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How materials, energy, transport, and capital contribute to emissions along the supply chain of Material Handling Equipment: The Path Extraction Method applied to USEEIO

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Abstract

The importance of machinery and equipment (ME) to the use of materials and thus to the circular economy and their contribution to climate change mitigation has only recently been recognized[1]. Previous analyses based on EXIOBASE distinguished only five types of ME, giving a coarse picture that is not satisfactory to pinpoint opportunities for mitigation. Here we utilize the US benchmark input-output tables, which represent the production and use of types of 65 ME. We use Hypothetical Extraction Method (HEM)[1,2] to identify the part of the carbon footprint that can be attributed to the input of materials and energy as well as the use of transport and capital equipment. We use Structural Path Analysis (SPA)[3,4] to identify those suppliers important for contributing to the carbon footprint of the product of interest through using materials, energy, transport, capital, or direct emissions. We illustrate the application of this path extraction (PEX) to the greenhouse gas emissions (GHGE) of the production of material handling equipment. Cut-off criteria need to be set to less than 0.5% of total impacts to consider more than the first tear of suppliers to each of the investigated production processes.

JEL-codes: D57, L60, L64, Q56, Q57

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Introduction

The research was prompted by the recognition that the second most important metal use is for machinery and equipment (ca. twice as important as vehicles and transport equipment)[1], but that there was a lack of a systematic top-down understanding or empirical bottom-up analysis of this sector. The recognition led to review papers[5,6] and an ongoing modelling exercise[7,8], which addresses both empirical aspects and scenario modelling. In previous work, we have used the MRIO database EXIOBASE to investigate the global role of machinery and equipment. EXIOBASE has only the ME sector/product detail that are also contained in the NACE classification, i.e. five sectors. We also have used detailed national-level databases for China, Japan, Korea, and the United States, which have a significantly higher level of detail. We showed that this detail can help us to meaningfully distinguish between different ME types, which have different production recipes and hence emissions multipliers. We have also found that life cycle assessments (LCAs), while in principle of interest because they are based on a technical representation of the product, are often very crude (consisting only of few inputs) and yield such a wide range of emissions multipliers (from several kg CO2e/EUR to <<1 g/EUR) that we do not find credible.

In a life cycle assessment, products are made from parts which are made from materials, using energy, machinery, and potential ancillary inputs, and involving transport between production steps. Materials, energy, and transport can be seen as generic activities, rather than being specific to a supply chain of a particular product. The aim of this research is to look at the production of products in input-output tables in a similar manner. We treat direct emissions and those associated with energy, materials, transport, and the depreciation of capital equipment in the same manner as factor-cost-adding processes to determining the total costs (footprint) of a product. We do so using a hypothetical extraction approach. We then rank the next tier of inputs. We find that we normally do not need to go to a second tier to identify all production processes causing more than 1 % emissions through their direct emissions or their use of energy, materials, transport, and capital. We focus the analysis on greenhouse gas emissions (GHGE), aggregated using the global warming potential with a 100-year time horizon.

Table 1: Nomenclature

A	Coefficients of input-output table ($/$)
A^k	Capital use coefficients (capital depreciated by capital producing sector per unit output) ($/$)
CS	Characterized emissions coefficients (kg CO_2e/$)
M	Multiplier (kg CO_2e/$)
L	Leontief inverse ($/$)

Γ	Direct emissions or those connected to extracted products (energy, materials, transport, capital)
o	Index for extracted/target sectors
*	Index for other sectors

Methods

Data

We use the United States Environmentally Extended Input-Output tables with capital use coefficients[9–11] for 2012, because this is the latest tables for which capital use coefficients are available. (The latest benchmark tables are for 2017[12] and emissions coefficients have been estimated up to 2023.)

