LANCASTER ENVIRONMENT CENTRE

Quantifying Greenhouse Gases in Business Supply Chains

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European Union
European Regional Development Fund

Declaration

I hereby declare that this work has been originally produced by me for the present thesis and it has not previously been submitted for the award of a higher degree at any other institution. Inputs from co-authors and collaborators are acknowledged throughout.

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Abstract

This thesis is written in the context of a world that is on the brink of experiencing severe climate change, and as a result must explore a variety of methods for reducing greenhouse gas (GHG) emissions. Whilst national governments and international organisations enact treaties and frameworks, the role of business as a driver of increasing GHG emissions is also being examined. In these circumstances the measurement of organisational footprints is of considerable interest.

(Berners-Lee*, et al.*, 2011) showed how the supply chain footprint of a small leisure business could be estimated using Environmentally Extended Input-Output (EEIO) modelling. The research presented in this thesis describes the updating of this model to use the most up to date ONS data. This model was used over several years with a UK based international telecommunications company. The implementation of the model, and several extensions to the methodology are presented along with summary results of the analysis. The case study demonstrates the suitability and flexibility of EEIO models for reporting supply chain footprints in organisations. A critique of the technique and further developments of the model are described.

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This research would never have begun and could not have continued without Mike Berners-Lee of Small World Consulting. What I have added was built on foundations that he built soundly, and as well as being very supportive he has encouraged, provoked, educated and entertained in almost equal measures.

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Abbreviations

Abbreviation	Definition
ASEAN	Association of South East Asian Nations
BEIS	Department of Business, Energy and Industrial Strategy
BP	Basic prices, prices quoted in national accounts are sometimes quoted in basic prices which is defined as the amount received by the supplier from purchaser for a unit of good/service minus tax payable plus subsidy receivable
CCC	Committee for Climate Change Non Departmental Body set up by the Climate Change Act 2008
CDM	Clean Development Mechanisms, a procedure allowed under the Kyoto Protocol to allow countries to meet their emissions responsibility
CDP	Carbon Disclosure Project – a not for profit organisation that facilitates the sharing of environmental information amongst interested parties
CGE	Computable General Equilibrium – a type of economics model that does not assume a constant production function
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalence, the quantity of Carbon Dioxide that will give the same Global Warming Potential as another greenhouse gas
COP	Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC)
CMP	Conference of Parties serving as a meeting of the Parties to the Kyoto Protocol
CPA	Conference of Parties serving as a meeting of the Parties to the Paris Agreement
CPI	Consumer Prices Index – time-series statistics produced by the United Kingdom Office of National Statistics on the prices paid by consumers for products
CRC	Carbon Reduction Commitment UK government programme to encourage energy efficiency in business
CSR	Corporate and Social Responsibility – a term used by businesses to cover a range of issues including carbon footprinting
DECC	The United Kingdom Governmental Department of Energy and Climate Change, which has been recently absorbed (2016) into the Department of Business, Energy and Industrial Strategy (BEIS)
DTA	Domestic Technology Assumption
EDGAR	Emissions Database for Global Atmospheric Research – an EU database of atmospheric emissions that includes GHG
EEBT	Environmental Extended Bilateral Trade
EEIO	Environmentally Extended Input-Output
EU	European Union
EU ETS	European Union Emissions Trading System – system for setting carbon prices within European Union and certain economies that are linked to it.
GBP	Great Britain Pound, unit of currency
GCF	Gross Capital Formation, sum of Gross Fixed Capital Formation, changes in valuables and changes in inventories in the UK national Accounts.
GDP	Gross Domestic Product. In the UK there are three measures of GDP – GDP(P) estimate by measure of production, GDP (E) estimate by means of expenditure, and GDP (I) estimate by means of income.
GFCF	Gross Fixed Capital Formation, the acquisition of goods and services that are

	not used up in production but rather are used over several accounting periods
GVA	Gross Value Added
GWP	Global Warming Potential of a gas (tonnes CO_2 equivalent/tonne of gas)
HERP	Harvard Economics Research Program
HFC	Hydro-fluorocarbons – organic compounds containing hydrogen and fluorine, potent greenhouse gases
HMRC	Her Majesty's Revenue and Customs, the UK department concerned with collecting taxes and duties on imports and exports.
ICE	Inventory of Carbon and Energy - database of carbon and energy impacts of construction materials
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard on Industrial Classification of All Economic Activities
JI	Joint Implementation, a mechanism of the Kyoto Protocol
LCA	Life Cycle Analysis
LULUCF	Land Use, Land Use Change and Forestry
N_2O	Nitrous Oxide
NAFTA	North American Free Trade Agreement
NPISH	Non-Profit Institutions Serving Households
OECD	Organisation for Economic Co-operation and Development.
ONS	Office of National Statistics - United Kingdom's independent producer of official statistics
PBLCA	Process-Based Life-Cycle analysis, a method of estimating the greenhouse gas footprint of a good or service. See 1.4.1 Process-Based Life-Cycle Analysis (PBLCA)
PFC	Perfluorocarbons – organic compounds containing only carbon and fluorine, potent greenhouse gases
PP	Purchaser's Prices – amount paid by purchasers to take delivery of good/service at a time and place of their choice – includes non-deductible Value Added Tax, tax less subsidy and transport costs
Scope 1	Emissions released directly by an organisation
Scope 2	Emissions that are released to provide electricity, heating or cooling for an organization
Scope 3	Emissions that result as a consequence of an organisation's activities but occurring at sources not owned or controlled by the organisation
SF_6	Sulphur Hexafluoride, greenhouse gas
SIOT	Symmetric Input-Output Tables
SPA	Structural Path Analysis – a technique of input-output modelling that allows an estimate of the impact of different tiers of the supply chain
SWC	Small World Consulting Ltd.
UK	United Kingdom
UKERC	UK Energy Research Council, research body funded by the Research Councils UK Energy Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VAT	Value Added Tax
WIOD	World Input Output Database
WBCSD	World Business Council on Sustainable Development
WRI	World Resources Institute

Chapter 1 Introduction

"The economics of climate change is straightforward. Virtually every human activity directly or indirectly involves the combustion of fossil fuels, producing emissions of carbon dioxide-the most important greenhouse gas-into the atmosphere." William D Nordhaus 2011 (Nordhaus, 2011)

1.1 The UK and the Kyoto Protocol

The fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC) noted that "…Global atmospheric concentrations of [carbon dioxide] CO_2, methane (CH_4) and nitrous oxide (N_2O) have increased markedly as a result of human activities..." (IPCC, 2007). The United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty which is intended to stabilise greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system." (United Nations, 1992). Altogether 195 countries have ratified the convention and 192 have ratified the Kyoto Protocol which was adopted in 1997 and ratified in 2004, and came into action in 2005. The Kyoto Protocol and the subsequent Doha amendment bind their signing parties to emissions reductions targets and to reporting on a regular basis on their emissions of greenhouse gases (GHGs). The protocol defines those greenhouse gases and their global warming potential. These gases are often referred to as the Kyoto basket and are outlined in Table 1. In 2015 at COP21 the Paris Agreement was announced which committed the participating nations to adopt a target of restricting global warming to 2^0C. Two of the largest global emitters the USA and China jointly ratified in early September 2016. The United Kingdom ratified the Paris Agreement in November 2016 at COP22 in Marrakesh.

