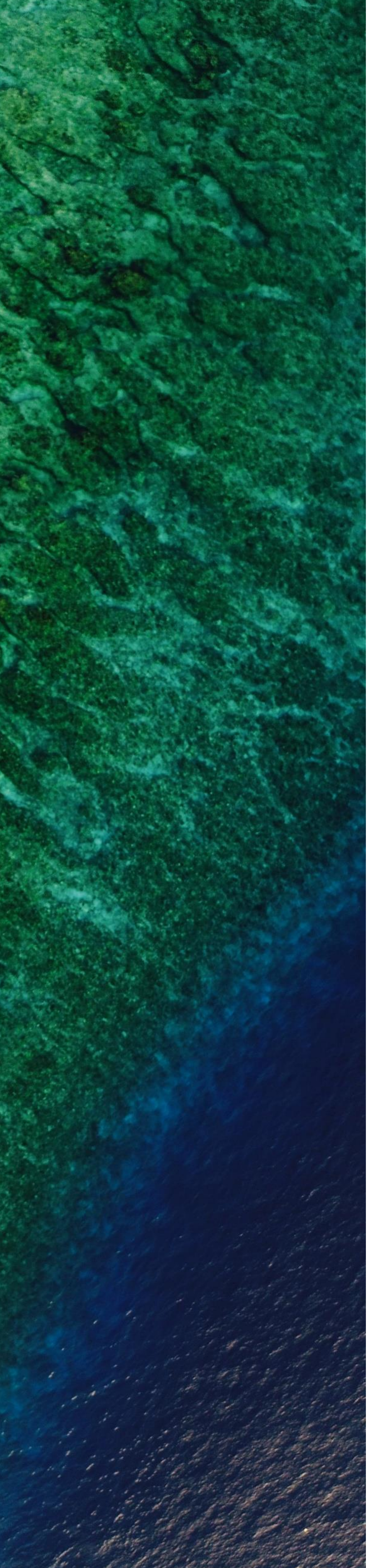

SMALL
WORLD
CONSULTING

Multi-regional Input-Output (MRIO) Emissions Factors v1.0

Concise Methodology

September 2023

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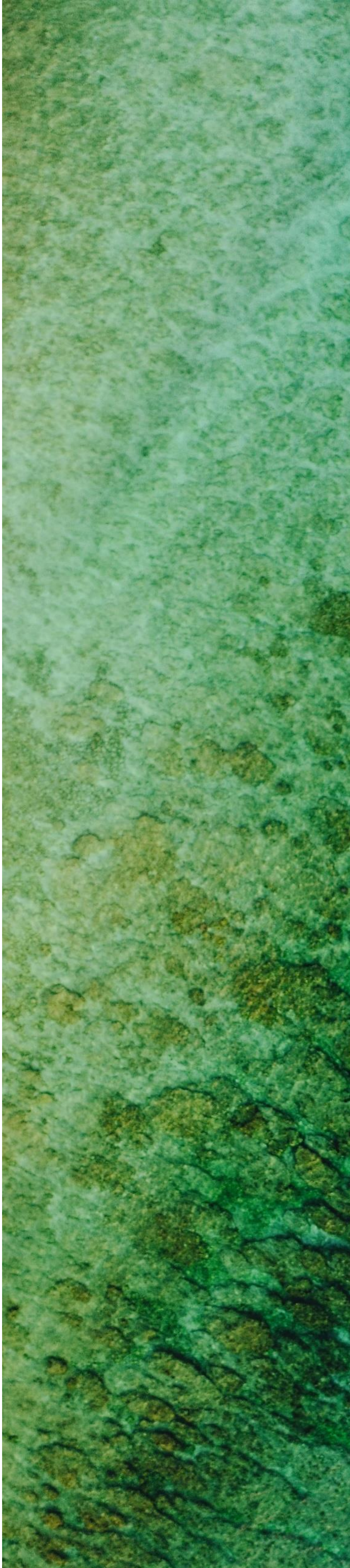

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Executive Summary

Purpose

SWC's Environmentally Extended Multi-Regional Input-Output (MRIO) model has been built to help companies and other organisations estimate their supply chain emissions in a way that is complete, realistic, practical and transparent. The model is designed to reflect the differences in average carbon intensity of goods and services from each industry, supplied from or purchased within different countries.

The overall purpose of the model is to make these datasets free and publicly available, together with basic guidance on how to use them, and in doing so to raise the standard and compatibility of company supply chain emissions reporting, globally.