Step 1: Multiplier decomposition using the hypothetical extraction method

We first calculate the multiplier for each sector[18]. The characterization matrix C (containing the global warming potentials) and the matrix of elementary flow coefficients S (GHGE) and the Leontief inverse define multipliers M of all products as $M = CS(I - A)^{-1}$ without the use of capital products, and $M^k = CS(I - (A + A^k))^{-1}$ including the use of capital products[13]. We decompose the original multiplier into six components, (1) describing the sectors' direct contribution, (2) input from other non-extracted sectors, (3) energy, (4) materials, (5) transport, and (6) the utilization of capital using a hypothetical extraction approach[1,2,14,15].

This represents the cradle-to-gate (system process) environmental impacts (or use of production factors). We define sets of sectors producing energy {e}, materials {m}, transportation services {t}, and non-extracted goods {*} such that these are mutually exclusive and collectively comprise the entire list of sectors. We apply the hypothetical extraction method[15,16], removing $o = e \cup m \cup t$, setting the respective rows of the input coefficient matrix A and the final demand matrix Y to zero, yielding A* and Y*. Leontief inverse of this matrix $L^* = (I - A^*)^{-1}$ describes the activity in non-extracted sectors to produce non-extracted products without considering the share needed to produce extracted products. We define A^o and Y^o as complements, such that $A = A^o + A^*$, $Y = Y^o + Y^*$. The multipliers are thus decomposed.

$$\widetilde{M_1} = CS \quad (1)$$

$$\widetilde{M_2} = CSL^* - CS = CSA^*L^* \quad (2)$$

$$\widetilde{M_3} = \widehat{M_e} A_e^o L^* \quad (3)$$

$$\widetilde{M_4} = \widehat{M_m} A_m^o L^* \quad (4)$$

$$\widetilde{M_5} = \widehat{M_t} A_t^o L^* \quad (5)$$

$$\widetilde{M_6} = M^k - M \quad (6)$$

Here, e, m, t refer to the rows/elements containing energy, material, and transport goods. It can be verified[15] that $M^k = \sum_{i=1}^{6} \widetilde{M}_i$.and $M = \sum_{i=1}^{5} \widetilde{M}_i$.

Step 2. Production layer decomposition

The multiplier has been derived from the Leontief price model, where the multiplier is the price of the goods produced by sectors in terms of the factor added at step of production[17]. Instead of taking the inverse, one can solve the equation iteratively through a Taylor series expansion[4,16].

$$M = CS(I - A)^{-1} = CS(I + A + A^2 + A^3 + A^4 + ..) \quad (7)$$

Each step represents a production layer.

Step 3: Production layers treating energy, materials, transport like direct emissions

We now change this approach to only decompose the L*. Each layer then represents the production of other inputs. The use of energy, materials, transport, and capital goods is accounted for in each layer and treated as the direct factor use.

$$\Gamma_1 = CS \quad (8)$$

$$\Gamma_2 = \widehat{M_e^k} A_e^o \quad (9)$$

$$\Gamma_3 = \widehat{M_m^k} A_m^o \quad (10)$$

$$\Gamma_4 = \widehat{M_t^k} A_t^o \quad (11)$$

$$\Gamma_5 = \widehat{M^k} A^k \quad (12)$$

With $\Gamma = (\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5)'$, we decompose M anew into the production layers in terms other inputs.

$$M = i\Gamma(I - A^*)^{-1} = i\Gamma(I + A^* + A^{*2} + A^{*3} + A^{*4} + ..) \quad (13)$$

We form a matrix that shows the layer of production at which a factor is added either through direct emissions or through the use of energy, materials, transport, or capital.

$$\ddot{M} = [\Gamma, \Gamma A^*, \Gamma A^{*2}, \Gamma A^{*3}, \Gamma A^{*4} ..) \quad (14)$$

By the Taylor series, $M = \sum_{i,j} M_{ij}$. $\widetilde{M}$ can also be obtained by summing the energy, material, transport, and capital components across production layers while keeping CS for the first layer separate from that of the subsequent layers.