The United Kingdom adopted the Kyoto Protocol in 1995 and with the Climate Change Act of 2008, it claimed to take a leading part in action on climate change. The Climate Change Act committed the UK to legally-binding targets for reductions in greenhouse gas emissions by 2020 and 2050. Part of the means of ensuring these targets were met was the formation of the Department of Energy and Climate Change (DECC)[1], and the Climate Change Committee (CCC). The Department of Climate Change is a UK government department established to coordinate action on energy and manage the UK's commitments on Climate change. The Committee on Climate Change is intended to provide independent advice to the government of the UK on the subject of climate change. In addition,

[1] The Department of Energy and Climate Change has been absorbed into the newly formed Department of Business, Energy and Industrial Strategy (BEIS). The implications of this change are unclear at the time of writing.

there is a House of Commons Select committee that provides parliamentary oversight on the policies of DECC.

The implementation of the Kyoto protocol is outlined in the Marrakesh Accords , article 7 of which requires the United Kingdom (UK) and other annexe 1 partners to report their emissions and removals of direct greenhouse gas emissions from the Energy, Industrial processes, Solvents, Agriculture, Land Use, Land Use Change and Forestry (LULUCF), and Waste sectors. In order to ensure that a universal standard for reporting emissions was followed, the Marrakesh Accords dictate that a particular accounting method for each nation's reporting of emissions be used. This method of accounting for emissions is referred to as territorial emissions and as a consequence of this only emissions that occur within the borders of the UK are counted. There are two other methods of accounting for emissions within the UK and these are used by the Office of National Statistics (ONS) and the Department for Food, Rural Affairs and the Environment (DEFRA)

The ONS uses a method of accounting known as resident's (or, broadly equivalently, production) basis where "emissions produced by UK residents and industry whether in the UK or abroad" are counted and "emissions within the UK that can be attributed to overseas residents and businesses" are excluded (House of Commons Committee on Energy and Climate Change, 2012). The residents' basis for counting emissions can be derived from the territorial emissions figure residents' basis figure by adding and subtracting the figures mentioned above. This approach is taken by the ONS so that financial measures such as Gross Domestic Product (GDP) which are also produced by the ONS that use the same underlying calculation basis and hence can be compared.

The final approach, usually referred to as consumption based emissions accounting, "measures the emissions associated with goods and services consumed in the UK, taking into account of the emissions embodied in UK imports and exports" (House of Commons Committee on Energy and Climate Change, 2012). These figures are produced by the Department for Environment, Food and Rural Affairs (DEFRA) and differ from the other two measures in that they do not take into account the full basket of Kyoto gases but consider only emissions of carbon dioxide. This estimate of emissions attempts to consider emissions that are caused in other countries for goods and services that benefit UK consumers, whilst subtracting the emissions that are produced within the UK for goods and services enjoyed by other consumers. This figure is higher in the UK than for emissions calculated using the residential or territorial basis. This suggests that the UK is in a sense responsible for more emissions globally then are attributed to it by the territorial or residential basis.

1.2 Carbon Leakage

According to the UK Energy Research Council (UKERC) territorial emissions have declined in the period 1990 to 2008 by 19% (Barrett*, et al.*, 2012). The development of renewable energy and the switch from coal to gas have reduced territorial emissions, according to reports by the Organisation for Economic Co-operation and Development (OECD) (Bowen and Rydge, 2011) and DECC (Ricardo-AEA, 2014). However according to the same body, UKERC, consumption based emissions have risen by 20% in the same period. An article by Barrett et al. (2013) provides further evidence that emissions have been stimulated in countries that supply goods to the UK. This effect was described as "carbon leakage" by Felder & Rutherford (1993), and could be summarised as the relocation of carbon emissions from an area such as the UK to areas with lower or no standards on constraining carbon emissions owing to either:

1) An increase in the regulation of carbon emissions in the first area, referred to as strong leakage (Peters and Hertwich, 2008).

2) An increase in the consumption of carbon intensive goods or services in the first area imported from areas with lower standards on carbon emissions, referred to as weak leakage (Peters and Hertwich, 2008).

The Carbon Trust (Carbon Trust, 2010; 2011) have also argued that there has been an increase in the GHG emissions arising from UK consumption. This effect is not just restricted to the UK. It is a problem experienced by several Western economies for example America, France and Germany. Whilst the Kyoto Protocol represented a huge step forward, the setting of emissions targets and the policies to achieve those targets has been left to individual states. The principle that one tonne of CO_2 equivalent will contribute equally to the stock that is accumulating in the atmosphere regardless of its origin would require a consensus across all greenhouse gas producing nations on how to deal with them. However, this has not yet happened and the history of global climate change policy has been littered with countries signing up for emissions reductions, removing themselves from emissions reductions, setting targets that will not achieve the stated objective of limiting the change in global temperatures to 2^{o}C etc. The absence of a universal agreement on dealing with greenhouse gas emissions leads to the opportunity for carbon leakage to occur.

In this environment and with vast differences in the circumstances of nations, it is difficult to see how emissions reductions might be made given that many of the commitments to GHG reduction are conditional. There is considerable resistance for nations to accept sovereignty over their affairs under the doctrine of Westphalian sovereignty, the principle of international law that holds that each nation state has dominion over its territory, should not be subject to interference in its internal affairs, and that each state is equal. Given the difficulties of politicians attempting to solve this "wicked" problem (Rittel and Webber, 1973) of climate change, it would seem appropriate to enlist citizens and businesses to take unilateral action to reduce GHG emissions, irrespective of national and or international arrangements. In this context, the quantifying of GHG emissions in business supply chains is part of an effort to understand the impact of UK consumption on globally increasing concentrations of greenhouse gases and is vital to businesses planning to act on reducing emissions. With this understanding of the impact of their expenditure it is hoped that organisations can be persuaded to work with their supply chain wherever that may be, and play a role in reducing worldwide greenhouse gas emissions.

Another consideration in the argument that consumption drives emissions is the lack of awareness that consumers have about the impacts of their decisions. If there is not one single price for carbon, or if that price is not a realistic one, then the pricing information passed to consumers is incomplete and the markets cannot be Adam Smith's "invisible hand" that will resolve the issue of climate change. Encouraging organisations to investigate, to understand and manage their supply chain emissions, and then to be responsible about publishing their environmental performance, allows consumers of their goods and services to be better informed and potentially, given a cumulative will to challenge climate change, modify their behaviour. These changes of behaviour may not only contribute to reducing emissions but send a clear message to the political classes that the issue of climate change is important and one upon which governments will be judged.

1.3 Organisational Emissions

This thesis considers the measurement of GHG emissions in the supply chains of organisations, so a definition of organisational GHG emissions should be provided. In the context of this thesis, greenhouse gas emissions are considered to be outputs of the gases listed in Table 1, unless otherwise noted. Although it is possible to list the emissions for each gas when reporting on greenhouse gas emissions, it is more common to report the total emissions as tonnes of CO_2 equivalent (tonnes CO_2e) using the Global Warming Potential (GWP) over 100 years for each individual gas. This can be calculated by multiplying the emissions of the individual gases by the GWP factor for each gas, see Table 1.

Secondly when considering the emissions of organisations, it is helpful to subdivide the types of emissions according to the control that the organisation has over the amounts of emissions that occur. The World Resources Institute (WRI) provides guidance on this categorisation and uses the terminology of "Scope 1", "Scope 2" and "Scope 3" emissions, with the implicit hierarchy indicating the degree of control. The scopes are outlined in Table 2 (World Resources World Resources Institute, 2011). The definition of scope 3 emissions covers both upstream emissions (those occurring in the organisation's supply chain) and downstream emissions (those associated with customers) such as transportation of purchased products, and the in use and end of life emissions associated with goods. For many industry sectors the amount of scope 3 emissions that are attributed to an organisation's purchasing activity outweigh the amount of scope 1 and scope 2 emissions of that organisation (Matthews*, et al.*, 2008). In the context of rising greenhouse gas emissions, some have argued that making people and organisations aware of these emissions (which are frequently referred to as embodied emissions) has become as important as the control of direct emissions (Munksgaard and Pedersen, 2001; Lenzen*, et al.*, 2007; Berners-Lee*, et al.*, 2011).

