *level effect* $D_{s,t}^{lev}$.

The Logarithmic Mean Divisia Index method (Ang and Liu, 2001) is applied to estimate the contribution of each effect to the change in RMC. The LMDI method has a number of favourable properties. It is robust to zero-values and enables to conduct a perfect decomposition, which means that no unexplained residuals remain. Moreover, it is invariant to time-reversals. I use a multiplicative decomposition to simplify the comparison between the individual countries. The five effects are estimated according to equations (4) to (8).

$$D_{s,t}^{int} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr,s,t} \ln\left(\frac{ex_{i,r,t}}{ex_{i,r,t-1}}\right)\right] \tag{4}$$

$$D_{s,t}^{leo} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr,s,t} \ln\left(\frac{l_{i,r,j,rr,t}}{l_{i,r,j,rr,t-1}}\right)\right] \tag{5}$$

$$D_{s,t}^{sup} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr,s,t} \ln\left(\frac{f_{j,rr,s,t}^{sup}}{f_{j,rr,s,t-1}^{sup}}\right)\right] \tag{6}$$

$$D_{s,t}^{str} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr,s,t} \ln\left(\frac{f_{j,s,t}^{str}}{f_{j,s,t-1}^{str}}\right)\right] \tag{7}$$

$$D_{s,t}^{lev} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr,s,t} \ln\left(\frac{f_{s,t}^{lev}}{f_{s,t-1}^{lev}}\right)\right] \tag{8}$$

$\omega_{i,r,j,rr,s,t}$ is computed according to the following equation in which $L(a,b) = \frac{a-b}{\log(a)-\log(b)}$ denotes the logarithmic mean of a and b:

$$\omega_{i,r,j,rr,s,t} = \frac{L\left(rmc_{i,r,j,rr,s,t}, rmc_{i,r,j,rr,s,t-1}\right)}{L\left(rmc_{s,t}, rmc_{s,t-1}\right)} \tag{9}$$

Equations (4) to (8) assume that all factors are positive in $t-1$ and t. In practice, this is not the case due to zero entries in the Leontief inverse, or because sectors do not extract materials. Usually, this problem is circumvented by replacing zero values with a small positive number. Wood and Lenzen (2006), however, point out that replacing zero values with small positive numbers leads to non-negligible biases in SDAs. Therefore, I use the analytical limits approach to deal with zero-entries (Ang and Liu, 2007; Ang et al., 2000).

2.3 Global Structural Decomposition

Extending the Structural Decomposition Analysis from the country level to the global level is straightforward. Let rmc^G denote the global Raw Material Consumption. It is computed according to equation (10).

$$rmc^G = \sum_{i,r,j,rr,s} ex_{i,r} l_{i,r,j,rr} f_{j,rr,s}^{sup} f_{j,s}^{str} f_s^{reg} f^{G,lev} \tag{10}$$

$f^{G,lev}$ is the global level of final demand. The share of country s in global final demand is denoted as f_s^{reg}. It represents the regional distribution of consumption.

Analogously to the country-level case, the change in global RMC $D_t^{tot,G}$ is decomposed into six effects. The *intensity effect* (D_t^{int}), the *Leontief effect* (D_t^{leo}), the *supplier effect* (D_t^{sup}), and the *structure effect* (D_t^{str}) can be interpreted as in the county-level SDA. D_t^{reg} is the impact of changes in the regional composition of final demand (*regional effect*). The consequences of global final demand growth are $D_t^{G,lev}$, called the *global level effect*. The formulas used to estimate the six effects are not displayed in order to save space.

$$D_t^{tot,G} = \frac{rmc_t^G}{rmc_{t-1}^G} = D_t^{int} D_t^{leo} D_t^{sup} D_t^{str} D_t^{reg} D_t^{G,lev} \tag{11}$$

3 Data

The following data is required to conduct the Structural Decomposition Analyses: the matrix of intermediate flows $\mathbf{Z}$ which is needed to compute the Leontief inverse $\mathbf{L}$, the matrix of final demands $\mathbf{F}$, and the vector of material intensities $\mathbf{ex}$. The latter is derived from dividing each sector's extraction of materials by its output in monetary terms ($\mathbf{x}$).

I use the World Input-Output Tables (WIOT) to quantify $\mathbf{Z}$, $\mathbf{F}$, and $\mathbf{x}$. The WIOTs are GMRIO tables which are part of the World Input-Output Database (Timmer, 2012; Timmer et al., 2015). They distinguish between 34 industries in 40 countries plus the RoW region (see Annex B for the sectoral classification).

Dietzenbacher et al. (2013) outline the construction of the WIOTs in detail. The compilation is based on national supply and use tables (SUTs) in which industry and product classifications have been harmonised. Goods which were imported for processing and then re-exported have been included in the SUTs, if necessary (for China and the US, for instance).

The frequency with which national SUTs are compiled varies between countries (Erumban et al., 2012). Most European countries have been publishing official SUTs annually from 1999 onwards. Before 1999, data is usually available either annually or biannually. Many non-EU countries publish official SUTs every five years. Missing years are interpolated by using an extended RAS procedure which exploits sectoral data on output, value added, final demand, and commodity imports (Temurshoev and Timmer, 2011). Taking into account that data is not solely based on original SUTs, the presentation of the results focuses on the developments between 1995 and 2008.

