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On the decomposition of total impact multipliers in a supply and use framework

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Abstract

This note describes a simple technique of decomposing total impact multipliers derived from input–output analysis. The approach uses a generalised supply and use table framework, explicitly distinguishing between industries and products. Contributions to total impact multipliers can be shown by either industry origin (answering the question: Where is the source of impacts and how large is the impact from that particular source?) or product embodiments (answering the question: What are the life cycle impacts of those products that are directly used in the production of a good or service?). Such information is routinely used in life cycle assessments and (hybrid) input–output analyses. A practical example of decomposing carbon footprint intensities of renewable electricity generation technologies is presented, and an Excel worksheet and MATLAB code accompany this note as Additional files 1 and 2.

Keywords: Input–output multipliers, Decomposition, Environmental footprint, Life cycle assessment, Impact analysis

1 Background

Total impact multipliers (TIMs) are factors derived from input–output analysis (IOA) that show the total, economy-wide attribution of impacts from production to one unit of final demand. One example is the attribution of greenhouse gas (GHG) emissions of all industries in an economy to the final demand of a particular product. This metric is called the carbon footprint of the product (Gao et al. 2014; Peters 2010; Wiedmann 2009). More precisely, it is the cradle-to-sale, life cycle inventory of total upstream GHG emissions released during the production of the product.

TIMs (denoted as **m** in the following equations) are the typical result of a demand pull, Leontief Type I calculation in the standard Leontief quantity model (Miller and Blair 2009, p. 447):

$$\mathbf{m} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{f} \cdot \mathbf{L} \quad (1)$$

where **f** is a matrix of direct intensity factors (or direct impact multipliers, DIMs), i.e. factors that represent the direct impact intensity of an industry (or sector) in the form of the total impact F of this industry divided by the industry's total output X (i.e. $\mathbf{f} = \mathbf{F} \cdot \widehat{\mathbf{X}}^{-1}$).

I is an identity matrix with ones on the diagonal and zeroes elsewhere. **A** is the technology coefficient matrix, calculated as the product of the input–output transaction matrix **T** and the inverse matrix $\widehat{\mathbf{X}}^{-1}$ of diagonalised total industry output (i.e. $\mathbf{A} = \mathbf{T} \cdot \widehat{\mathbf{X}}^{-1}$).

L is the standard Leontief Inverse ($\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$).

m is the resulting matrix of total impact multipliers with the same dimensions as the **f** matrix (usually row vectors).

To provide detailed information regarding the origins of impacts along the production (supply) chain of a product, its TIM can be decomposed into contributions from sectors involved directly or indirectly in the production. It may be of interest to know in detail which industries or which products contribute the most to the total impact, for example, if the aim is to reduce impacts (e.g. climate mitigation, resource efficiency and cost savings) or to increase factors of production (e.g. employment and profits). In the following, this paper will distinguish between impact contributions from industries and from products and will elaborate on two different ways of decomposing TIMs in a supply and use table (SUT) framework.

A SUT framework shows the sales of products to industries (intermediate demand) in the use table part and the value of products produced by industries in the supply table part (Eurostat 2008). It can be regarded superior to a symmetric (industry-by-industry or product-by-product) input–output table, in the sense that more original information on sales and production structures is preserved (Rueda-Cantuche 2011). In particular, information on co- or by-production is valuable for applications in industrial ecology and related fields. Lenzen and Rueda-Cantuche (2012) demonstrate how, in a SUT framework, impact satellite data can be assigned to both industries and products and that total impact multipliers are obtained for both entities.[1]

Whilst impact analyses have been performed in SUT frameworks many times (e.g. Fry et al. 2015; Kagawa and Suh 2009; Lenzen et al. 2004; Malik et al. 2014, 2016; Suh et al. 2010; Wachsmann et al. 2009;Wiedmann et al. 2006, 2011) and whilst the decomposition of TIMs has been described in general terms before (Nakamura and Nansai 2016, section 3.7.1), a decomposition that explicitly distinguishes industries and products in a generalised SUT framework has—to the knowledge of the author—not been described yet.