Step 4. Ranking significant suppliers

The US input-output table has 400 sectors. Even when energy, transport, and materials sectors are removed, a lot of sectors remain. We would like to understand who the important suppliers are. We hence produce for each sector in A* a ranking of suppliers in their contributions to the M of each sector. To identify the contributing sector, we determine

$M_{rank} \leftarrow rank(\widehat{M}A^{*})$, a matrix of ranks of each column. The top n suppliers are thus identified, and their contributions to M are specified.

Step 5. Identifying the most important suppliers in the supply chains.

A modification of the structural path approach[4] is used on the A* to calculate a list containing the most impactful paths, their level of activity at the last node, and the environmental impact associated with that activity. For each entry in A*, we treat direct emissions, the use of energy, materials, transport, and capital as adding emissions, reflecting the analysis in step 3 (eqs. 8-12).

Results

Step 1: Hypothetical extraction - multipliers

We calculated the multipliers and used them to investigate both the investment in machinery and equipment and the total demand for machinery and equipment including intermediate inputs triggered by US final consumption. While the picture differs between the two, investment is the most important use of ME in the US.

Figure 1 shows a hypothetical extraction analysis where input of energy, materials, transport, and use of capital are identified in the entire supply chain, following[18].The production of material handling equipment was associated with emissions of nearly 15 million metric tons of CO_2 equivalents in 2012. Materials accounted for 63% of the carbon footprint, energy 12%, transport 7%, and direct emissions from the sector only 2 %. 5% of emissions were in other sectors, i.e. not associated with materials, energy, or transport. 11% was needed to replace the capital depreciated in any of the sectors contributed.