UN Comtrade data on merchandise trade has been exploited to construct international SUTs. Data on trade in services has been taken from various sources including the UN, the OECD, and Eurostat. For each importing nation, the shares of countries from which imports were sourced have been compiled. These shares are computed for three end-use categories: intermediate consumption, final consumption, and capital goods. Import proportionality has only been assumed within the end-use categories. Bilateral trade flows have been adjusted by using the RAS approach. The SUTs have been compiled into a GMRIO table assuming that each product has the same sales structure, independent of the producing sector. I aggregated the WIOTs to 38 countries and 31 industries in order to improve the numerical tractability. Therefore, Luxembourg and Cyprus are considered as part of the RoW region.

The WIOTs in current prices are published for the years 1995 to 2011 and in previous year's prices for the period from 1995 to 2009. The generalised RAS procedure has been used to deflate the IO tables (Los et al., 2014, describe the deflation in detail). I conduct the SDAs in constant prices on a year-by-year basis, from year $t-1$ to year t. The results are chained in order to compute the effects from 1995 to 2008. The chained total effect in country s in 2008, for instance, is calculated as $D^{tot}_{s,95-08} = D^{tot}_{s,1996} \cdot D^{tot}_{s,1997} \cdot \ldots \cdot D^{tot}_{s,2008}$.

WIOD provides data on material extraction based on the Global Material Flow Database (SERI, 2013) and Eurostat's Material Flow Accounts. Twelve types of extraction are distinguished. Extraction is measured in (metric) tons. I only take used extraction, which enters the economic system, into consideration. Unused extraction, which does not enter any production processes, such as overburden from mining, is omitted due to limited data quality.

Two extractive industries are distinguished in the WIOD: AtB (Agriculture, hunting, forestry and fishing) and C (Mining and quarrying). The extraction of biomass has been allocated to the agricultural sector while fossil fuel and mineral extraction have been allocated to the mining sector. As is customary in the literature, I reallocate the extraction of construction minerals to the construction sector F. Annex C displays the materials considered in the WIOD and the sectors which are assumed to extract these.

4 Results

4.1 Raw Material Consumption

Before addressing the SDAs' results, I present data on the extraction and the RMC in the sample countries. Table 1 displays the extraction (EX) and the Raw Material Consumption (RMC) in billion tons as well as in tons per capita (EX^{cap} and RMC^{cap}).

	1995				2008			
	EX	EX^{cap}	RMC	RMC^{cap}	EX	EX^{cap}	RMC	RMC^{cap}
AUS	1.16	64.36	0.58	44.63	1.69	79.31	0.81	37.95
AUT	0.15	19.22	0.22	32.08	0.17	20.78	0.25	30.58
BEL	0.14	13.60	0.22	24.43	0.12	10.95	0.25	23.12
BRA	2.01	12.43	1.84	14.19	3.10	16.15	2.30	11.98
BGR	0.09	11.20	0.07	11.69	0.14	19.17	0.10	13.12
CAN	1.05	35.92	0.78	30.32	1.04	31.40	0.89	26.77
CHN	7.90	6.56	7.32	14.15	18.12	13.68	17.04	12.87
CZE	0.19	18.11	0.17	18.28	0.19	18.05	0.19	18.18
DNK	0.11	20.28	0.13	29.91	0.12	22.20	0.16	28.49
EST	0.02	14.48	0.02	21.30	0.04	27.36	0.03	22.88
FIN	0.14	26.58	0.16	42.03	0.18	33.20	0.21	40.40
FRA	0.67	11.28	1.00	22.60	0.72	11.17	1.35	20.90
DEU	1.34	16.41	2.03	22.81	1.08	13.19	1.86	22.69
GRC	0.14	12.76	0.17	24.20	0.16	13.90	0.26	23.00
HUN	0.10	10.13	0.13	11.72	0.12	12.17	0.12	12.06
IND	2.72	2.85	2.61	4.38	4.41	3.76	4.19	3.56
IDN	0.97	4.98	0.78	5.15	1.57	6.69	1.00	4.27
IRL	0.09	25.55	0.08	51.41	0.18	41.09	0.19	41.33
ITA	0.56	9.93	0.92	17.44	0.56	9.52	0.99	16.86
JPN	0.88	7.00	2.28	15.47	0.63	4.93	1.94	15.20
KOR	0.51	11.28	0.81	18.11	0.46	9.31	0.82	16.69
LVA	0.03	13.02	0.03	16.22	0.04	19.66	0.04	18.52
LTU	0.02	6.03	0.03	14.53	0.05	14.75	0.05	16.48
MLT	0.00	0.29	0.00	12.32	0.00	0.32	0.00	11.15
MEX	0.87	9.12	0.80	11.82	1.06	9.19	1.13	9.80
NLD	0.14	9.04	0.25	19.03	0.14	8.41	0.29	17.89
POL	0.48	12.50	0.42	15.51	0.61	15.97	0.60	15.70
PRT	0.10	9.87	0.14	30.43	0.21	19.56	0.31	28.89
ROM	0.31	13.87	0.29	20.50	0.52	25.16	0.47	22.65
RUS	2.03	13.70	1.31	12.85	2.64	18.58	1.90	13.41
SVK	0.04	7.82	0.06	15.53	0.07	12.81	0.08	15.48
SVN	0.03	14.03	0.04	26.54	0.03	17.08	0.05	26.12
ESP	0.42	10.63	0.60	26.58	0.66	14.31	1.05	22.78
SWE	0.19	21.60	0.21	28.39	0.22	23.68	0.25	27.18
TWN	0.18	8.45	0.35	31.81	0.14	6.03	0.68	29.49
TUR	0.51	8.72	0.58	14.45	0.80	11.43	0.85	12.02
GBR	0.76	13.10	0.93	20.16	0.59	9.56	1.17	18.92
USA	8.38	31.47	8.94	37.37	7.96	26.18	9.95	32.72