Table 1 Greenhouse Gases and Global Warming Potentials (summarised from Table 4 IPCC 2nd Assessment report, Climate Change 1995, Working Group 1)

Greenhouse Gas		Global Warming Potential (GWP) (tonnes CO_2 equivalent/tonne gas)
Carbon Dioxide	CO_2	1
Methane	CH_4	21
Nitrous Oxide	N_2O	310
Hydrofluorocarbons	HFC	140-11,700
Perfluorocarbons	PFC	6500-9200
Sulphur Hexafluoride	SF_6	23,900

The awareness of embodied emission does not necessarily lead to control of them, but businesses can exert a degree of influence on their supply chain. As businesses are in competition for customers, an organisation appearing to offer a good or service with lower greenhouse gas emissions might enjoy a competitive advantage, other things being equal and if consumers prefer to buy goods or services with lower emissions. This might provide the incentive for industries to improve their efficiency with respect to GHG emissions. Balanced against this is the innate capacity of sellers to find a way to market, so a producer that is inefficient in greenhouse gas emissions may find other customers who take their product perhaps given the incentive of a lower price. The original company that has driven change for the better may now find itself undercut by competitors and either go out of business or revert to the behaviour of the rest. Thus the process of counting greenhouse gases has to be fair and universally applicable and the measures taken need to be equitable and if possible distributed throughout the supply chain.

Table 2 Definition of Scopes according to WRI

Scope	Title	Description
Scope 1	Direct Emissions	Direct emissions from sources that are organised or controlled by the organisation
Scope 2	Electricity Indirect Emissions	Emissions arising from electricity, and purchased steam, heating or cooling.
Scope 3	Other Indirect Emissions	Emissions arising as a consequence of the activities of the company but occurring from sources not owned or controlled by the organisation

1.4 Measuring Embodied Emissions

1.4.1 Process-Based Life-Cycle Analysis (PBLCA)

One of the difficulties associated with measuring the emissions embodied in goods or services for final consumption is the complexity of modern supply chains and technology. An item such as a computer includes a considerable number of components that are combined into sub-assemblies and then these are combined into the final product. These holds true for most goods and services, even for a service such as providing insurance, where an office has to be run, administration of the policy has to be undertaken, the risks for the insurance have to be calculated and so on. Many of these processes take place in countries distant from the point of retail and accounting for all the emissions associated with all the steps of manufacture or delivery of service is a Herculean if not Sisyphean task.

A common-sense approach to calculating embodied emissions was by identifying processes associated with a particular good or service, and then quantifying the inputs to and outputs from these processes. From this detailed process analysis, the amounts of greenhouse gases (an output of the process) per unit, either financial or physical, of produced good can be calculated. This approach is commonly described as Process-Based Life-Cycle Analysis (PBLCA) and as outlined is straightforward in concept but in detail is very complicated; see for example Global Guidance Principles for Life Cycle Assessment Databases (UNEP, 2011).

The processes considered can be those directly involved in providing a good or service but in order to address embodied supply chain emissions the analysis needs to be extended to further upstream processes. In turn, these upstream processes will have processes upstream of them and it can be seen that the analysis has to consider an exponentially increasing, but finite, number of processes. In practice extending the analysis to the extractive industries that are the starting point for most goods and services may prove infeasible to undertake. So, most process based life cycle analyses make some simplifying assumptions and exclude processes that only contribute (as far as the analysts are aware) a small amount of the emissions (Bullard Iii and Herendeen, 1975; Suh and Huppes, 2005). This leads to "truncation errors" where parts of the life-cycle analysis are not carried out. By their nature these truncation errors are of unknown magnitude and therefore the most meticulous of analysts may miss important sources of emissions particularly if those sources are two or more tiers up the supply chain. Lenzen (2000) estimates that whilst refining industries might reach a minimum 80% coverage of emissions from two tiers of the supply chain, industries such as retail require four tiers of the supply chain, and insurance six tiers.

For any given organisation, this analysis should be carried out across all goods and services provided and in the modern technological age this encompasses a vast amount of detailed data, if the results are to be meaningful. With technology advancing each year the analysis process needs to be updated for each new set of products and services. Tackling the total of embodied emissions in all products and services by using a PBLCA could be considered onerous.

Whilst PBLCA has made and remains an important contribution to our knowledge of embodied emissions, the discussion above indicates that there are both advantages and limitations to the approach which are summarised in Table 3.

Table 3 Advantages and disadvantages of PBLCA

Advantages of PBLCA	Limitations of PBLCA
High level of detail	Truncation errors
Actual observations of emissions	High data and analysis requirements
Specificity to product	Quickly out of date

A technique is required that overcomes the limitations of the process based life cycle analysis and to this end a top down technique that can account for all industries and products has been developed and is outlined in the next section.

1.4.2 Environmental Input-Output Modelling

Input output modelling was developed by Wassily Leontief in the late thirties (Polenske, 1999). This technique considers the inputs to and outputs from industrial sectors within an economy. Leontief himself provided a framework for using input-output modelling to measure the impacts of pollution, and the technique has been extended by several to measure embodied energy and emissions of greenhouse gases (Bullard Iii and Herendeen, 1975; Lenzen, 2001a; Hertwich, 2005; 2011; Barrett*, et al.*, 2013). The object of this modelling has been to derive estimates of the amount of greenhouse gases (or other environmental impact) that are produced on an economy wide scale per unit of final demand. These quantities are usually referred to as total greenhouse gas emissions intensities in this thesis. Input-output modelling begins with data about inter-industry transactions, final consumption of goods and services, imports and exports, and the outputs of each sector both in terms of money and emissions of the GHG, which are usually combined to give an intensity measure i.e. the outputs of a given pollutant per pound sterling of output of a sector.

The ONS provides information on the structure of the UK economy by issuing supply and use tables (SUT) that show the inter-industry sector transactions, supply and imports and consumption and exports. This allows the construction of an input-output matrix for the UK economy by a process that will be discussed in detail in Chapter 2. In brief though, a coefficients matrix can be constructed that includes estimates of the amount per unit output that each industrial sector purchases from each of the other sectors and itself taking into account the whole supply chain. This can be combined with the direct emissions of each sector to make an estimate of the total GHG emissions intensity for each sector. For example, according to the Office of National Statistics (ONS) in 2010 the UK industry sector for "Employment services" was responsible for 243.18 kilo-tonnes CO_2e of GHG emissions and had a domestic output of £32,401 million (at basic prices), leading to an estimated direct GHG intensity of 0.00751 kg CO_2e per pound sterling of output. Using the model outlined in chapter 2, an estimate for the total GHG emissions intensity is 0.170 kg CO_2e per pound sterling of final demand. The total emissions intensity is a factor of 22 greater than the direct emissions intensity, indicating the impact on emissions intensity that the demand for "employment services" has on the UK emissions as a whole. Similar calculations are carried out for the other sectors of the UK economy to derive a vector of total GHG emissions intensity for each sector of the UK economy.

Assuming that the coefficients matrix remained constant for small changes in output i.e. that the production functions are constant, and that the direct emissions intensity also remained constant for small changes, then this vector of total GHG emissions intensity will also be constant for small changes. Thus, it is possible to model the effect on total emissions of a small change in final demand in any or several sectors by multiplying a vector of small changes in final demand by the vector of total emissions intensity.