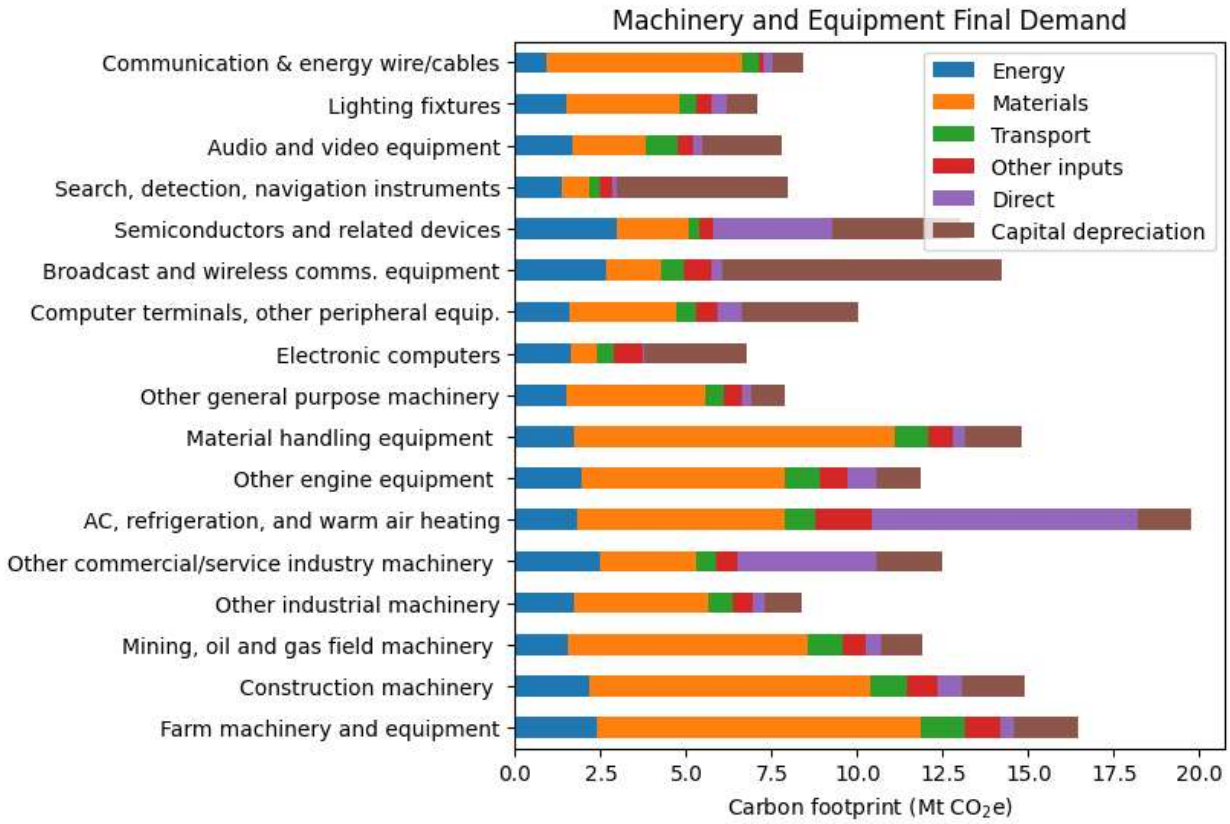

Figure 1: Carbon footprint machinery and equipment purchased in the United States as investment and intermediate input triggered by domestic US final demand, decomposed according to important inputs. Only sectors above 5 $MtCO_2e$ are shown.

Step 2. Production layer decomposition

A production layer decomposition, focusing on where direct emissions occur, shows a peak of emissions in the second layer, i.e. in suppliers of suppliers (Fig 2a). In the first layer, the most important suppliers in terms of emissions are iron, steel and ferroalloys, truck transportation, and electricity. In the next four layers, electricity dominates (Table 2). Iron & steel are second in layers 2-3, third in layer 4-5. Looking at Figure 1, this is not surprising. Most GHG emissions are associated with energy conversion, material production, and transport. In the production layer analysis, emissions in each layer are added from all activities, and all industries use electricity, rely on transport etc. The production layer decomposition hence adds little knowledge about the structure of the supply network apart from the insight that basic utilities dominate the picture.

Table 2: The top emitting activities in each of the layers of the production layer decomposition. The value for iron and steel in layer 1 is above 88gCO2e/$, while coal mining in layer 5 is 0.8g/$ of material handling equipment.

Rank	***0***	***Layer 1***	***Layer 2***	***Layer 3***	***Layer 4***	***Layer 5***
1	Material handling equip.	Iron, steel, & ferroalloys	Electricity	Electricity	Electricity	Electricity
2		Truck transportation	Iron, steel, & ferroalloys	Iron, steel, & ferroalloys	Oil and gas extraction	Oil and gas extraction
3		Electricity	Truck transport	Truck transport	Iron, steel, & ferroalloys	Iron, steel, & ferroalloys
4		Alumina refining, primary aluminum prod.	Coal mining	Coal mining	Truck transport	Truck transport
5		Rail transportation	Iron, gold, silver, and other mining	Oil and gas extraction	Coal mining	Coal mining

Step 3. Production layer decomposition in terms of direct emissions, energy, materials, transport, and the use of capital

The picture changes significantly when the supply chains of energy, materials, and transport are not investigated further. In this case, only suppliers that do not deliver those are looked at, and their use of these emissions-causing inputs is treated as the event which causes emissions, just as their combustion of fuels. We see the peak in the material handling equipment sector itself, a still significant but smaller contribution from the direct suppliers, and a steep decline in subsequent layers (Fig. 2a). In the sector and the first two layers of suppliers, the input of materials dominates (Fig. 2b).