Table 1: Material Extraction and Consumption in 1995/2008. Absolute extraction (EX) and consumption (RMC) in billion tons, per capita extraction (EX^{cap}) and consumption (RMC^{cap}) in tons per capita.

In 1995, the United States had the largest absolute material extraction in our sample (8.4 billion tons). China came second in the ranking, extracting 7.9 billion tons. Australia had the biggest per-capita extraction amounting to 64.4 tons per capita. In absolute terms, the US and China exhibited the highest RMC in 1995. Regarding per capita terms, the US, Australia, and Finland had the highest RMC. Each of those had an RMC^{cap} of more than 30 tons, exceeding the Chinese numbers about five times.

With an amount of 18.1 billion tons, China's material extraction has more than doubled in 2008. This is more than twice as much as the United States' extraction of 8 billion tons. In per capita terms, Australia still shows the highest extraction (79.3 tons). Chinese RMC strongly grew to 17 billion tons. With a material extraction greater than RMC, the People's Republic remained to be a net exporter of materials, however. Only three countries reduced their RMC from 1995 to 2008: Germany, Japan, and Hungary.

4.2 Global Structural Decomposition

4.2.1 Baseline

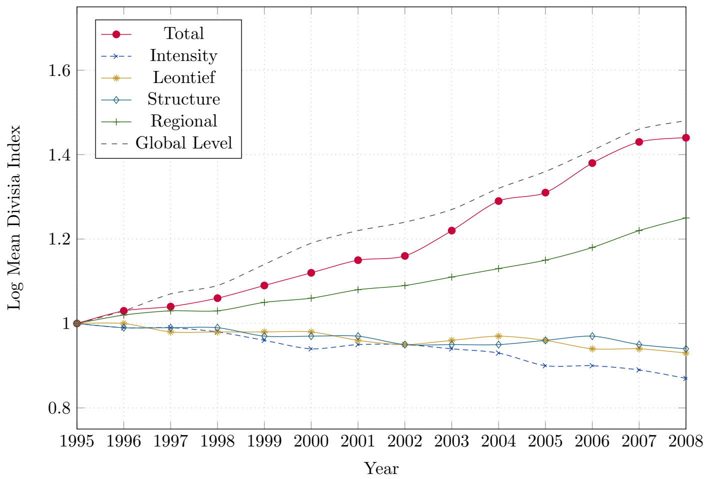


Figure 1: Global Structural Decomposition

Figure 1 displays the results of the global SDA which includes all countries in the sample except for the RoW region. The results can be interpreted as follows: the red line shows the change of Raw Material Consumption relative to 1995 (total effect). A value of 1.44 in 2008 indicates that the global RMC was 44 per cent higher than in 1995.

The other lines correspond to the effects that explain the change in RMC. The dashed black line depicts the global level effect. In 2008, it took a value of 1.48 which means that global RMC would have exceeded the number of 1995 by 48 per cent if all other effects had remained unchanged. Globally, growing consumption was the most important driver of increasing RMC.

The second driver boosting RMC was the regional effect represented by a solid green line. The regional effect amounted to 1.25 in 2008. This indicates that final demand has shifted into countries which consume more material intensive goods.

Other effects decelerated the increase in global RMC. The dashed dark blue line depicts the intensity effect. It indicates that extractive industries have become less material intensive between 1995 and 2008. In the case of exhaustible resources, this implies that improved technology in the extractive industries overcompensated for the deteriorating quality of deposits (Slade, 1982). In 2008, the Leontief effect (solid yellow line), which represents changes in production and intermediate trade, reduced the global RMC by 7 per cent relative to 1995.

The solid blue line represents the structure effect which has also slowed down the growth of global RMC. Consumption patterns have slightly dematerialised between 1995 and 2008. The structure effect amounts to 0.94 in 2008. The supplier effect is not shown due to its negligible impact.

4.2.2 Material Groups

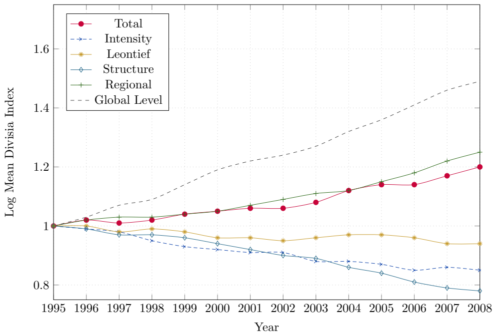
In order to assess the heterogeneity between materials, I conduct individual global SDAs for three material groups: biomass (Figure 2a), industrial minerals and fossil fuels (Figure 2b), and construction minerals (Figure 2c).[4]

Decomposing the three material groups individually leads to qualitatively similar results as decomposing them together. The global level effect as well as the regional effect contributed to growing global RMCs. The former has had a stronger impact than the latter. The other effects usually reduced RMC growth.