Furthermore, organisations that provide goods and services remain in business by understanding and controlling their financial costs. By expressing these expenditures in terms of a subset of the industry sectors of the national accounts then those expenditures can be presented to a model of the economy as a vector of small change in final demand and hence allow an estimate of the emissions arising from the organisational expenditures. This combines an organisation's detailed knowledge of its financial expenditures with a model of the emissions that arise from intra-industry expenditures and provides a way to answer limitations 1 and 2 in table 4. The ONS provide national accounts on an annual basis and so changes in technology are incorporated automatically which answers the third limitation. In principle then, combining an organisation's audited financial records, with publicly available information about the UK economy can provide an insight into the emissions arising from any UK organisation. This exercise can be repeated at will but commonly on an annual basis to track how an organisation is performing with respect to supply chain GHG emissions. It has the advantage of using data that the business will have produced to meet legal requirements and that are currently being used to manage the organisations affairs thus the overhead to the business in producing an estimate of supply chain emissions is kept small. The method and model can be applied to any business, so in principle it can be universally applied and the estimates of supply chain GHG emissions that are produced would be on the same basis for all organisations.

However, EEIO modelling has its own limitations which arise for example from the aggregation of sectors within an economy. These sectors are generic in nature for example in the Office of National Statistics, UK (ONS, 2012a) the sector for "computer, electronic and optical products" includes products as diverse as "optical and magnetic media" and "non-electronic industrial process control equipment". The emissions of this sector are divided over the products of this sector by value and this takes no account of the actual product being supplied or the individual production unit that makes the product. As the processes that are associated with manufacture of "optical and magnetic media" are different to those for manufacturing "non-electronic industrial process control equipment" a PBLCA would make different estimates of the total emissions intensity of each product. In EEIO modelling both would have the same emissions intensity per financial unit of final demand.

In addition, there are issues of completeness of the underlying data and the subsequent requirement to use statistical inference. The process by which the ONS makes its estimates of inter-industry transactions is by that of business survey and then extrapolation from individual producing unit responses to industry sector level. The estimates of each sector's purchases and sales are derived from the survey data which means that there is statistical inference and hence uncertainty involved. Sectors may be widely or poorly represented by companies taking part in the business survey. Other data points may be relatively well estimated particularly if they involve the collection of taxes or duties.

Finally, there is the issue of co-products or by products, which again arise from the aggregate nature of the economic sectors as discussed above. For example, the food industry has several sectors that can be seen in

The final part of the model - the process of attributing emissions to industries is also troublesome, as measuring the emissions of an industry sector can only be carried out by a partial survey and then use of statistical methods to make an estimate of the total amount of greenhouse gases emitted. Errors in these stages will propagate through the system and may lead to unknown errors in the final results.

, but a single producing unit might output products to several of these sectors. Specifically, a vegetable oil processing unit produces oils and fats (sector 10.4) but also animal feeds (sector 10.9). In its response to the survey, a representative of this industry sector will report its principle product i.e. vegetable oils, and by-products animal feeds, however its inputs may not be evenly distributed over these processes. Refining of oil is a high energy process, whereas the processing of animal feedstuffs is less energy intensive. Determining the balance of the inputs between the two products is difficult and subject to error.

Table 4 Breakdown of Sectors within the Food Industry

SIC	Description
10.1	Preserved meat and meat products
10.2-3	Processed and preserved fish, crustaceans, molluscs, fruit and vegetables
10.4	Vegetable and animal oils and fats
10.5	Dairy products
10.6	Grain mill products, starches and starch products

10.7	Bakery and farinaceous products
10.8	Other food products
10.9	Prepared animal feeds

The final part of the model - the process of attributing emissions to industries is also troublesome, as measuring the emissions of an industry sector can only be carried out by a partial survey and then use of statistical methods to make an estimate of the total amount of greenhouse gases emitted. Errors in these stages will propagate through the system and may lead to unknown errors in the final results.

Even given these drawbacks, the ability to draw information from across the economy, and ensure that there are no truncation errors, means that for businesses that are based in the UK, the use of the UK national accounts framework and emissions inventory to estimate supply chain emissions may well be a reasonable approximation. However, trade in the UK is historically, and currently, very important. Whilst imports are known and considered in the UK national accounts, in the model described in this thesis it is assumed that these imports are produced using the same technology as the UK – the Domestic Technology Assumption. However, this is unlikely to be the case, for example the energy structures, even within Europe, vary markedly with high proportions of nuclear energy in France, renewable energy being widely used in Germany, hydropower used extensively in Scandinavian countries, but with some former Eastern Bloc Nations relying heavily on coal for power. Looking further afield at other trading partners of the UK, energy sources vary widely and also the structure of the economy; for example the formerly central-planned economies in China and Russia. For bigger businesses and/or those that include a high proportion of imports it is important to consider international trade.

1.4.3 Hybrid Methodology

The process based life cycle approach has the strengths of considering individual products, using actual emissions data and being detailed albeit suffering from unknown and possibly significant truncation errors. The EEIO method provides full supply chain coverage and offers generic but reasonably current information but with the weakness of being non-product or process specific. So the weaknesses of a particular method may be addressed in part by using the other technique to address those weaknesses. Typically, this would involve using PBLCA to investigate energy intensive sectors that have been identified by an EEIO analysis. Alternatively, EEIO analysis may be used to estimate the emissions arising from processes in LCA that are not calculated explicitly. This approach of combining LCA and EEIO is usually referred to as a "hybrid" approach (Suh and Huppes, 2002; 2005). A key issue with hybrid models is avoiding double counting (i.e. inadvertently counting emissions via PBLCA and EEIO), and the corollary of this is to ensure there are no emissions that are not captured by either method. In order to mitigate this issue a clear understanding of the boundaries between emissions assessed by EEIO and those assessed by LCA is required. This must be understood at the beginning of any process of measuring the greenhouse gas footprint of an organisation and will be illustrated later using a case-study.

Note that the term "hybrid input-output tables" is sometimes used for an IO table that is in both monetary terms and physical units, for example with outputs from for example the energy industries being measured in energy units rather than monetary units.

1.5 Aims, Research Questions and an Outline of the thesis

Berners-Lee et al. (2010) have developed such a hybrid methodology for assessing organisational emissions. This is based upon 2007 statistics from the ONS that divide the economy into 123 sectors, and emissions factors issued by DEFRA which are updated on an annual basis. The consumer price inflation figures also produced by the ONS are used to adjust the 2007 figures to match the reporting year chosen by the organisation. The scope of the model extends to the supply chain scope 3 emissions, i.e. those arising from the organisation's spending with their supply chain, scope 3 emissions arising from business travel, and commuting; and the scope 3 emissions that arise from scope 2 emissions, i.e. those associated with the supply chains for electricity in particularly but also supplied heating/cooling/steam. The model does not extend to scope 3 downstream emissions, e.g. those arising from customers' use of products or services or end of life emissions associated with the disposal particularly of goods.

Chapter 2 of the thesis explores the development of environmentally extended input-output models and sets the global governance structures in place relating to Climate Change. There is also a consideration of the impact of business action on reducing their supply chain carbon footprint.

Chapter 3 provides a brief overview of estimating Carbon Footprints, then considers the datasets that are available to construct Environmentally Extended Input-Output Models before considering the construction of a single region model. This model will use latest ONS classification scheme based on Standard Industry Classification (SIC) 2007.The primary objective of the project is to develop this model and apply it to estimate the Carbon Footprint of a large UK-based company There are several reasons for such an approach and these are summarised in Table 5.

Table 5 Advantages and Disadvantages of using UK economic data for Modelling

Advantages	Disadvantages
Data on the UK economy is readily available and extensive metadata is available	For many companies there is a large international aspect to their trade and the UK model may not represent successfully the economy which the organisation deals with
The organisations that the object of the process of modelling are UK based	The ONS presentation of national accounts is highly aggregated with only 110, now 106 sectors, other countries for example the USA present a more disaggregated view of their economy
The UK can be considered to be a reasonable proxy of developed world economies	

Chapter four describes the use of the new model the organisation over a period of 4 years, and discusses some useful techniques of EEIO modelling that allow companies to understand the significance of particular product sectors in their supply chain. The results of the estimate and the impact upon the organisation are discussed.