This note provides the mathematical description of SUT-based TIM decompositions in the following section as well as a worked example in the form of an Excel worksheet and MATLAB code as Additional files 1 and 2. Results from the worked example are presented in the figures.

2 Methods for decomposing TIMs

This section describes two types of decomposition—by industry and by products—and explains the differences. The framework chosen is a generalised SUT system with m industries and n products, which may have square ($m = n$) or rectangular ($m \neq n$) supply and use tables.

[1] One drawback of a SUT framework, however, is that a structural path analysis produces longer paths and results that require more explanation than those from a symmetric IO table (Owen et al. 2016).

Figure 1 shows the example SUT data with environmental extensions. Note that in this framework, the supply table is transposed with industries in rows and products in columns. This is usually referred to as a 'make' matrix (Eurostat 2008). Because of its widespread use, however, the acronym SUT is retained throughout this text.

2.1 Decomposing TIMs by industry

A decomposition of a product's impact multiplier by *industry* answers the question: How large is the impact from one particular industry involved in all of the production steps of this particular product? The decomposition shows the contribution of an industry as the ultimate emissions source in the whole production/supply chain of the product. An example is the emissions from electricity as part of the total carbon footprint of a product. This refers to the total use of electricity during the production of the product, independent of which process or industry actually uses the electricity (most likely, electricity was used in virtually all steps of the product's cradle-to-shelf life cycle).

A decomposition by industry is achieved by creating a diagonal matrix of direct impact multipliers (DIMs) which is post-multiplied with the Leontief Inverse:

$$\mathbf{M}^i = \hat{\mathbf{f}} \cdot \mathbf{L} \tag{2}$$

where $\hat{\mathbf{f}}$ is a $(m + n) \times (m + n)$ matrix with DIMs placed on the diagonal of a $(m + n) \times (m + n)$ matrix of zeros. The hat symbol ($\hat{}$) denotes the diagonalisation which is accomplished by row-wise multiplication (symbol $\times$) of the row vector of impact intensities $\mathbf{f}$ with the identity matrix (note that only *one* row of DIMs can be diagonalised in this way):

$$\hat{\mathbf{f}} = \mathbf{f} \times \mathbf{I} \tag{3}$$

$\mathbf{M}^i$ is a $(m + n) \times (m + n)$ matrix of TIMs decomposed by industry; column sums add up to total TIMs for industries and products.

$\mathbf{L}$ is the Leontief Inverse of the SUT with dimensions $(m + n) \times (m + n)$.

This method recognises the ultimate origin of impacts making up the life cycle inventory of a product. All the possible supply chain paths that start with industry i (and its impact) and end with product p sum up to the total share of industry i in the TIM of product p (independent of how long these paths may be). This information is useful if a particular industry is targeted in an impact reduction strategy. For example, if direct emissions from electricity generation become zero because a whole country's electricity comes from 100% renewable power, then the carbon footprint intensity (TIMs) of all products is reduced by the electricity sector's contribution of the industry-decomposed TIMs.

The results of the TIM decomposition are in SUT format, i.e. the contributions of both industries to both, industry and product TIMs, are shown. More precisely (see example in Fig. 2), the left part of the TIM decomposition matrix, i.e. the first m columns, shows the contributions of industries to industry TIMs. In the right part, i.e. the last n columns, the industry contributions to product TIMs are shown. It is this latter breakdown of product TIMs that would usually be used for further footprint calculations, since it is products for which there is a (final) demand, not industries. Note that if a product is only produced by one industry, the TIM of this product and the corresponding industry TIM are identical (for example Ind A and Prod 1 and 2 in Fig. 2).