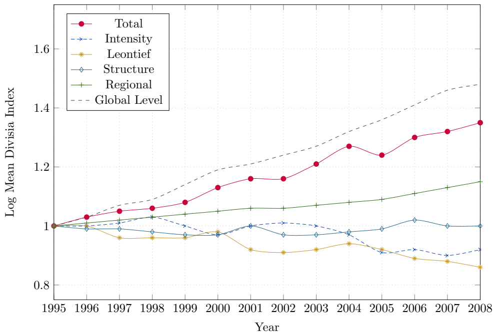
Biomass exhibited the lowest RMC growth. It grew by less than 20 per cent from 1995 to 2008. The RMC of industrial minerals and fossil fuels increased by 48 per cent. In case of industrial minerals and fossil fuels, the intensity effect fell visibly from 2004 to 2005. It equaled 0.92 in 2008.

The RMC of construction materials increased by 72 per cent from 1995 to 2008. Since 2002, the total effect has been exceeding the global level effect. This can be attributed to the regional effect. The regional effect increased RMC of construction minerals by 35 per cent in 2008 relative to 1995. Leontief and structure effects exerted negligible influences. The only factor that has decelerated the RMC growth is a more efficient use of materials in the construction sector. In 2008, the intensity effect was 0.86.

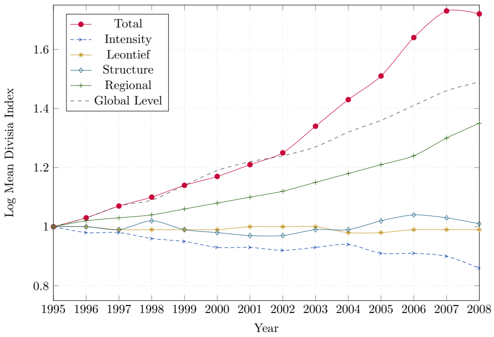
[4] Steinberger et al. (2010) also jointly present results on fossil fuels and industrial minerals. They argue that their use evolves similarly in the course of economic development.



(a) Biomass



(b) Minerals & fossil fuels



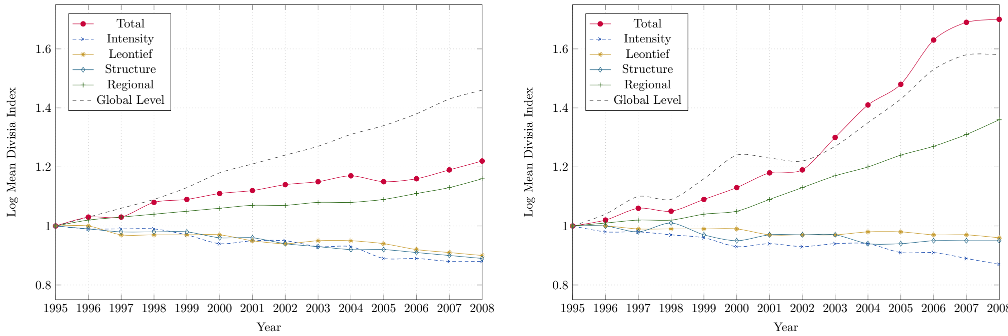
(c) Construction minerals

Figure 2: Global SDA results by type of material

4.2.3 Consumption and Investment

Final demand consists of final consumption and investments including changes in inventories. I run separate SDAs in order to explain the RMC growth due to final consumption and due to investment.

Figure 3a shows the results for final consumption. RMC due to final consumption grew by merely 22 per cent in 2008 relative to 1995. In 2008, the structure effect was 0.89 in the case of final consumption and 0.94 in the case of final demand. This implies that the mix of goods in final consumption has dematerialised more strongly. The share of final consumption spent on services, for instance, increased continuously between 1995 and 2008. In 1995, the countries in the sample spent, on average, 65.2 per cent of final consumption on services (excluding construction). This number reached 70 per cent in 2008. Furthermore, the regional effect was less pronounced in the case of final consumption. It increased the RMC due to final consumption by only 16 per cent in 2008 relative to 1995.



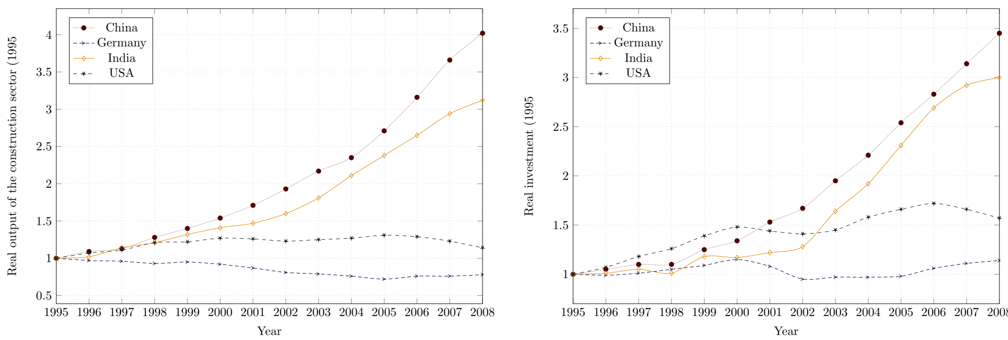
(a) Final consumption

(b) Investment

Figure 3: Global SDA by type of final demand

The RMC due to investment increased by 70 per cent from 1995 to 2008. The regional effect boosted RMC growth by 36 per cent. Thus, it appears that investments strongly shifted into countries which invest in more material intensive goods. Together with the results on construction materials (Figure 2c), this suggests that infrastructure investment in industrialising nations was a key driver of growing global RMC.