Output

The output of the model is a set of spend-based GHG emissions factors for purchases from 105 industry categories in 65 countries. Each emissions factor is broken down into the supplier's scope 1, 2 and upstream scope 3 components. Emissions factors are reported in both basic prices and purchasers' prices; in other words, both with and without distributors' margins (wholesale, retail and transport markups) and taxes.

There is also a second set of emissions factors for use if only the country of purchase – not the country of production – is known; for example, if a company in a known country buys something but does not know where it was produced. These datasets use a weighted average of emissions factors for countries supplying the country in question with products from the industry concerned.

Usages

These emissions factors can be combined with organisational spend data to provide a rough first estimate of company supply chain emissions and some guidance as to likely hotspots. This estimate can then be improved by augmenting with elements of process-based life cycle analysis, where appropriate physical consumption data exists. In such instances, great care should be taken to preserve the system-complete boundary conditions that are essential and easy to achieve through EEIO spend-based assessments[1].

[1] This process is described in more detail in a separate document: *Integrating process-based life cycle analyses (LCAs) into spend-based environmentally extended input-output (EEIO) emissions estimates for company supply chains.*

Methodology Overview

Economic input-output models use data on trade between industries to estimate, for each industry, the total output that is required, directly and indirectly, from every other industry in the economy in order to produce each industry's products. This can be 'environmentally extended' by combining with data on each industry's total emissions, to produce industry-specific estimates of the emissions arising directly and indirectly from every industry in the economy, per unit of output. A multi-regional input-output model (MRIO) distinguishes between industries in different regions of the world. Environmentally extended MRIOs seek to estimate the carbon intensity, and sometimes the water intensity, per unit of financial output of every industry in every region within the model. They rely on industry-specific data on trade between every country or region in the model, much of which is difficult or impossible to obtain with a high-level industry resolution.

This model adopts an approach designed to obtain sufficient granularity with somewhat fewer problematic requirements regarding the data, in order to increase both the realism of the results for our intended purpose and the practicality of creating and updating the model. We begin by developing an environmentally extended MRIO model by drawing upon a coarse-grained Inter-Country Input-Output (ICIO) table produced by the OECD, covering 45 industry sectors in 65 countries. We environmentally extend this using country and industry emissions data, drawn from the OECD data where this is available. Where it is not, we make estimates using energy and emissions data from the United Nations and other sources. To increase the granularity of the model we separately produce a 105-sector EEIO based on UK data alone, using relatively high-quality data from the Office of National Statistics. We use the results of this model to upscale the 45-sector MRIO to 105 sectors, by making the core approximation that the ratio of carbon intensities between each disaggregated subsector is similar in each country in the model.

A few other core methodology details deserve a mention in this short overview. The model treats capital investment as part of the supply chain for a company, so that associated emissions become part of company supply chain emissions. A markup factor of 1.9 is applied to high-altitude emissions to take account of the additional radiative forcing effects that occur at high altitude. Finally, the model deals with the full Kyoto basket of greenhouse gases covered by the Greenhouse Gas Protocol (GHGP) and combines these into a single metric in terms of their carbon-dioxide-equivalent warming potential over a 100-year period. The emissions units of emissions factors are expressed as $kgCO_2e/£$.

Validation

The results have been tested against process-based analyses of a simple commodity, and against other leading MRIO models. The work is ongoing, and the results so far have been both encouraging and supportive of the approach taken and assumptions made. As and when time and resources permit, we hope to make these checks and comparisons public.

Principles of Environmentally Extended Input-Output Analysis

EEIO Modelling & Leontief

Input-Output Modelling was developed by Wassily Leontief in the late 1930s to demonstrate how changes in final demand for products and services stimulate activity in industry sectors other than the supplying sector. It is widely used in economics to estimate the impacts of economic activities. EEIO combines economic information about the trade between industrial sectors (IO tables) with environmental information about the emissions (environmental accounts) arising directly from those sectors, to produce estimates of the emissions per unit of output from each sector (emissions factors). The central technique is long established and well documented (Leontief 1986, Miller and Blair 1985). EEIO offers some key advantages, worth noting, over more traditional process-based life cycle approaches:

- EEIO does not suffer from 'truncation error', the systematic underestimation that process-based analyses incur through their inability to trace every single pathway in the supply chains. Although, as with process-based life cycle approaches, there may be inaccuracies in EEIO's methods of avoiding this underestimation.
- To produce a crude, simple but complete assessment of supply chain emissions the data requirement is very small: no more than a purchase ledger, categorised by types of goods and services purchased.
- EEIO has at its root a transparently impartial process for calculating emissions factors, whereas life cycle approaches entail more subjective judgements regarding the setting of boundaries and the selection of secondary conversion factors.
- EEIO can be used to estimate the footprints resulting from complex activities, such as the purchase of intangible services, that life cycle approaches struggle to account for.