	Ind A	Ind B	Ind C	Ind D	Ind E	Ind F	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7	Prod 8	Prod 9	Prod 10	Final demand (y)	**Total output (X')**	Units
Ind A	-	-	-	-	-	-	320	205	30	-	-	-	-	-	-	-	-	**555**	$m
Ind B	-	-	-	-	-	-	-	-	310	400	200	-	-	-	-	-	-	**910**	$m
Ind C	-	-	-	-	-	-	-	-	-	10	330	490	100	-	-	-	-	**930**	$m
Ind D	-	-	-	-	-	-	-	-	-	-	-	-	400	700	-	-	-	**1,100**	$m
Ind E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1,800	-	-	**1,800**	$m
Ind F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1,700	-	**1,700**	$m
Prod 1	20	30	40	35	55	20	-	-	-	-	-	-	-	-	-	-	120	**320**	$m
Prod 2	-	25	10	35	25	30	-	-	-	-	-	-	-	-	-	-	80	**205**	$m
Prod 3	100	10	10	10	50	50	-	-	-	-	-	-	-	-	-	-	110	**340**	$m
Prod 4	10	200	20	-	20	20	-	-	-	-	-	-	-	-	-	-	140	**410**	$m
Prod 5	50	20	200	-	40	40	-	-	-	-	-	-	-	-	-	-	180	**530**	$m
Prod 6	-	20	-	310	50	-	-	-	-	-	-	-	-	-	-	-	110	**490**	$m
Prod 7	10	5	30	10	200	100	-	-	-	-	-	-	-	-	-	-	145	**500**	$m
Prod 8	-	25	20	20	200	200	-	-	-	-	-	-	-	-	-	-	235	**700**	$m
Prod 9	10	25	10	5	300	500	-	-	-	-	-	-	-	-	-	-	950	**1,800**	$m
Prod 10	80	5	5	-	50	400	-	-	-	-	-	-	-	-	-	-	1,160	**1,700**	$m
Value added	275	545	585	675	810	340	-	-	-	-	-	-	-	-	-	-			$m
Total input (X)	**555**	**910**	**930**	**1,100**	**1,800**	**1,700**	**320**	**205**	**340**	**410**	**530**	**490**	**500**	**700**	**1,800**	**1,700**			$m
																		Total E	
Direct emissions (F)	100	300	300	100	1,000	1,700	-	-	-	-	-	-	-	-	-	-		**3,500**	kt
DIMs (f = F / X)	0.180	0.330	0.323	0.091	0.556	1.000	-	-	-	-	-	-	-	-	-	-			kg/$

Fig. 1 Example asymmetric make (supply) and use table for six industries and ten products with extensions for industrial greenhouse gas emissions (all numbers are fictitious; zeros are depicted with a hyphen)

Decomposition of TIMs by INDUSTRY

Total TIMs	0.649	0.568	0.530	0.299	0.906	1.801	0.649	0.649	0.576	0.568	0.545	0.530	0.346	0.299	0.906	1.801	kg/$
	Ind A	Ind B	Ind C	Ind D	Ind E	Ind F	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7	Prod 8	Prod 9	Prod 10	Units
Ind A	0.199	0.018	0.016	0.018	0.019	0.021	0.199	0.199	0.034	0.018	0.017	0.016	0.018	0.018	0.019	0.021	kg/$
Ind B	0.116	0.446	0.068	0.032	0.045	0.059	0.116	0.116	0.417	0.437	0.211	0.068	0.039	0.032	0.045	0.059	kg/$
Ind C	0.046	0.033	0.390	0.117	0.065	0.068	0.046	0.046	0.034	0.041	0.255	0.390	0.172	0.117	0.065	0.068	kg/$
Ind D	0.009	0.006	0.007	0.096	0.025	0.031	0.009	0.009	0.006	0.006	0.007	0.007	0.078	0.096	0.025	0.031	kg/$
Ind E	0.063	0.033	0.019	0.013	0.686	0.272	0.063	0.063	0.036	0.033	0.025	0.019	0.015	0.013	0.686	0.272	kg/$
Ind F	0.216	0.032	0.028	0.023	0.067	1.350	0.216	0.216	0.048	0.032	0.030	0.028	0.024	0.023	0.067	1.350	kg/$
Prod 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	kg/$

(columns add up to total TIMs)

Fig. 2 Example decomposition of total impact multipliers by industry (matrix $\mathbf{M}^{i}$)

2.2 Decomposing TIMs by product

Whilst the previous type of decomposition reveals industry contributions, it does not provide any information on the contribution of products that are required to produce a particular good or service. The latter type of information is often reported in the life cycle inventory (LCI) of products or processes and of high relevance if, for example, one product in the production chain is replaced by a different product with a different impact (e.g. normal concrete with low-carbon concrete).