The data presented in Figure 4a and Figure 4b support this presumption. The former shows the real output of construction sectors in China, India, the US, and Germany. The latter displays the real investment in these countries. The values are normalised to one in 1995. From 1995 to 2008, the output of the construction sector quadrupled in China and tripled in India. In the US, it only grew slightly and it fell in Germany. Real investment also grew much more strongly in China and India than in the US and Germany.



(a) Construction

(b) Investment

Figure 4: Real output of the construction sector and real investment in selected countries (1995=1). Source: WIOD.

4.3 Country-Level Structural Decomposition

This subsection explores how global trends can be transferred to the country level. Figure 5 plots the average annual growth rate of RMC against the average annual growth rate of consumption. The dotted lines denote the mean growth rates of the sample countries, the dashed line depicts a linear regression. Figure 5 confirms the correlation between final demand growth and RMC growth. It also suggests a notable heterogeneity between countries. The country-level SDAs disentangle the impact of rising final demand and the effects that are exerted by other factors determining the RMC.

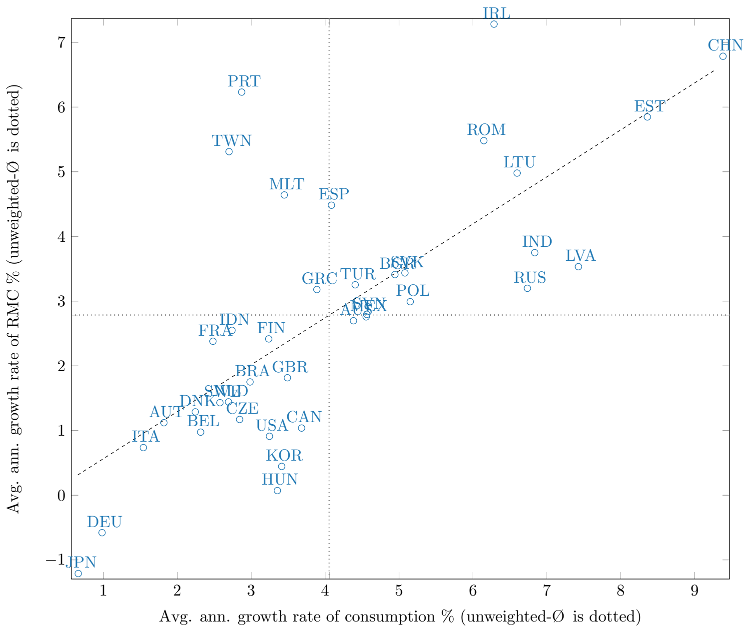


Figure 5: Final demand and Raw Material Consumption

Table 2 summarises the results of the country-level SDAs. It displays the five effects explaining the total effect and the total effect itself in 2008. The interpretation is analogous to the global SDA. The total effect in Australia was 1.38, for instance, implying that Down Under increased its RMC by 38 per cent in 2008 relative to 1995.

The level effect was the most important driver of RMC growth in almost all nations in the sample. In all 38 nations, it was positive in 2008. It exceeded 2.0 in eight countries, which implies that the level effect alone would have caused more than a duplication of RMC in these nations.

The results suggest a slight dematerialisation of the final demand mix in most countries. In 2008, the value of the structure effect was usually located between 0.85 and 0.95.

	$DTot_{s,95\text{-}08}$	$DInt_{s,95\text{-}08}$	$DLeo_{s,95\text{-}08}$	$DSup_{s,95\text{-}08}$	$DStr_{s,95\text{-}08}$	$DLev_{s,95\text{-}08}$
AUS	1.38	0.96	0.86	0.99	0.96	1.74
AUT	1.15	0.92	1.03	1.05	0.92	1.26
BEL	1.13	0.80	1.00	1.09	0.97	1.34
BRA	1.25	0.95	0.91	1.02	0.97	1.46
BGR	1.35	1.17	0.83	0.85	0.99	1.64
CAN	1.14	0.72	0.96	1.02	1.01	1.60
CHN	2.33	0.78	0.93	1.01	1.00	3.20
CZE	1.14	1.00	0.92	0.99	0.88	1.43
DNK	1.16	0.92	0.95	1.05	0.95	1.33
EST	1.91	1.11	0.79	0.84	1.01	2.58
FIN	1.36	0.85	0.96	1.02	1.08	1.51
FRA	1.35	0.94	1.03	1.04	0.97	1.37
DEU	0.92	0.98	0.88	1.06	0.88	1.13
GRC	1.48	1.00	0.79	1.01	1.14	1.62
HUN	0.95	0.94	0.80	0.99	0.84	1.52
IND	1.61	0.87	0.88	1.00	0.90	2.35
IDN	1.28	1.15	1.14	0.70	1.00	1.40
IRL	2.43	1.29	0.97	1.01	0.89	2.17
ITA	1.08	0.90	0.99	1.03	0.97	1.22
JPN	0.85	0.98	0.93	1.05	0.82	1.09
KOR	1.00	0.87	0.90	1.03	0.83	1.50
LVA	1.54	0.97	0.80	0.97	0.83	2.46
LTU	1.81	1.12	0.80	0.99	0.91	2.25
MLT	1.74	0.91	1.11	1.17	0.98	1.52
MEX	1.40	0.82	0.96	1.02	1.00	1.76
NLD	1.20	0.89	1.00	1.08	0.89	1.41
POL	1.44	1.08	0.81	0.98	0.89	1.90
PRT	2.11	1.55	1.05	1.01	0.90	1.44
ROM	1.59	1.03	0.79	0.98	0.95	2.09
RUS	1.45	0.83	0.84	0.99	0.95	2.23
SVK	1.48	1.11	0.79	1.02	0.89	1.85
SVN	1.41	0.78	0.93	1.04	1.06	1.77
ESP	1.75	0.99	1.02	1.04	0.99	1.68
SWE	1.20	0.95	0.92	1.03	0.96	1.39
TWN	1.93	0.87	1.65	1.03	0.94	1.40
TUR	1.47	0.98	0.99	1.03	0.85	1.71
GBR	1.26	0.82	0.95	1.10	0.94	1.56
USA	1.11	0.86	0.91	1.02	0.92	1.51