In chapter five, three revisions to the model are presented:

1) One that includes process based emissions and shows a general method for customising national accounts sectors to better match customers purchases.
2) A revision to show how supplier reported scope 1 and 2 emissions can be incorporated. For an organisation investigating its scope 3 emissions, the scope 1 and 2 emissions that arise from direct combustion, or from the supply of electricity or other energy respectively, of its suppliers are part of its scope 3 emissions. The estimates of scope 1 and 2 emissions from EEIO modelling can be replaced by supplier reported figures, and a revised estimate of the total scope 3 emissions obtained.

Chapter six provides an extended critique of the methods applied, and discusses how weaknesses in the modelling process might be addressed.

Chapter seven draws together the ideas introduced in the body of the thesis, and answers the following research questions:

1) How can Environmentally Extended Input-Output models influence business decision making in relation to their supply chain impacts?

2) What are the impacts in the use of an EEIO model to estimate the supply chain footprint of a major multinational company over a 4 year timescale?
3) How can EEIO models be extended to use "real world" data such as that available from PBLCA or from suppliers?

Chapter 2 History of Environmentally Extended Input-Output Modelling

2.1 Introduction

The input-output structure that forms the basis of the models described in this thesis was formulated initially by Wassily Leontief; however, his work was based upon the work of others and has in turn been developed by later workers. This chapter will highlight briefly some of the predecessors to Leontief's work and those contributions made by others that are applicable to environmentally extended input-output modelling and finishing with a look at the application of EEIO modelling to the estimation of supply chain footprints in organisations.

2.2 Early Pioneers

Probably the most common name mentioned in the prehistory of input-output modelling is that of François Quesnay, an eighteenth century French intellectual and contemporary of Adam Smith. Trained as a surgeon, he became interested in political economy and a founding member of a group of economics thinkers known as the Physiocrats. His Tableau showed the interplay of investment between 2 sectors, an agricultural sector which Quesnay regarded as the only productive sector in that investment in it, generated a surplus. The second element of the economy he considered to be manufacturing and this sector's output is regarded as being only the inputs that enter it. Two ideas emerged from this analysis one being the movement of money between the sectors of the economy, which in time leads to the concept of the circular economy. The second was the re-investment of the surplus of the agricultural sector, which leads to a greater contribution to the economy than the original investment. (Baumol, 2000)

Achille-Nichole Isnard was a countryman and contemporary of Quesnay who criticised the assumption that the agricultural sector was the only productive one. He argued that any sector can generate a surplus dependent on the prices of commodities exchanged and that those prices arose from a market and are not simply derived from the costs of the inputs (Kurz and Salvadori, 2000). He also derived equations to represent a model of the economy – an analogue of the input-output models produced later. Karl Marx was impressed by the idea of Quesnay's Tableau and the idea of the flow of products between different sectors of the economy. He used it to demonstrate his labour theory of value, which argued that growth in the economy came from value added by labour, which was not fully compensated by the wages paid to the labour force. He believed that this model would allow for the determination of prices and profits but it did not allow for the market determination of prices (Kurz and Salvadori, 2000).

At the end of the 19th century a number of economists were adopting an idea from the physical sciences, that of an equilibrium arising as a result of input and output to a physical system being in balance. This led to the idea of the economy being in some form of equilibrium and eventually was to lead to a class of models known as computable general equilibria (CGE) models. Input-output models are one realisation of this type of model with the chief characteristic that the technology of the economy is static, and that production functions are constants. Leon Walras contributed the idea of production coefficients for the factors of production that remained in proportion to the output of the product, an idea that leads to the technical coefficients of Leontief's formulation. (Miller and Blair, 2009)

Von Bortkiewiecz was Leontief's PhD supervisor but he also contributed to the analysis of the factors of production, using both a linear approach whereby price was determined by a finite sequence of labour inputs and a circular approach, which more closely resembles the way that an input-output model is set up in terms of determining the total labour input as a function of the total labour input and some other variables. He produced a description of an economy in *n* commodities, which was represented by a system of equations in which the price of each commodity was determined by the price of the other commodities (multiplied by the quantity of that commodity required) plus labour costs plus profit. There are thus *n* equations (1 for each of the commodities) but *n+2* unknowns - labour rate and profit rate. Von Bortkiewiecz solved this system by fixing the wage rate and designating one of the commodities as a numeraire (-a commodity used to measure the value of other commodities) to give the rate of profit and prices (Kurz and Salvadori, 2000). The inclusion of fixed production coefficients, labour and profits resembles the later input-output model and Von Bortkiewiecz extended his earlier work to include the use of fixed capital that is production used to facilitate further production.

John von Neumann made some important contributions to modelling the economy using linear programming and allowing the use of inequalities to represent constraints upon production andthere are some who argume that the dynamic model of Leontief is a special case of von Neumann's model (Rose and Miernyk, 1989). Von Neumann considered however a system that used every good available in an economy in order to produce each good, although the quantity of any of the goods could be arbitrarily small. The system included labour inputs. By comparison, Leontief makes no such assumption in his model. Von Neumann showed that his system could be solved only when in a quasi-stationary equilibrium that is the whole economy is growing at a consistent rate. Von Neumann uses the mathematics of the system to show an emergent property – growth of the whole economy. By contrast Leontief was much more concerned with surveying the economy to understand how the economy worked, i.e. in providing the data that would provide the coefficients for the system of equations.

The data generated would also have need to be manipulated and this required some automatic way of dealing with the large quantities of data that are generated by modern economies. Currently high performance computer systems are available that can solve systems involving thousands of variables but this technology was only just becoming available in the 1930's when Leontief was beginning his analyses. John Wilbur designed and built the Mechanical Simultaneous Equation Solver which was used in 1935 to generate IO tables of US economy for 1919 and 1929 from data gathered by Leontief (Leontief*, et al.*, 1985). Now that the stage has been set we can consider the playwright Wassily Leontief himself.

2.3 Leontief

Leontief began working on constructing his models in 1928 and initially considered the structure and theory of the model (Leontief, 1991). This analysis was at a level of abstraction that did not encompass data gathering, or a realisation of the model. However, what is interesting is a perceptive look into the future postulating a way to solve the linear equations arising out of the model automatically. This was before the use of computers as solvers for linear programming, and describes a theoretical basis for the practical work that was to follow.

Leontief joined the Chinese National Bureau of Economic Analysis in 1931, but was recruited to the Harvard Economics department in 1932 with the promise of a grant and research assistant but not much confidence that his project would succeed (Polenske, 1999). Thus began the more applied section of his work. Initially Leontief constructed a model of the US economy for 1919 and 1929 in 46 sectors (solved for 19 sectors). This led to the development of a 92 sector model of the US economy in 1939, constructed in 1941 for the US department of Labour and used for predicting the impacts that disarmament at the end of the Second World War would have on the US economy. In 1949, a division of the Department of Labour –the Bureau of Labour Statistics took on the task of preparing a 450 sector model of the 1949 US economy,which was the beginning of a consistent presentation of the National Accounts through to the present day, although now it is the Bureau of Economic Analysis (BEA) that produces the figures (Polenske, 1999). Leontief went on to establish the Harvard Economic Research Project (HERP) where many of the concepts discussed later in this thesis had their origins. He retired from Harvard in 1975 and promptly set up the Institute of Economic Analysis at New York University where he remained active in research until his death in 1999

Throughout his career, Leontief was keen that his work should be accessible to all scholars and commonly used a simple model to explain his ideas. The model that Leontief used considered an agricultural sector, a manufacturing sector, and the household sector that would consume the finished goods (Leontief, 1986). Although simple, it included the important idea that the model should be grounded in reality. In addition, this model made no demand that the data used should be in financial terms, it worked equally well when considering material flows measured in physical units provided of course that there was consistency throughout a sector i.e. the output of the agriculture sector was measured in bushels throughout. The final important point was that following the work of Walras the economy was regarded as being in equilibrium but with a simplifying assumption that the technical coefficients remained constant within the period of analysis. This made the model much more tractable to being solved and hence useful for estimating the impacts of changes in final demand.