One serious limitation of EEIO in its most basic form is that it assumes homogeneity of the direct emissions and the demands placed on other sectors, per unit of output within each sector. For example, a basic EEIO model does not take account of the carbon efficiencies that may arise from switching expenditure on paper to a renewable source from a virgin source, without reducing the actual spend. In order to mitigate this weakness, adjustment multipliers may be applied to the EEIO emissions factors based on LCA data. Overall, therefore, a hybrid methodology, drawing on the strengths of both life cycle analysis and environmental input-output approaches, is widely considered to be best practice.

EEIO models are derived from IO tables, often compiled using nationally published statistical data on the supply and consumption of goods and services within each sector in an economy. The columns of IO tables encode purchasing sectors, while the rows are filled with selling sectors, which means that each value in the table represents, in monetary units, the trade flows between each sector required to produce a given sector's output. This table is used to produce a table of 'technical coefficients' which quantify the direct financial spend on one industry by another industry per unit of the spender's output. This table is in turn used to produce the 'Leontief Inverse' matrix which represents the cumulative required inputs of a sector all the way up the supply chain. The mathematics of this are relatively simple and can be described by the equation below, where L is the Leontief Inverse, A is the technical coefficients matrix, and I is the identity matrix.

$$L = (I - A)^{-1}$$

This model can then be environmentally extended by first taking the greenhouse gas emissions of each sector and dividing this by the total output from that sector to give a direct GHG intensity per £GBP of output. Then, multiplying each sector's total required inputs (the Leontief) with this direct GHG intensity produces an emissions factor for each sector, representing the total GHG intensity per £ which therefore encompasses each sector's entire supply chain.

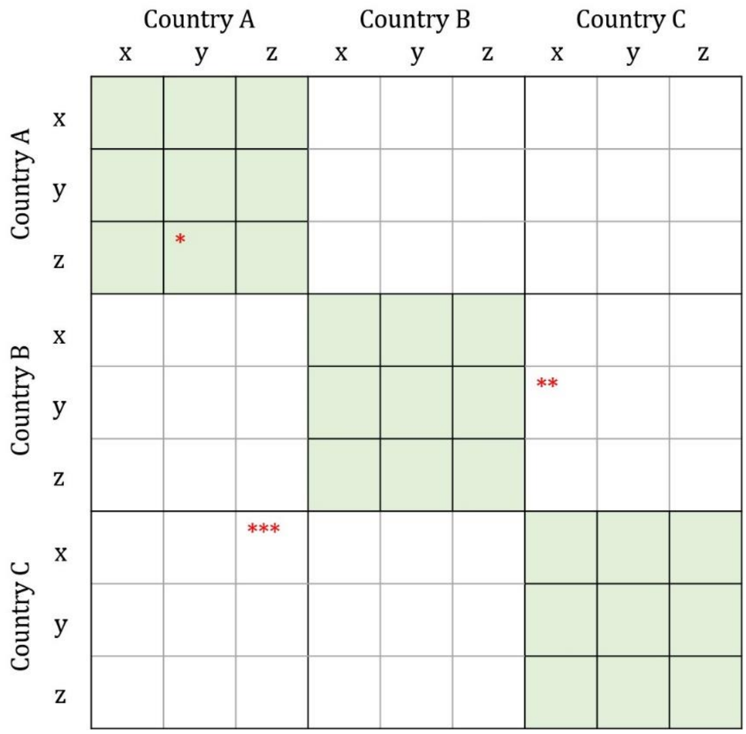
Multi-regional Input-Output (MRIO) Analysis

In a globalised world where the consumption of goods and services is often separated from the initial origins of production, it becomes more difficult to estimate the social and environmental impact of a product or service. As they undergo different stages of production, goods and services can pass through a network of several countries and be reassembled at various levels in the supply chain before reaching the end consumer. This issue necessitates an inter-regional approach to quantifying and modelling sustainability and ecological impact – including greenhouse gas emissions.