Table 2: Country-level Structural Decomposition AnalysGroup IV. All effects displayed for 2008 relative to 1995.

As in the global case, changing suppliers of final demand goods have had a small impact on RMC, with a few exceptions (Indonesia, Estonia, Bulgaria, Malta).

The supply side slowed down RMC growth. Both the intensity effect and the Leontief effect are found to be below the value of 1.0 in the majority of nations. However, some heterogeneity occurs. The intensity effect, for instance, ranged from 0.72 in Canada to 1.55 in Portugal.

With a value of 3.2 in 2008, China exhibited the strongest level effect in the sample. China's total effect of 2.33 was exceeded solely by Ireland. Structure and supplier effect have had a negligible impact on increasing RMC in the People's Republic. Only the Leontief effect (0.93 in 2008) and, more importantly, the intensity effect (0.78 in 2008) decelerated China's RMC growth.

Pothen and Schymura (2015) employ Index Decomposition Analyses and the WIOD to investigate the drivers of Material Use. Reflecting the beginning of the value chain, Material Use measures the utilization of materials after their extraction. Pothen and Schymura (2015) find that Material Use in China more than tripled between 1995 and 2008. Material Use grew more quickly than RMC which indicates that China utilized an increasing share of its materials to produce goods earmarked for export.

The country-level SDA for the Czech Republic yields similar results than Weinzettel and Kovanda (2011). Growing final demand was the main driver of Czech RMC growth while the mix of goods in final demand mildly dematerialised.

4.4 Sectoral Aggregation

An important issue is the sectoral aggregation of the WIOD data. I distinguish between three extractive industries and implicitly assume that each dollar of their output contains the same amount of materials. In practice, extractive sectors produce numerous outputs with different value-to-weight ratios. Materials with high value-to-weight ratios are more likely to be traded internationally. Thus, exports of extractive sectors are expected to be less material intensive than domestic sales. Unfortunately, the WIOD does not allow for a distinction between more extractive industries. Considering intermediate flows among all sectors, the SDAs' results might be sensitive to the sectoral aggregation of non-extractive industries as well.

There is no agreement in the literature about the importance of sectoral aggregation for the results of SDAs. Employing four multi-regional input-output databases, Steen-Olsen et al. (2014) find that sectoral aggregation has a notable effect on CO_2 multipliers. Weber (2009) investigates the United States' energy use by applying Index and Structural Decomposition techniques. He examines whether his results are sensitive to the level of sectoral aggregation. He ascertains considerable quantitative impacts of aggregating sectors. The results are not qualitatively affected on a reasonable level of aggregation. Su et al. (2010) find that approximately 40 sectors are sufficient to capture the carbon emissions embodied in China's and Singapore's exports.

To illustrate how sensitive the results of this study are, I aggregate the 31 sectors into 10. The three extractive industries remain unaggregated. Appendix D displays the correspondence between WIOD sectors and aggregated industries. I conduct a global as well as country-level SDAs by using the aggregated sectoral structure.

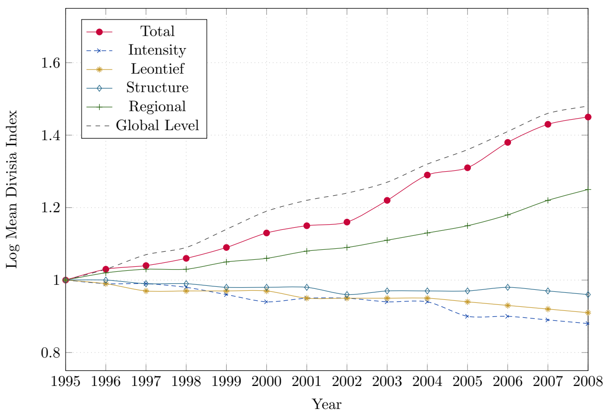


Figure 6: Global Structural Decomposition with Aggregated Sectors

Figure 6 displays the global SDA for the case of aggregated sectors. Differences to the global SDA, which was conducted by using 31 sectors, are in a magnitude of one percentage point. Replicating the country-level SDAs does not reveal major changes either. The correlation between the effects computed with 31 and with 10 sectors is high, ranging from 0.956 for the structure effect to 0.998 for the intensity effect. This suggests that results are robust to further aggregating WIOD's (non-extractive) sectors. Comparing the outcomes of this study to results derived from a less aggregated dataset than WIOD, nevertheless, continues to be an essential next step, in particular for extractive industries.