With the ability to include physical flows of materials, Leontief extended his model to consider the impact of a pollutant generated by industry and showed how a consistent structure could be used to analyse the impacts of changes in final demand upon the amounts of pollutant discharged to the ecosphere. This model was based around the idea of incorporating the pollutant as a product and an industry (Leontief, 1970). This approach is not used for the modelling carried out for this thesis, but indicates the importance that Leontief attached to using the technique in practice, rather than purely for academic research. The research however depended on data and the framework for gathering data about national accounts is discussed next.

2.4 National Accounts

In order to construct an Input-Output model there is a requirement for data about the economy of interest. This data usually comes from the National Accounts of that economy but when preparing his model Leontief had no access to such data as it did not exist for the United States at that time. Hence he had to gather his own data. As noted above, this task was taken on by the Bureau of Labour Statistics in the United States. In the UK, Meade & Stone presented a method of construction for national accounts with the primary purpose of estimating national income (Meade and Stone, 1941). A further elaboration of the methods of estimating national incomes is described by Stone et al (Stone*, et al.*, 1942) and it is these ideas that were developed by the "Sub-Committee on National Income Statistics of the League of Nations Committee of Statistical Experts" led by Stone in a 1947 report that is the first in a series of manuals on constructing a set of national accounts (The Sub-Committee on National Income Statistics of The League of Nations Committee of Statistical Experts, 1947). Thereafter follow a number of updates to the methodologies which are documented by the

United Nations Department of Economic Affairs and its later incarnations (United Nations Department of Economic Affairs Statistical Office, 1953; United Nations Department of Economic and Social Affairs, 1968; 1993; 2008). The System of National Accounts (SNA) is intended to provide a guide as to best practice but each national statistical bureau generally documents how the accounts of that particular nation are produced. With a system for gathering underlying economic data, it is time to consider the applications of input-output modelling to the impact of consumption on the environment.

2.5 The Energy Crises of the 70's

The genesis of environmentally extended input-output modelling can be traced to the energy crises of the 1970's and concerns about human impact on the planet arising in the late 1960's (Cole, 1968). Keeling published the measurements of rising carbon dioxide emissions less than a decade before (Keeling, 1960). A paper in the same journal as Keeling's article, by Kaplan shows the embryonic state of atmospheric modelling and estimates that a 10% rise in CO_2 concentrations would result in a warming of the atmosphere by 0.25K (Kaplan, 1960). In the UK, Sawyer in his 1972 paper reports the observations of rising carbon dioxide from observations made at Mauna Loa and the South Pole (Sawyer, 1972). However, the oil crises of 1973 and 1979 focussed the minds of researchers on energy use and energy security. The concerns about shortages in fuel supplies caused by for example the Organisation of Petroleum Exporting Countries (OPEC) embargoes ensured the development of embodied energy models. These type of models are quite closely related to environmentally extended input-output models as the generation of energy is intimately linked with the emission of greenhouse gases. At this point, the emphasis was on further research to investigate the impacts of these rises but the primary reason for considering energy embodied in products was to mitigate the impact of rising prices and insecurity of fuel supplies. American and European researchers in particular began the process of investigating how much energy was being used in the supply chain of products consumed in the developed countries.

In the US, Bullard and Heerendeen were at the forefront of this research into embodied energy (Bullard and Herendeen, 1975). In an early paper (Bullard and Herendeen, 1975) they consider the two methods outlined in the introductory chapter, what they term a "vertical analysis" being in effect a PBLCA, and then an input-output approach that considers the energy intensities of the industries involved and calculates those simultaneously (Bullard and Herendeen, 1975). Interestingly their model is constructed in hybrid units using energy flows as well as financial ones following Leontief's example (Leontief, 1986). They go on to use this model in a variety of different applications considering for example the calculation of a family's purchases, the impact of government spending, and the energy dependence of the nation. Although not directly related to greenhouse gas emissions, it is possible that these models could be used to calculate them, particularly as Bullard and Heerendeen consider the impact of differing fuels which potentially allows the use of specific emissions calculations by fuel used.

In a second paper (Bullard Iii and Herendeen, 1975), they use a broadly similar model to consider the calculation of embodied emissions in products such as a car and an electric mixer but also the cost of energy within the US. Although the emphasis of the analysis differs in that products and services are considered rather than the impacts of an organisation, there is no reason why the model could not be used for calculating that energy impact and again with appropriate multipliers used in estimating greenhouse gas emissions.

In Europe, Estrup (1974) (Estrup, 1974) considers the importance of embodied energy also, considering the German economy in 1960 and using an Input-Output methodology. Again this interest seems to be sparked by an increasing realisation that energy resources are scarce and that there is frequently a mismatch between a country's internal resources of energy and the demand within that country for them.

Ayres & Kneese (Ayres and Kneese, 1969; 1971) consider the weaknesses of economic modelling because of what is ignored i.e. the outputs to the environment arising from production and the limited capacity of that environment to absorb those outputs. This again is not specifically related to GHG, which were not identified as much of an issue in this paper, but for other pollutants e.g. particulate matter, although in the 1969 paper the increasing accumulations of Carbon Dioxide was noted and that this may have an impact on future weather. This approach is mixing ecology and economics highlights the increasing importance of dealing with the "residuals" of production as society becomes more developed. They are keen to include the extractions from the environment as well as disposals to the environment, and in general take a much more holistic view of the economy than a narrow financial one. This is an interesting theoretical development but is actually not applied and no mechanism of applying their equilibrium model in a specific context is discussed. As this modelling exercise was intended to draw attention to the wider issues this is not a weakness of their approach. Amongst the conclusions drawn is that economics should be extended to include social costs in order for economics to come up with a socially acceptable use of resources. The social costs include the external costs e.g. the damage done to the ecosystem by absorbing the residuals of production. Only when these external costs are included can a satisfactory social solution be found. This solution being one that benefits the whole of society rather than just the businesses. Ayres and Kneese (1969, 1971) argue that the issue must be tackled by an approach that takes into account all of the possible impacts of production on the environment rather than considering each individual impact.

Tummala and Connor extend the input-output ideas by including elements from engineering to again reintroduce the idea of mass and energy flows into the input-output models (Tummala and Connor, 1973). Again the idea stems from a system that is in balance but in this case inspiration is sought from Kirchoff's laws of current and potential difference. This model allows labour to be included as an energy resource but the method could also be extended to consider the impact of greenhouse gases.

2.6 Duchin

There seems to be a brief hiatus in the publication of the applications of economic input-output models to the issues of environmental impacts in the 1980s. A co-worker of Leontief, Duchin looked at the conversion of waste products and residues into useful raw materials (Duchin, 1990)and followed this up with a paper which considered the flows of wastes through the economy using input-output modelling (Duchin, 1992). Although not directly concerned with the measurement of carbon footprints, the tracking of pollutants through the economy has relevance to the aim of measuring the impacts of those pollutants. This is part of an emerging concept of industrial ecology whereby the interdependent business sectors of an economy are seen as parts of an ecosystem with energy and resources being interchanged between them. The waste outputs of one process could become the inputs of another. Furthermore, the economic ecosystems interact with natural ecosystems by drawing upon natural resources. In natural ecosystems, the processes and agents have evolved over millennia and through the process of natural selection unsustainable ecosystems have been lost. However, there is the potential of the newer and rapidly evolving industrial ecosystems to out-compete natural ecosystems and ultimately force these into extinction. These issues can only be tackled by considering the whole system and not the individual processes within the system. So industrial ecology is both a philosophy – an intent to move towards sustainable use of resources by ensuring that they cycle through the economy, and also a framework for understanding how these cycles work.