Environmentally extended multi-regional input-output analysis (MRIO) takes the concept of standard single-region input-output analysis and applies it at a larger scale by incorporating regional-level data and, crucially, the flows between regions. Often this is in the form of an input-output table which encodes not only the domestic trade of each sector within each country included in the model, but also the trade between every sector and country combination.

An MRIO table is essentially a large, amalgamated matrix, with domestic transaction matrices (national IO tables) occupying the diagonal blocks (shaded light grey, below) whilst the off-diagonal blocks show trade matrices between countries. This general format is depicted in the figure below. * represents a domestic transaction between sectors y and z in country A, while ** and *** represent international trade between different sectors in different countries.

Most commonly, MRIOs are constructed by taking national IO tables and linking them together using trade data. This is trickier than may be expected, as trade statistics often incur disagreement due to recording complications and the fact that different countries report figures with varying levels of granularity. Consequently, a vast amount of data goes into combining these sources, aiming to create a balanced MRIO table which stays close to reality whilst allowing IO analysis to be carried out.



Construction of the SWC MRIO Model

Core Data

SWC's model makes use of data from the Organisation for Economic Co-operation and Development (OECD). The OECD publishes a set of harmonised, industry-by-industry IO tables for countries that together account for around 93% of global GDP. This set comprises separate national IO tables as well as a single large MRIO table, the intercountry input-output table (ICIO) (OECD, 2021a). The OECD makes this data freely available for anyone to use, which simplifies the task of incorporating data into the model and ensures that transparency is upheld, since anyone may access and use the source data. The OECD tables, as of the 2021 data release, cover 66 countries and 45 economic sectors in the ISIC Rev. 4 format, making them compatible with the UN's System of National Accounts 2008 (SNA08, UN 2008) and the System of Environmental-Economic Accounting (SEEA, UN 2012). The tables are available as a time series dating from 1995 up to 2018, and the unit for all values is millions of $US in current prices for each year. The list of regions and the list of sectors covered by the OECD dataset are presented in Table 1 and Table 2, in Appendix A and Appendix B respectively.

For the required environmental accounts, OECD data is employed again where possible, as the organisation also publishes Air Emission Accounts (AEAs) in the ISIC Rev. 4 format on a residence basis (OECD, 2021b). In terms of the countries and sectors concerned, these accounts overlap significantly with the IO tables, and therefore require less harmonisation work before being combined in an EEIO model. An important quality of the data is that it is compiled using the residence basis, which covers all emissions under the direct control of the residents of each country, even if the emissions occur elsewhere. This contrasts with territorial-based methods, which only include emissions occurring within the borders of a given country, even if said emissions are economically linked to and directly controlled by another country. The OECD AEAs cover all the main greenhouse gases, which are converted and combined into tonnes of CO_2 equivalent (CO_2e) using standard IPCC factors.

A key issue with the OECD environmental accounts is that most countries for which they are available are in Europe. Environmental accounts are not always available for some of the most economically and environmentally important countries (such as India, China, Russia, and the USA), since many of these countries do not publish GHG data in sufficient granularity to create a set of accounts. For all the countries absent from the OECD data, a set of environmental accounts needed to be estimated via other sources, in accordance with the guidelines set out by the SEEA-approved “Manual for Air Emissions Accounts” from Eurostat (Eurostat, 2015).

Estimating Environmental Accounts

The basis for this estimation is energy balance data from the United Nations Statistics Division (UNSD) (UNSD, 2019) which provides information on the supply and use of various energy commodities and fuels within each country and sector. The first step is to convert the data from a territorial basis to a residence basis by remapping international aviation and shipping via two sub-models. This ensures compatibility with the OECD IO tables and other environmental accounts. The data is then mapped onto the relevant sectors to create a set of accounts relating to emissions-relevant energy use. Using the standard IPCC emissions factors for GHG emissions arising from the burning of different fuels, the data is further transformed into a set of combustion emissions accounts.

To complete the environmental accounts, data from the EU’s Emission Database for Global Atmospheric Research (EDGAR, 2021) is used to fill in the remaining gaps relating to non-combustion-related emissions, including agricultural, as well as various other minor GHGs. This process requires mapping from EDGAR’s lower-resolution sectoral classification system to the ISIC Rev. 4 classification employed by the OECD IO tables. This is why the more compatible UN energy balance data is used to estimate the initial combustion emissions, versus simply disaggregating EDGAR data for the whole set of accounts.