5 Conclusions

This study presents the first global Structural Decomposition Analysis (SDA) of Raw Material Consumption (RMC). A series of global SDAs are conducted as well as country-level SDAs for 38 major economies. They decompose the increase in RMC from 1995 to 2008 into five drivers: the growth of final demand, the change of goods in final demand, the change of countries supplying final demand, the input-output structure of the world economy, and the change in material intensity of extractive industries. The study utilises the global multi-regional input-output tables provided by the World Input-Output Database. The effects that drive the changes in Raw Material Consumption are estimated by using the multiplicative Logarithmic Mean Divisia Index approach.

Raw Material Consumption quantifies all materials that are used to produce a country's final demand. It includes indirect flows which become unobservable once goods cross a border. Understanding the drivers of RMC is important for policy makers who aim at reducing material use without merely shifting it abroad. China exemplifies the problem of such a "material leakage". Pothen and Schymura (2015) find that material use in the People's Republic almost tripled from 1995 to 2008. This increase is predominantly driven by a boosting production. In 2008, China's RMC is merely 2.3 times higher than 1995. These results suggest that the People's Republic increasingly processed materials for the purpose of export.

The global SDAs suggest increasing final demand to be the most important driver of RMC growth. If all other factors had remained as they were in 1995, rising final demand would have increased RMC by 48 per cent between 1995 and 2008. Moreover, final demand shifted into countries consuming more material intensive goods. The regional shift is particularly pronounced for construction minerals and investment. This implies that growing infrastructure investment in industrialising nations is a key driver of RMC growth. It will be of major importance for global material flows if and when this infrastructure investments will be completed.

The sectoral mix of final demand slightly dematerialised. Reducing RMC by 6 per cent in 2008 relative to 1995, the dematerialisation was far from a compensation for the rising level of final demand. Final consumption dematerialised more strongly than investment. Improved material intensity in extractive industries and changes in international production patterns decelerated the global RMC growth.

Country-level SDAs yield qualitatively similar results. RMC grew in almost all countries in the sample and an increase in final demand was its most important driver. For the majority of nations, the country-level SDAs suggest a slight dematerialisation of the goods mix in final demand. The material intensity of extractive industries as well as the production and trade flows of intermediate goods usually reduced RMC, but the results indicate a notable heterogeneity between countries.

The sensitivity check suggests that the results are robust to further aggregations of non-extractive sectors. A more disaggregated sectoral structure, in particular in the extractive extractive industries, would allow for a more precise allocation of material flows. Therefore, replicating this study on a more detailed data set is important in order to verify the results.

Empirical studies suggest that international value chains have become increasingly complex and global in recent years (Hummels et al., 2001; Yi, 2003; Koopman et al., 2014). Future research could investigate how these developments affected the use of materials. Furthermore, the drivers behind changing consumption and investment patterns are not explored. Linking macro-level studies with micro-level research on the behaviour of individuals appears to be another important next step towards understanding the nexus between final demand and the use of materials.

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A Decomposition of the Final Demand Matrix

The final demand matrix $\mathbf{F}$ is decomposed into three parts as follows: The first part is a matrix recording the share of country s's final demand which is supplied by country r. Second, there is a matrix representing the share of sector i's goods in country s's final demand. The third part is a vector which contains the levels of final demand.

To ease the presentation, I illustrate the procedure by using the example of a world economy consisting of two countries $R = \{A, B\}$ and two sectors $I = \{1, 2\}$. The extension to N sectors and countries is straightforward. Let us arrange $\mathbf{F}$ into a block matrix of dimension $I \times R$. Each element of this matrix is a vector of length R.

$$\mathbf{F} = \begin{bmatrix} \mathbf{f}_{1,A} & \mathbf{f}_{1,B} \\ \mathbf{f}_{2,A} & \mathbf{f}_{2,B} \end{bmatrix}, \mathbf{f}_{j,s} = \begin{pmatrix} F_{j,A,s} \\ F_{j,B,s} \end{pmatrix} \forall j \in \{1,2\}, s \in \{A, B\} \tag{12}$$

A block matrix $\mathbf{F}^{sup}$ with the same dimensions as $\mathbf{F}$ is introduced. The vectors in this matrix record the regional structure of supply, i.e. the share of final consumption in country s supplied by country rr. Their elements are $f^{sup}_{j,rr,s} = \frac{f_{j,rr,s}}{\sum_r f_{j,r,s}}$, and denote the share of final demand for good j that country s purchases from country rr.

$$\mathbf{F}^{sup} = \begin{bmatrix} \mathbf{f}^{sup}_{1,A} & \mathbf{f}^{sup}_{1,B} \\ \mathbf{f}^{sup}_{2,A} & \mathbf{f}^{sup}_{2,B} \end{bmatrix}, \mathbf{f}_{j,s} = \begin{pmatrix} f^{sup}_{j,A,s} \\ f^{sup}_{j,B,s} \end{pmatrix} \forall j \in \{1,2\}, s \in \{A, B\} \tag{13}$$