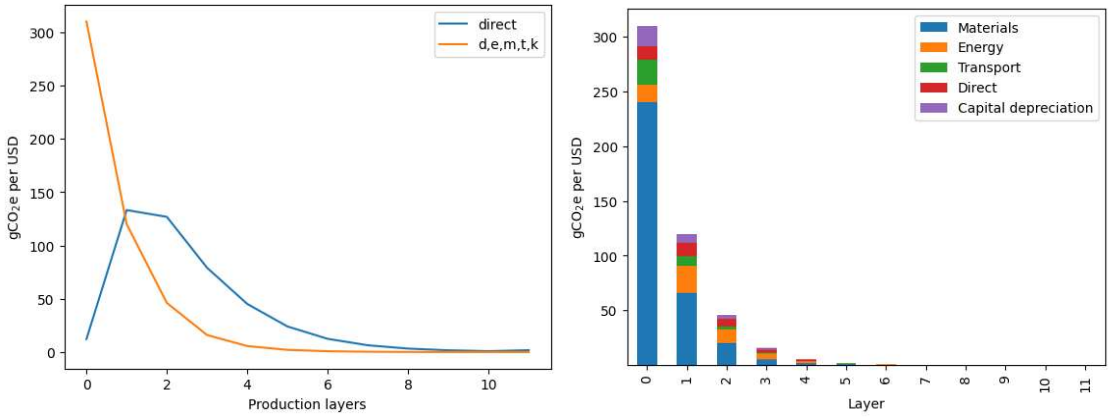

Figure 2: a) Production layers in which direct emissions, or the addition of emissions through direct emissions, energy, materials, transport and capital occurs. b) Contribution of d,e,m,t,k in each layer.

Table 3: The top emissions-adding activities in the supply chain of material handling equipment when the use of materials, energy, transport, and capital is counted as emissions-adding in addition to direct emissions.

Rank	***0***	***Layer 1***	***Layer 2***	***Layer 3***	***Layer 4***	***Layer 5***
0	Material handling equipment	Fluid power process machinery	All other forging, stamping, sintering	Other real estate	Other real estate	Other real estate
1		All other forging, stamping, and sintering	Other real estate	All other forging, stamping, sintering	Waste and remediation	Waste and remediation
2		Paint and coating manufacturing	Turned product and screw, nut, and bolts	Waste and remediation	All other forging, stamping, and sintering	Nonresidential maintenance and repair
3		Other vehicle parts	Management of companies and enterprises	Warehousing and storage	Warehousing and storage	Warehousing and storage
4		Motor and generators	Plastics packaging, unlaminated film/sheets	Management of companies	Nonresidential maintenance and repair	Management of companies

In layer 1, genuine inputs of parts dominate (Table 3). In layer 2, we begin to see more generic activities such as real estate, and management. These become then more important further down, again, because they occur in all businesses and are added across the entire layer. If some other ME product had been investigated, the role of suppliers might be larger and contribution of materials somewhat smaller.

Step 4. Ranking significant suppliers

The list of suppliers (Table 4) shows that 15 sectors contribute at least 1% to the carbon footprint of farm machinery and equipment, led by fluid power process machinery.

Such a ranking of suppliers was conducted for the entire table of non-extracted sectors and used in the next steps. The idea is that this ranking would immediately allow us to identify the most important supplier to a specific supplier. By referring to a table of ranked suppliers, we can readily identify the most important inputs to the supplier and assess whether it is above or below the threshold for inclusion in the structural path analysis.

Table 4: Contribution of non-e,m,t,k sectors to the carbon footprint of material handling equipment

Supplier	gCO2e/$	Share
Fluid power process machinery	23,7	4,7 %
Other vehicle parts	9,8	2,0 %
All other forging, stamping, and sintering	8,0	1,6 %
Motor and generators	8,0	1,6 %
Paint and coating manufacturing	6,9	1,4 %
Other durable goods wholesale	6,5	1,3 %
Gasoline engine & engine parts	6,1	1,2 %
Relay & industrial controls	5,8	1,2 %
Mechanical power transmission equip.	5,8	1,2 %
Machinery and equipment wholesale	5,5	1,1 %
Material handling equipment	5,3	1,1 %
Speed changer, industrial high-speed drive, & gears	5,2	1,0 %
Machine shops	5,1	1,0 %
Coating, engraving, heat treating, allied activities	5,0	1,0 %
Turned product and screw, nut, and bolts	4,9	1,0 %
Other suppliers		22,6 %

Step 5. Identifying the most important suppliers in the supply chains.