Duchin also defines structural economics as "a detailed, disaggregated description of an entire economy in terms of its concrete and observable constituent parts and their interrelationships."(Duchin, 1992) The link back to Leontief's input-output tables is clear and includes the concept of material goods as well, ores and fossil fuels as inputs, and particulates and pollutants as outputs. Duchin notes three changes in the input-output world (Duchin, 1992):

1) Extension of the model beyond the financial transactions to include other measures such as on labour and environmental;
2) The use of dynamic models to analyse economies over time
3) The development of worldwide databases using inter-regional modelling.

Point 1 harks back to the work of Ayres and Kneese (1969; 1971) in acknowledging the importance of measures other than purely economic ones for assessing the progress of a country or even the world. Points 2 and 3 deal with the requirements for improved models to assess the quickly evolving technologies and the importance of understanding global issues like pollution using global data. A set of tools is evolving that would form a part of the next important motivation for estimating carbon footprints – the Kyoto Protocol and subsequent developments in global climate change policy.

2.7 1997 Kyoto Protocol

The increasing concern about rising levels of greenhouse gases and the impacts upon the atmosphere led to the formation in 1994 of the United Nations Framework Convention on Climate Change (UNFCC) following the “Rio Earth Summit” in 1992. The UNFCC introduced three principles: 1) that there was an issue with emissions of greenhouse gases; 2) that it was incumbent upon the world that greenhouse gas concentrations would be stabilized at a level that would prevent dangerous interference with climate and 3) that developed nations would have to lead the way, as they were responsible for past and current emissions (United Nations, 1992). The convention’ Article 7 established a “Conference of the Parties” (COP), which has taken place annually since 1995. The schedule of COP is in Table 6. This also includes Conference of Parties serving as the meeting of Parties to the Kyoto Protocol (CMP) and lastly Conference of Parties serving as the meeting of Parties to the Paris Agreement (CMA).2.7 1997 Kyoto Protocol

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Table 6 Schedule of Conference of the Parties UNFCC (adapted from (UNFCC, 2017)

COP no	Year	Location	Outcomes comments
COP 1	1995	Berlin	
COP 2	1996	Geneva	
COP 3	1997	Kyoto	Kyoto Protocol
COP4	1998	Buenos Aires	Buenos Aires plan of action to implement Kyoto Protocol
COP5	1999	Bonn, Germany	
COP6	2000	The Hague	Unable to conclude negotiations on Buenos Aires Plan
COP6-2	Jun 2001	Bonn	Negotiations on Buenos Aires Plan, USA rejects Kyoto Protocol
COP 7	2001	Marrakech	Marrakech Accords, IPCC AR3
COP 8	2002	New Delhi	
COP 9	2003	Milan	
COP 10	2004	Buenos Aires	
COP 11/CMP 1	2005	Montreal	First CMP and the date that the Kyoto protocol came into force. Montreal Action Plan
COP12/CMP 2	2006	Nairobi	
COP13/CMP 3	2007	Bali	IPCC AR 4
COP14/CMP 4	2008	Poznan	
COP15/CMP 5	Dec. 2009	Copenhagen	Another crisis moment preceded by meetings in Bonn, Bangkok, Barcelona

COP16/CMP 6	Nov-Dec 2010	Cancun	
COP17/CMP 7	Nov-Dec 2011	Durban	
COP 18/CMP8	2012	Doha	
COP 19/CMP 9	2013	Warsaw	IPCC AR5 "The Physical Science Basis"
COP20/CMP10	2014	Lima	IPCC AR5 remaining three reports including synthesis report
COP21/CMP11	2015	Paris	
COP22/CMP12/CMA1	2016	Marrakech	
COP23/CMP13/CMA1-2	2017	Bonn	

The first major guidance that emerged from UNFCCC was the Kyoto Protocol, adopted in 1997 and which was entered into force in 2005. Many countries realised the importance of the Kyoto Protocol and adopted it in advance of the final ratification. One of the requirements of the Kyoto Protocol is for Annex 1 Parties to the Kyoto Protocol to present national communications (NC) that report on GHG inventories and these reports are made as part of the COP/CMP. The Kyoto Procotol also includes commitments for countries to reduce their emissions, and the protocol intends generally that these should be implemented by measures in the country. However, it also allows for three market – based methods: 1) emissions trading, 2) the Clean Development Mechanism (CDM), and 3) Joint Implementation (JI). Emissions trading is straightforward in principal although more complicated in implementation. It allows countries to trade unused commitment period emissions with other countries who might not meet their commitment. The CDM allows for countries with commitments to reduce emissions to set up projects in developing world countries to reduce emissions. The emissions reductions brought about by these projects can then be used to offset emissions in the country sponsoring the project. Finally, JI allows two countries which both have emissions reductions commitments to set up joint projects to reduce emissions. These market based methods are intended to facilitate the transfer of technology and capital between countries that are party to the Kyoto Agreement and support an overall global reduction in associated emissions. The detailed procedures were developed and negotiated over COP4-7 and published at COP 7 in Marrakech in 2001 (See Table 6 above).

2.8 Marrakech Accords, 1st Commitment Period

The Marrakech (or Marrakesh) accords represent the first attempts to implement the measures of the Kyoto Protocol, and identified the first commitment period which began in 2008 and was intended to end in 2012. This ended the negotiation period related to the Buenos Aires Plan and allowed the Kyoto Protocol to be ratified and to come into force. This took place at COP11/CMP1, the first meeting of the parties to the Kyoto Protocol at Montreal in 2005. The first commitment period was marked by 37 countries and the EU27 member states agreeing to reduce their greenhouse gas emissions by an average of five percent from the measured 1990 levels.

2.9 Copenhagen COP 15 2009

The COP following Montreal were not marked by notable developments, although the Bali Action Plan (COP13) marked the beginning of the process of considering a second implementation period, to follow the first. COP15 in Copenhagen began to consider the possibility of implementing a comprehensive global climate change agreement to succeed the first implementation period of Kyoto. The COP was preceded by various rounds of talks in Bonn, Bangkok, and Barcelona. Unfortunately agreement could not be reached and although an accord was reached, it was generally felt that the COP had failed in its objectives (Falkner*, et al.*, 2010). At COP16 in Cancun, the headline was the announcement of a commitment of parties to restrict the level of warming to the IPCC recommendation of 2°C (Pachauri*, et al.*, 2007). In 2012, COP18 in Doha saw the adoption of a second implementation period of the Kyoto Protocol, which was considered critical as the first implementation period had reached its end. The second implementation period runs from 2013 to 2020 but only covered 15% of global emissions, as both USA and Canada had withdrawn from Kyoto, and other countries including Japan had not committed to emissions reductions. Unfortunately, the next COP's in 2013 and 2014 did not prove fruitful so the stage was set for COP 21 in Paris in 2015.