Let us define a matrix $\tilde{\mathbf{F}}$ of dimension $I \times R$. Its entries record the total final demand for good j in country s.

$$\tilde{\mathbf{F}} = \begin{bmatrix} \tilde{F}_{1,A} & \tilde{F}_{1,B} \\ \tilde{F}_{2,A} & \tilde{F}_{1,B} \end{bmatrix}, \tilde{F}_{j,s} = \sum_{rr} F_{j,rr,s} \forall j \in \{1,2\}, s \in \{A, B\} \tag{14}$$

Equation (15) displays the relationship between $\mathbf{F}$, $\mathbf{F}^{sup}$, and $\tilde{\mathbf{F}}$. $\circ$ denotes the entry-wise or Hadamard product of two matrices.

$$\mathbf{F} = \begin{bmatrix} \mathbf{f}^{sup}_{1,A} & \mathbf{f}^{sup}_{1,B} \\ \mathbf{f}^{sup}_{2,A} & \mathbf{f}^{sup}_{2,B} \end{bmatrix} \circ \begin{bmatrix} \tilde{F}_{1,A} & \tilde{F}_{1,B} \\ \tilde{F}_{2,A} & \tilde{F}_{1,B} \end{bmatrix} = \mathbf{F}^{sup} \circ \tilde{\mathbf{F}} \tag{15}$$

The matrix $\tilde{\mathbf{F}}$ is further decomposed into the mix of goods and the overall level of final demand. Pre-multiplying $\tilde{\mathbf{F}}$ with the transposed summation vector $\mathbf{e}^\intercal$ yields the vector of final demand levels $\mathbf{f}^{lev}$, measured in monetary terms.

The sectoral structure of final demand is captured by the matrix $\mathbf{F}^{str}$. Its elements record the share of good i in s's final demand. It is computed according to equation (16). $\hat{\mathbf{f}}^{lev^{-1}}$ denotes the diagonalised and inverted vector of final demand levels.

$$\mathbf{F}^{str} = \tilde{\mathbf{F}} \cdot \hat{\mathbf{f}}^{lev^{-1}} \tag{16}$$

Thus, the vector of Raw Material Consumption $\mathbf{rmc}$ can be computed according to the following equation.

$$\mathbf{rmc} = \mathbf{ex}^\intercal \cdot \mathbf{L} \cdot \mathbf{F}^{sup} \circ \mathbf{F}^{str} \cdot \hat{\mathbf{f}}^{lev} \tag{17}$$

B WIOD Sectors

NACE	WIOD industries
AtB	Agriculture, hunting, forestry and fishing
C	Mining and quarrying
15t16	Food , beverages and tobacco
17t18	Textiles and textile products
19	Leather, leather products and footwear
20	Wood and products of wood and cork
21t22	Pulp, paper, paper products, printing and publishing
23	Coke, refined petroleum and nuclear fuel
24	Chemicals and chemical products
25	Rubber and plastics
26	Other non-metallic mineral products
27t28	Basic metals and fabricated metal products
29	Machinery nec
30t33	Electrical and optical equipment
34t35	Transport equipment
36t37	Manufacturing nec, recycling
E	Electricity, gas and water supply
F	Construction
50	Sale, maintenance and repair of motor vehicles
51	Wholesale trade and commission trade
52	Retail trade, except of motor vehicles and motorcycles
H	Hotels and restaurants
60	Inland transport
61	Water transport
62	Air transport
63	Supporting and auxiliary transport activities
64	Post and telecommunications
J	Financial intermediation
70	Real estate activities
71t74	Renting of machinery and equipment and other business activities
L	Public administration and defence, social security
M	Education
N	Health and social work
O	Other community, social and personal services

Table 3: Industries in the WIOD.

C Materials

Materials	**Extracting Sector**
Biomass Animals	AtB
Biomass Feed	AtB
Biomass Food	AtB
Biomass Forestry	AtB
Biomass Other	AtB
Fossil Coal	C
Fossil Gas	C
Fossil Oil	C
Fossil Other	C
Minerals Construction	F
Minerals Industrial	C
Minerals Metals	C

Table 4: Materials and Extracting Sectors in WIOD

D Industries in the 10 Sector Aggregation

WIOD industries	Aggregated industries
AtB	AtB
C	C
15t16	MANU
17t18	MANU
19	MANU
20	MANU
21t22	EINS
23	23
24	EINS
25	EINS
26	MTLS
27t28	MTLS
29	MANU
30t33	MANU
34t35	MANU
36t37	MANU
E	E
F	F
50	TRNS
51	SERV
52	SERV
H	SERV
60	TRNS
61	TRNS
62	TRNS
63	TRNS
64	SERV
J	SERV
70	SERV
71t74	SERV
L	SERV
M	SERV
N	SERV
O	SERV

Table 5: Correspondence between WIOD Industries and Aggregated Industries (10 sectors).

AtB: Agriculture, hunting, forestry and fishing. C: Mining and quarrying. MANU: Manufacturing. EINS: Energy Intensive Sectors. 23: Coke, refined petroleum and nuclear fuel. MTLS: Metals. E: Electricity, gas and water supply. F: Construction. TRNS: Transport. SERV: Services