Table 5 shows the results of the structural path analysis in terms of the contribution of each origin node to the carbon footprint of the destination node. A cut-off of 0.05% of the overall footprint was used to terminate a path, but not all direct inputs to material handling equipment are shown. Higher cut-off values would result in no investigation of inputs to inputs. While there are many inputs from layer 2 contributing to layer 1, their contribution is limited. For example, the sum of listed inputs to fluid power process machinery is 5.1 g/$. Most of the rest of 23.7 g/$ value is from direct emissions and inputs of materials, energy, transport, and No 3rd-layer supplier is of importance.

Table 5: Network path list and edge table of the structural path analysis, indicating the edge strength (emissions embodied in the origin node contributing to the destination).

PATHS	DESTINATION	ORIGIN	FLOW
[72, 77]	**Material handling equipment**	**Fluid power process machinery**	23,7
[72, 77, 77]	Fluid power process machinery	Fluid power process machinery	1,0
[72, 77, 31]	Fluid power process machinery	All other forging, stamping, and sintering	0,6
[72, 77, 42]	Fluid power process machinery	Turned product and screw, nut, and bolts	0,6
[72, 77, 229]	Fluid power process machinery	Other durable goods wholesale	0,4

[72, 77, 106]	Fluid power process machinery	Motor and generators	0,3
[72, 77, 84]	Fluid power process machinery	Semiconductors and related devices	0,3
[72, 77, 41]	Fluid power process machinery	Machine shops	0,3
[72, 77, 228]	Fluid power process machinery	Machinery and equipment wholesale	0,3
[72, 77, 46]	Fluid power process machinery	Ball and roller bearings	0,3
[72, 77, 196]	Fluid power process machinery	Paperboard containers	0,3
[72, 77, 291]	Fluid power process machinery	Management of companies and enterprises	0,3
[72, 77, 45]	Fluid power process machinery	Non-plumbing valve and fittings	0,2
[72, 77, 209]	Fluid power process machinery	Paint and coating manufacturing	0,2
[72, 127]	**Material handling equipment**	**Other vehicle parts**	9,8
[72, 127, 126]	Other vehicle parts	Vehicle metal stamping	1,0
[72, 127, 127]	Other vehicle parts	Other vehicle parts	0,8
[72, 127, 221]	Other vehicle parts	Other plastics products	0,2
[72, 31]	**Material handling equipment**	**All other forging, stamping, and sintering**	8,0
[72, 31, 31]	All other forging, stamping, and sintering	All other forging, stamping, and sintering	0,7
[72, 106]	**Material handling equipment**	**Motor and generators**	8,0
[72, 106, 69]	Motor and generators	Other engine equipment	0,5
[72, 106, 106]	Motor and generators	Motor and generators	0,5
[72, 106, 42]	Motor and generators	Turned product and screw, nut, and bolts	0,3
[72, 106, 32]	Motor and generators	Crown & closure manufacturing, metal stamping (non-auto)	0,3

Discussion

We find that most of the GHG emissions are associated with energy use, materials, transport, and the consumption of fixed capital. Specific suppliers play a secondary role. Even for those suppliers, it is their materials and energy use that makes them important. Life cycle assessments usually collect information on a product's life-time input of materials, energy, as well as transport, using generic life cycle inventory databases as a source on emissions caused by these inputs. These databases are widely applied, and the product-specific foreground is applied to various background, reflecting different energy mixes and material production technologies which vary across location and time. The investigation of US production and use of machinery and equipment in this paper shows

that such a strategy may also be feasible here. It probably requires adjusting for price differences when the inputs of energy and materials are measured in monetary terms or converting it to physical quantities.

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