Finally, the IPCC’s global warming potential (GWP) factors for a 100-year time scale are applied in order to combine all the different GHGs into one CO_2-equivalent (CO_2e) figure. The final estimated environmental accounts span the same 45 sectors as the OECD IO tables, to ensure compatibility, and they include CO_2, CH_4, N_2O, SF_6, NF_3, HFCs and PFCs. With both the MRIO table and the environmental accounts available, the IO analysis can be performed.

Calculating the Final Emissions Factors

The OECD ICIO table is used to calculate the associated ‘Leontief Inverse’ in the standard manner described previously, before being environmentally extended using the OECD and estimated environmental accounts. This gives a set of emissions factors covering 65 countries and 45 sectors, representing the total emissions intensity per $US of output for each sector in each country. A final demand-based set of factors is also calculated by employing both the industry output-based factors and the final demand data within the OECD ICIO table to calculate weighted average emissions factors. The final demand-based factor for each sector in each country represents the weighted average of the goods or services bought by the final consumer within that sector, taking account of the country of origin. For example, the final demand-based factor for textiles in the UK is higher than the industry output-based factor, due to the higher prevalence of carbon-intensive imports in final demand compared to the intermediate demand of UK-based textile producers.

Using the environmentally extended MRIO model, both these sets of factors can be split further into Scope 1 (direct emissions), Scope 2 (indirect emissions from electricity consumption), and Scope 3 (all other upstream indirect emissions). Each set of factors is combined with additional layers of modelling, focusing on price margins and inflation. All factors thus far are calculated at basic prices, which represent the basic cost of the product or service; however, this is not usually the price paid by the consumer. Purchasers' prices are defined as the basic price plus taxes (less subsidies), wholesale/retail margins, and transport margins. For each sector in each country, a ratio of purchasers' prices to basic prices is estimated using supply and use tables sourced via the OECD and national statistical agencies. This ratio is used to adjust each set of emissions factors so that they can be expressed as either basic or purchasers' prices.

Data from the International Monetary Fund (IMF, 2022) on the consumer price index (CPI) for each country is used to adjust each set of factors for inflation between 2018 and 2021, and thereby bring the prices and emissions factors more up to date. The IMF CPI sectors are coarse, meaning that only a rough mapping of these indices onto the MRIO model's sectors can be carried out; however, this is still preferable to using 2018 figures. More recent quarterly data relating to the current year has been published; however, this data is only available for selected countries, and consequently has not been used. Due to recent high inflation rates, adjusting the emissions factors for specific countries of interest using the latest available CPI data would be recommended.

Four scopes (total, scope 1, scope 2, scope 3), two bases (country of production -based, and country of demand -based), two prices (basic and purchasers'), and two years (2018, 2021) give a total of 32 different variations of the original set of factors from the MRIO model. The final step entails incorporating these factors with the SWC UK single-region model. The purpose: to upscale the sectoral resolution from 45 to 105 sectors by assuming that some SWC subsectors within each OECD/MRIO sector have a similar ratio to each other. This is achieved by applying sector- and country-specific multipliers, derived from the emissions factors from the full MRIO model, to the 2018 SWC UK model. The multipliers are calculated using the 2018 single-region OECD IO table for the UK, in order to calculate a baseline emissions factor comparable to the SWC UK model. Every emissions factor from each of the 32 variant sets of the MRIO model is then divided by the relevant sector's baseline emissions factor from the OECD-based UK single-region model, resulting in a multiplier which can be used to adjust the 2018 SWC UK model.

The final dataset of emissions factors therefore covers 65 countries, 105 sectors, 4 scopes, 2 bases, 2 prices, and 2 years to give a total of 218,400 emissions factors in units of kgCO_2e / £GBP.

SWC UK Model Methodology

The following methodology describes the SWC UK model to which the MRIO-derived multipliers are applied. In the UK, the main data sources are the combined supply and use matrix for 105 sectors provided by the Office of National Statistics (ONS, 2021a), and the UK environmental accounts (ONS, 2021b). The specific model used for this project was developed by Small World Consulting with Lancaster University (Berners-Lee *et al*., 2011).