A decomposition of a product's impact multiplier by *product* answers the question: What are the life cycle impacts of those products that are directly used in the production of a good or service? In other words, what are the indirect impacts that are *embodied* in products that act as inputs to the industry that produces said good or service.

One example may be the material composition of wind turbines, which are mostly made of steel, plastic, concrete and copper (amongst other, minor materials). A decomposition by product identifies the full, life cycle contribution of these materials. If steel is fully replaced by a different material, then the contribution of steel to the wind turbine's TIM becomes zero.

Mathematically, the decomposition by product proceeds via the isolation of inputs of products m to the production of product n. In the technical coefficient matrix A these are all elements $a_{\mathrm{m,n}}$ in the column of industry n, constituting the final stage of all inputs needed by industry n (to produce product n). Using the power series approximation (also called Taylor expansion or Neumann series; Waugh 1950; Miller and Blair 2009, section 2.4) and following the decomposition described by Nakamura and Nansai (2016, section 3.7.1), we can write:

$$\mathbf{m} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{fI} + \mathbf{fA} + \mathbf{fA}^2 + \mathbf{fA}^3 + \mathbf{fA}^4 + \cdots \tag{4}$$

This can be disaggregated into one term that shows direct contributions from industries (**f**) as well as one term that isolates **A** and shows the total contributions from products (**mA**) as follows:

$$\mathbf{m} = \mathbf{fI} + \left(\mathbf{fI} + \mathbf{fA} + \mathbf{fA}^2 + \mathbf{fA}^3 + \ldots\right)\mathbf{A} \tag{5}$$

$$\mathbf{m} = \mathbf{f} + \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{A} \tag{6}$$

$$\mathbf{m} = \mathbf{f} + \mathbf{mA} \tag{7}$$

Similar to Eq. 1, we can derive disaggregated TIMs ($\mathbf{m}^{ip}$) as a $(m + n) \times (m + n)$ matrix of contributions:

$$\mathbf{M}^{ip} = \widehat{\mathbf{f}} + \widehat{\mathbf{m}}\mathbf{A} \tag{8}$$

$\widehat{\mathbf{f}}$ and $\widehat{\mathbf{m}}$ are diagonalised vectors of DIMs and total TIMs, respectively (only one row of DIMs/TIMs at a time). The superscript ^{ip} for the TIM matrix $\mathbf{m}^{ip}$ is meant to symbolised that the initial results of the TIM decomposition are in SUT format that shows the decomposition of industry TIMs on the left-hand side (first m columns) as well as the decomposition of product TIMs the right-hand side (last n columns). Again, we are interested in the breakdown of the product TIMs, since footprint calculations are based on multiplying expenditure data with product TIMs, not industry TIMs. So far, however, the breakdown of product TIMs only shows the contributions from industries. An additional step is necessary to achieve a product-by-product decomposition (denoted as $\mathbf{m}^p$). If a product is only produced by one industry, then (as stated above) the product TIM and the industry TIM are identical, and therefore, the product decomposition of the corresponding industry TIM is the result we are looking for: it also constitutes the product decomposition of the product TIM. For example, the column for Ind A adds up to the TIM for Prod 1 (and Prod 2); see Fig. 3.

However, in those cases where one product is produced by two or more industries, the TIMs of these industries (and their product decompositions) need to be scaled according to the proportion of the industry's contribution to the production of the product. This proportion can simply be derived from the supply (make) table part of the A matrix.

Let $\mathbf{a}_{1:\boldsymbol{m},\boldsymbol{p}}$ be the first m rows of product column p in the $\mathbf{A}$ matrix derived from the SUT (which has the dimensions $(m+n) \times (m+n)$). Transposing this column (into one row with m values, symbol $'$) and row-wise multiplying it (symbol $\times$) with the industry TIM columns from the previous step ($\mathbf{M}^{\boldsymbol{ip}}_{1:(\boldsymbol{m}+\boldsymbol{n}),1:\boldsymbol{m}}$) results in new columns of decomposed industry TIMs that are scaled according to the contribution of all industries to the production of product p. This scaled matrix shall be denoted $\mathbf{S}^{\boldsymbol{p}}$ to symbolise that it is specific to product *p:*

$$\mathbf{S}^{\boldsymbol{p}} = \left(\mathbf{a}_{1:\boldsymbol{m},\boldsymbol{p}}\right)' \times \mathbf{M}^{\boldsymbol{ip}}_{1:(\boldsymbol{m}+\boldsymbol{n}),1:\boldsymbol{m}} \tag{9}$$

These columns simply need to be added together to result in one column that shows a decomposition of the TIM of product p.

$$\mathbf{m}^{\boldsymbol{p}}_{\boldsymbol{p}} = \mathbf{S}^{\boldsymbol{p}} \cdot \mathbf{1}_{\boldsymbol{m},\mathbf{1}} \tag{10}$$

$\mathbf{m}^{\boldsymbol{p}}_{\boldsymbol{p}}$ is product p's column in the desired product-by-product TIM decomposition matrix $\mathbf{M}^{\boldsymbol{p}}$.

$\mathbf{1}_{\boldsymbol{m},\mathbf{1}}$ is a summation vector and contains one column of 1's in m rows.

Repeating Eqs. 9 and 10 for each product p results in the fully populated product-by-product TIM decomposition matrix $\mathbf{M}^{\boldsymbol{p}}$. Each column of $\mathbf{M}^{\boldsymbol{p}}$ then contains contributions from both industries (first m rows) and products (last n rows) which can be interpreted as follows (see Fig. 4). Contributions from industries are the *direct* emissions from industries that produce product p as a direct output. These include emissions from the 'own' industry where product p is the main product and from other industries where product p is a by-product, as shown in the supply table. Contributions from products are as described above: life cycle (cradle-to-sale) impact inventories of products needed to produce product p.

3 Application example

In this section, a practical example is presented in which the decomposition of TIMs is applied to different electricity generation technologies, using an environmentally extended input–output model of the Australian economy. The same data and model were used as applied in Wolfram et al. (2016) where the economy-wide carbon footprint of different renewable electricity scenarios in Australia was calculated. The

From additional file Matlab script:

Decomposition of TIMs by PRODUCT

Initial decomposition, distinguishing industry and product contributions

	Ind A	Ind B	Ind C	Ind D	Ind E	Ind F	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7	Prod 8	Prod 9	Prod 10	Units
Total TIMs	**0.649**	**0.568**	**0.530**	**0.299**	**0.906**	**1.801**	**0.649**	**0.649**	**0.576**	**0.568**	**0.545**	**0.530**	**0.346**	**0.299**	**0.906**	**1.801**	kg/$
Ind A	0.180	-	-	-	-	-	0.649	0.649	0.057	-	-	-	-	-	-	-	kg/$
Ind B	-	0.330	-	-	-	-	-	-	0.518	0.555	0.215	-	-	-	-	-	kg/$
Ind C	-	-	0.323	-	-	-	-	-	-	0.013	0.330	0.530	0.106	-	-	-	kg/$
Ind D	-	-	-	0.091	-	-	-	-	-	-	-	-	0.240	0.299	-	-	kg/$
Ind E	-	-	-	-	0.556	-	-	-	-	-	-	-	-	-	0.906	-	kg/$
Ind F	-	-	-	-	-	1.000	-	-	-	-	-	-	-	-	-	1.801	kg/$
Prod 1	0.023	0.021	0.028	0.021	0.020	0.008	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 2	-	0.018	0.007	0.021	0.009	0.011	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 3	0.104	0.006	0.006	0.005	0.016	0.017	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 4	0.010	0.125	0.012	-	0.006	0.007	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 5	0.049	0.012	0.117	-	0.012	0.013	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 6	-	0.012	-	0.149	0.015	-	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 7	0.006	0.002	0.011	0.003	0.038	0.020	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 8	-	0.008	0.006	0.005	0.033	0.035	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 9	0.016	0.025	0.010	0.004	0.151	0.267	-	-	-	-	-	-	-	-	-	-	kg/$
Prod 10	0.260	0.010	0.010	-	0.050	0.424	-	-	-	-	-	-	-	-	-	-	kg/$