Description of EEIO Modelling

A technical coefficients matrix of inputs from each sector per unit output of each sector is derived from Table 2: “Industries’ intermediate consumption in 2018, The ‘Combined Use’ matrix”, in combination with Table 4: “Gross fixed capital formation by industry 2018”, based on 2018 data and figures obtained from the ONS (2021a). This matrix summarises the inter-industry spending of industries in the UK economy by 105 industry groups. This information is usually derived from use tables of inputs at basic prices, which are output prices before distributers’ margins, taxes or subsidies have been applied. However, for the UK, basic prices have not been published since 1995, the ‘Combined Use’ matrix now being published in purchasers’ prices. Therefore, the latter are used in subsequent calculations. This entails the assumption that demand at purchasers’ prices (including taxes, subsidies and distributors’ margins) is as good a guide to industry activity as demand at basic prices. The summation of the ‘Combined Use’ matrix and the ‘Gross fixed capital formation by industry’ table form the basis of the IO model. From this, the technical coefficients matrix and the Leontief Inverse are constructed using the standard method described previously.

The dataset *Atmospheric emissions: greenhouse gases by industry and gas* (ONS, 2021b) gives the GHG emissions in 2018 arising directly from 132 Standard Industrial Code (SIC 2007) sectors. These are mapped onto the 105 ONS IO Table industry groups using a process of combining SIC codes into single Input-Output industry groups. Emissions from aviation at altitude are known to have a higher global warming impact than the same emissions at ground level. An emissions weighting factor of 1.9 was therefore applied to the CO_2 emissions associated with the air transport sector, to reflect additional radiative forcing per unit of GHG emitted. This is the figure currently recommended by BEIS (2021). The application of this multiplier provides a first approximation of the impact of a complex yet poorly understood set of scientific phenomena surrounding aviation emissions.

UK output by sector at basic prices (ONS, 2021a) is combined with UK GHG emissions arising directly from each sector, to derive coefficients of emissions per £GBP of UK output from each sector at basic prices. The total GHG emissions arising from each industry, covering their whole supply chain, may then be calculated by multiplying the Leontief Inverse matrix and the direct GHG intensity of each industry. This produces total GHG emissions factors in units of kgCO_2e per £GBP of industry output at basic prices.

In the UK IO tables, three distribution sectors require special treatment, since the products they deal with are not counted as inputs and only the marginal increase in their value is counted as an output. These sectors are '45 Wholesale And Retail Trade And Repair Of Motor Vehicles And Motorcycles', '46 Wholesale trade, except of motor vehicles and motorcycles' and '47 Retail trade services, except of motor vehicles and motorcycles'. The emissions associated with these three sectors have been aggregated and redistributed between the industries they serve, in proportion to the distributors' margins associated with their products.

Other Key Notes on Methodology

Treatment of High-Altitude Emissions

High-altitude aeroplane emissions are known to have a higher global warming impact than their low-altitude counterparts. Although the science of this is still poorly understood, this study has applied a multiplier of 1.9 to aircraft emissions, to take account of their higher impact. This is the figure currently recommended by BEIS (2021).

Gross Fixed Capital Formation

The SWC UK model includes in its IO modelling gross fixed capital formation (GFCF), which is not a typical feature of many environmentally extended IO and MRIO models. However, since large, fixed assets can be key to certain industries and do indeed require the emission of GHGs in order to be produced, GFCF is included.

Uncertainties

There is great uncertainty over supply chain emissions resulting from the purchase of goods and services. The EEIO methodology adopted here removes the problem of systematic underestimation that compromises traditional life cycle approaches. Nevertheless, as with all footprint studies, the best estimates should be viewed as a broad guide.

A weakness is that the model is based on financial transactions, so there is no link to physical processes. This means it has the potential to be unrealistic when applied to the production of commodity materials. EEIO models depend on the structure of the national accounts, which usually aggregate a wide range of products into industry sectors, and so the results are very general. For example, a basic EEIO model does not take account of the carbon efficiencies that may arise from switching expenditure on paper from a virgin source to a renewable source, without reducing the actual spend.