(columns add up to total TIMs)

Fig. 3 Interim stage of a TIM decomposition by product (matrix $\mathbf{M}^{ip}$). Product information is shown under industry TIMs but has not been assigned to product TIMs yet

Decomposition of TIMs by PRODUCT

Final decomposition of TIMs by PRODUCT (as calculated in additional file Matlab script)

	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6	Prod 7	Prod 8	Prod 9	Prod 10	
Total TIMs	**0.649**	**0.649**	**0.576**	**0.568**	**0.545**	**0.530**	**0.346**	**0.299**	**0.906**	**1.801**	kg/$
Ind A	0.180	0.180	0.016	-	-	-	-	-	-	-	kg/$
Ind B	-	-	0.301	0.322	0.124	-	-	-	-	-	kg/$
Ind C	-	-	-	0.008	0.201	0.323	0.065	-	-	-	kg/$
Ind D	-	-	-	-	-	-	0.073	0.091	-	-	kg/$
Ind E	-	-	-	-	-	-	-	-	0.556	-	kg/$
Ind F	-	-	-	-	-	-	-	-	-	1.000	kg/$
Prod 1	0.023	0.023	0.022	0.022	0.025	0.028	0.022	0.021	0.020	0.008	kg/$
Prod 2	-	-	0.016	0.018	0.011	0.007	0.018	0.021	0.009	0.011	kg/$
Prod 3	0.104	0.104	0.015	0.006	0.006	0.006	0.005	0.005	0.016	0.017	kg/$
Prod 4	0.010	0.010	0.115	0.122	0.055	0.012	0.002	-	0.006	0.007	kg/$
Prod 5	0.049	0.049	0.015	0.015	0.077	0.117	0.023	-	0.012	0.013	kg/$
Prod 6	-	-	0.011	0.011	0.004	-	0.119	0.149	0.015	-	kg/$
Prod 7	0.006	0.006	0.002	0.002	0.008	0.011	0.005	0.003	0.038	0.020	kg/$
Prod 8	-	-	0.008	0.008	0.007	0.006	0.006	0.005	0.033	0.035	kg/$
Prod 9	0.016	0.016	0.024	0.025	0.015	0.010	0.005	0.004	0.151	0.267	kg/$
Prod 10	0.260	0.260	0.032	0.010	0.010	0.010	0.002	-	0.050	0.424	kg/$

(columns add up to total TIMs)

Fig. 4 Final stage of product TIM decomposition by product (matrix $\mathbf{M}^{p}$). Contributions from industries represent 'own' impacts from the industry (or industries) that produce the product

input–output-based hybrid LCA model consists of a 2-region SUT with 215 Australian industries and products each, as well as a 26-sector representation of the rest of the world. The electricity sector of the Australian economy has been disaggregated into several sectors representing different electricity generation technologies by replacing technology-specific inputs of products in the use table columns with process data from the Ecoinvent database. Greenhouse gas emissions from industries are represented in four satellite rows to the SUT (for CO_2, CH_4, N_2O and CO_2e). As part of their investigations, Wolfram et al. (2016) performed a decomposition of carbon footprint intensities (greenhouse gas life cycle inventories) by industry for renewable electricity generation technologies (see Fig. 1 on page 240 therein). The analysis is extended in this work by adding a TIM decomposition by product as described in Sect. 2.2.

Figure 5 shows that the TIM decomposition by industry and product yields significantly different results. The material composition of electricity generation plants is clearly reflected in the contributions of these materials to the overall carbon footprint. Examples are the metals used for wind turbines (steel) or solar photovoltaic panels (aluminium), glass used for PV panels or cement used in the foundations of concentrated solar power plants. The product can also be a service, e.g. mining is the product (activity) that contributes most to the total carbon footprint of geothermal power. The importance of using electricity in the life cycle of power plants is confirmed in the product breakdown, even though electricity as a product contributes less to the carbon footprints than electricity as an industry in all cases. This is because the industry emissions represent contributions to *all* supply chains, whereas the products represent the (life cycle) inputs to the last stage of inputs to the power generation technologies. The same effect can be observed for transport: As an industry, transport requirements apply to all supply chains, related to power plants; however, these can be very indirect and remote, e.g. transport of iron ore to steel factories that produce wind turbine towers. As a product (service), only the (life cycle) impacts of direct transport requirements for power plant construction, operation and removal are included, e.g. the transport of the turbine to the site of the wind farm. For all technologies shown, these transport product impacts are smaller than those from the transport industry across the economy.

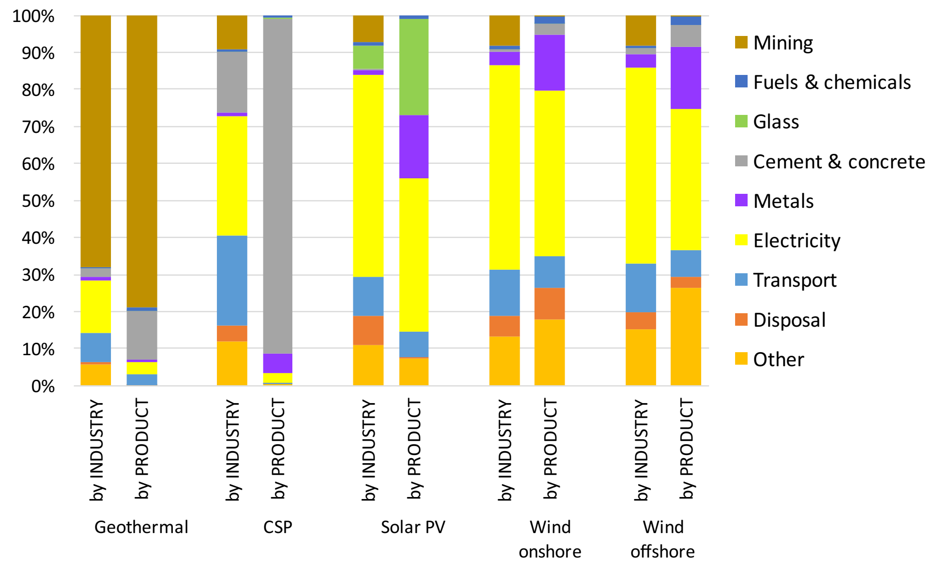

Fig. 5 Decomposition of greenhouse gas life cycle (carbon footprint) inventories of renewable electricity generation technologies by industry (*left column*, cf. Wolfram et al. 2016) and by product (*right column*, this work). *CSP* concentrated solar power, *PV* photovoltaic

4 Concluding remarks

Life cycle assessment and input–output analysis are the two leading methods for attributing environmental, social and other impacts to products, sectors or consumption (Hellweg and Milà i Canals 2014; Nakamura and Nansai 2016). To add information and meaning to life cycle inventory or footprint results, the analysis of contributions from either industries or products has proved an indispensable tool. This can be achieved by using a supply and use table framework in input–output or hybrid input–output analysis. Contributions can be shown by either industry origin (where is the source of impacts?) or product embodiments (what burden carry the products used in the life cycle or supply chain?). This note presents a simply technique of decomposing total impact multipliers from a SUT modelling framework and provides a practical example. It is shown that significantly different information is obtained by the two methods of decomposition, thus adding to the usefulness of IO-based analysis in LCA.

Additional files

Additional file 1. Supplementary Excel spreadsheet with example data and calculations.
Additional file 2. Supplementary Matlab script with example data and calculations.

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