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Appendix A: Regional Coverage of the OECD ICIO Tables

OECD economies		Non-OECD economies	
AUS	Australia	ARG	Argentina
AUT	Austria	BRA	Brazil
BEL	Belgium	BRN	Brunei Darussalam
CAN	Canada	BGR	Bulgaria
CHL	Chile	KHM	Cambodia
COL	Colombia	CHN	China (People's Republic of)
CRI	Costa Rica	HRV	Croatia
CZE	Czechia	CYP	Cyprus
DNK	Denmark	IND	India
EST	Estonia	IDN	Indonesia
FIN	Finland	HKG	Hong Kong, China
FRA	France	KAZ	Kazakhstan
DEU	Germany	LAO	Lao PDR
GRC	Greece	MYS	Malaysia
HUN	Hungary	MLT	Malta
ISL	Iceland	MAR	Morocco
IRL	Ireland	MMR	Myanmar
ISR	Israel	PER	Peru
ITA	Italy	PHL	Philippines
JPN	Japan	ROU	Romania
KOR	Korea	RUS	Russian Federation
LVA	Latvia	SAU	Saudi Arabia
LTU	Lithuania	SGP	Singapore
LUX	Luxembourg	ZAF	South Africa
MEX	Mexico	TWN	Chinese Taipei
NLD	Netherlands	THA	Thailand
NZL	New Zealand	TUN	Tunisia
NOR	Norway	VNM	Viet Nam
POL	Poland		
PRT	Portugal		
SVK	Slovak Republic		
SVN	Slovenia		
ESP	Spain		
SWE	Sweden		
CHE	Switzerland		
TUR	Turkey		
GBR	United Kingdom		
USA	United States		

Table 1: The full list of regions covered by the OECD IO tables in the latest 2021 release, split into OECD members and non-OECD members. The shading signifies countries for which the OECD also publishes Air Emission Accounts (AEAs) in sufficient sectoral detail to match the IO tables.

Appendix B: Sectoral Classification of the OECD ICIO Tables

Code	Industry	ISIC Rev.4
D01T02	Agriculture, hunting, forestry	01, 02
D03	Fishing and aquaculture	03
D05T06	Mining and quarrying, energy producing products	05, 06
D07T08	Mining and quarrying, non-energy producing products	07, 08
D09	Mining support service activities	09
D10T12	Food products, beverages and tobacco	10, 11, 12
D13T15	Textiles, textile products, leather and footwear	13, 14, 15
D16	Wood and products of wood and cork	16
D17T18	Paper products and printing	17, 18
D19	Coke and refined petroleum products	19
D20	Chemical and chemical products	20
D21	Pharmaceuticals, medicinal chemical and botanical products	21
D22	Rubber and plastics products	22
D23	Other non-metallic mineral products	23
D24	Basic metals	24
D25	Fabricated metal products	25
D26	Computer, electronic and optical equipment	26
D27	Electrical equipment	27
D28	Machinery and equipment, nec	28
D29	Motor vehicles, trailers and semi-trailers	29
D30	Other transport equipment	30
D31T33	Manufacturing nec; repair and installation of machinery and equipment	31, 32, 33
D35	Electricity, gas, steam and air conditioning supply	35
D36T39	Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39
D41T43	Construction	41, 42, 43
D45T47	Wholesale and retail trade; repair of motor vehicles	45, 46, 47
D49	Land transport and transport via pipelines	49
D50	Water transport	50
D51	Air transport	51
D52	Warehousing and support activities for transportation	52
D53	Postal and courier activities	53
D55T56	Accommodation and food service activities	55, 56
D58T60	Publishing, audiovisual and broadcasting activities	58, 59, 60
D61	Telecommunications	61
D62T63	IT and other information services	62, 63
D64T66	Financial and insurance activities	64, 65, 66
D68	Real estate activities	68
D69T75	Professional, scientific and technical activities	69 to 75
D77T82	Administrative and support services	77 to 82
D84	Public administration and defence; compulsory social security	84
D85	Education	85
D86T88	Human health and social work activities	86, 87, 88
D90T93	Arts, entertainment and recreation	90, 91, 92, 93
D94T96	Other service activities	94,95, 96
D97T98	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	97, 98

Table 2: The full list of the 45 sectors covered by the OECD IO tables and Air Emission Accounts.

Appendix C: Full List of Data Sources by Organisation

The following is an exhaustive list of the data sources used within the SWC MRIO model, broken down by the organisation supplying the data.

OECD

- Air Emissions Accounts
  https://stats.oecd.org/Index.aspx?DataSetCode=AEA
- Input-Output Tables (IOTs) 2021 ed.
  https://stats.oecd.org/Index.aspx?DataSetCode=IOTS_2021
- Inter-Country Input-Output (ICIO) Tables 2021 ed.
  https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm
- Air Transport CO2 Emissions
  https://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2
- Trade in Employment (TiM) 2021 ed.
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