2.10 Paris Agreement

Possibly the most notable achievement of the UNFCCC has been the negotiation and ratification of the Paris Climate Agreement. This agreement was negotiated in 2015 and entered into force on the 16th November 2016 when 55 countries covering 55% of global emissions ratified the agreement. The UNFCCC have negotiated one of the most significant global climate change agreements that commits its signatories to achieving a temperature rise of less than 2°C, and aims for 1.5°C. It aims for a peak in emissions before 2020, and aims for net zero emissions by the second half of the 20th century. To reach these aims, a significant response will be required from the countries of the world. Both China and USA ratified together on 3 September 2016, with the UK ratifying on 18 November 2016. The impact of President Trump's announcement that the USA will withdraw in

2019 has yet to be analysed (BBC News, 2017). Initial speculation has been mixed with some arguing that the US withdrawal may galvanise other countries to act together, and counteract the effects while others argue it is a significant setback in tackling global climate change and may result in the imposition of carbon tariffs on US imports as sanctioning instrument to coerce the US into compliance. (Betsil, 2017; Bohringer and Rutherford, 2017). Notwithstanding the recent US withdrawal, a global commitment to tackle the issues of climate change has now come into force. Next, we consider the response of business to climate change.

2.11 The response of Business to Climate change

In response to growing political, investor, and NGO pressure coupled with increasing scientific consensus regarding the factors influencing the rate, and pace, of climate change (and associated global warming), many organisations and institutions (corporate, public and not for profit) have started, and/or are being required, to consider their contribution to, role in, and responsibility for, reducing the type, and amount of harmful GHG emissions coming from their organisations, institutions and associated supply chains (Kolk and Pinkse, 2005; Kolk*, et al.*, 2008; Schaltegger and Burritt, 2014). While traditionally debates on climate change have been dominated by scientists, economists, corporate interests and environmentalists, very recent research (and wider socio-political discourse) has identified the need for a wider interdisciplinary evidence base that actively investigates organisational innovation and institutional change (in the face of climate change) and which prioritises measuring the impact of climate change mitigation policies and initiatives on emission reduction and financial performance (Kolk*, et al.*, 2008; Doda*, et al.*, 2015). As such, climate change is increasingly being viewed, by multiple stakeholders, as not only an environmental problem requiring technological and managerial solutions. Increasingly it is being viewed as an institutional, economic, social, cultural and political challenge which requires radical and fundamental shifts in socio-political structures, technological and economic systems, organisations forms and modes of organising (Wittneben*, et al.*, 2009) and urgently requires a universally agreed and globally applied regime of action, reporting and verification (Kolk*, et al.*, 2008; Finkbeiner, 2009; Wright*, et al.*, 2011).

At the centre of organisational responses to climate change have been the development of, and organisational engagement with, globally signed and politically driven protocols such as Kyoto and the Paris Agreement and associated carbon reporting and emission trading schemes such as the Carbon Disclosure Project (CDP), the EU Emissions Trading Scheme (EU-ETS), World Business Council for Sustainable Development (WBCSD)/World Resources Institute (WRI) – GHG Protocol and the ISO 14064 International Standard Framework methodology for the reporting of organisational GHG emissions. Central to these developments have been: 1) the widespread acceptance of carbon emissions, for the time being, as the globally recognised measurement for reporting organisational and institutional GHGs and; 2) the resulting commodification of carbon through the establishment of politically agreed, and institutionally applied, rules, infrastructure and verification programmes that cross both national boundaries and different carbon jurisdictions (Kolk et al., 2008). As participation in these reporting, and trading, initiatives has grown, and the associated benefits are starting to be slowly recognised and even accrued (especially in the case of emissions trading), a growing minority of businesses are beginning to view, and frame, climate change more positively as an opportunity rather than a burden and financial risk (Kolk and Pinkse, 2005; Kolk*, et al.*, 2008).

Central to managing these risks or opportunities (depending on your viewpoint) is how we measure carbon emissions. This can be considered in the context of three domains. Firstly, and perhaps the most resourced, is the measurement by scientists of budgets or flows of carbon, typically by using experimental methods, and subject to the constraints of the scientific method. These imply defining the "thing" to be measured quite carefully and deploying appropriate scientific techniques to measure it. From these measurements, we can obtain estimates of, for example, the total carbon in the atmosphere, or the flux of carbon between ecosystems e.g. ocean and atmosphere. While such measures (and associated methods of measurement) are often contested as per normal scientific practices, regional and/or globally consensus has begun to emerge as to the amounts of CO2 emitted globally. At a regional level, this emerging consensus is visible in the work, and impact, of EDGAR, the Emissions Database for Global Atmospheric Research. A Joint Research Centre funded through the EU Research Framework programme (to which all EU27 members states contribute), EDGAR provides global past and present day anthropogenic emissions of greenhouse gases and air pollutants by country and on spatial grids providing a comparable evidence base upon which EU policy and decision making can be made (EDGAR, 2017). At a global level, the work of the Independent Panel on Climate Change (IPCC), a global body with representation from 195 countries, has produced globally agreed, and applied, assessments which provide a scientific basis for governments at all levels to develop climate related policies, and which underlie negotiations at the UN Climate Conference – the United Nations Framework Convention on Climate Change (UNFCCC). The challenge is that while the work of organisations like EDGAR and the IPCC are conducted at the supra national or global or ecosystem scale, it is often very difficult for non-scientific stakeholders to understand and translate resulting measurements such that they can appreciate, and respond to, what they may mean for their organisational and/or personal practices. In response, sectorial and organisational level methods have emerged that draw on these scientific measure but which are designed help non-scientific stakeholders make better, and more practical, sense of GHG emissions within, and between, economies (and associated sectors) and within specific organisations. Generally referred to as Lifecycle Analysis (LCA), two distinct methods have developed namely Environmental Input-Output analysis (EIOA) and Process Based Lifecycle Analysis (PBLCA). While EIOA focuses on sectorial and national level analysis of carbon emissions within, and between, sectors of one or multiple economies, PBLCA is designed to facilitate organisational level measurement of carbon emissions for specific products, processes or supply chains (Wiedmann and Minx, 2007). Interesting, recent academic research has strongly advocated for the application of a combination of PBLCA and EIOA known as Hybrid EIO-LCA methods for the measurement of carbon emissions where PBLCA is conducted for specific processes known to be embedded within already calculated EIOA (Wright, et al., 2014).

The second type of measurement is that undertaken by nation states and reported to the UNFCCC annually as National Inventory Reports (NIR), a requirement of the Kyoto Protocol. A great deal of care is taken over these measurements as they form the evidence for how countries are assessed against global agreements like Kyoto and form a useful validation of the total emissions to for example the atmosphere. As discussed in the introduction, owing to the increased globalisation of trade, these measures may not fully reflect a nation's impact on the global emissions as it makes no account for emissions embedded in imports or exports.

The third type of measurement is located firmly at the organisational level, is generally associated with accounting measures and commonly referred to as Carbon Accounting (Stechemesser and Guenther, 2012). This term appears to reflect the primary focus, which is on accounting for liabilities, fossil fuel reserves that might be stranded, liabilities or credits under emissions trading schemes, potential impacts of carbon taxes. To date, these measurements have been made in both financial and physical terms with both being viewed as legitimate measures that can be used for, and absorbed into, strategic decision making processes perhaps leading to a sense that organisations are managing a problem (their carbon emissions), responding sensibly, and accurately, about their carbon emissions, absorbing their emissions into their social licence to operate and as such do not require further state intervention into, or regulation of, their carbon emissions (Kolk et al., 2008; Stechmesser et al., 2012; Schalteger & Burnitt, 2014). In many cases both financial and environmental impacts may be aligned, as efficiencies acquired through reducing carbon emissions almost always result in cost reductions accrued from the associated process based improvements made (Kolk and Pinkse, 2005; Kolk et al., 2008).

In addition to the methods of measurement discussed above, there is emerging evidence as to how organisations are responding to political, investor, environmental NGO and wider societal pressure to make their supply chains more sustainable, and in particular reduce carbon emissions from their products, processes and supply chains (Kolk et al, 2008). In their seminal article, Kolk and Pinske (2005) discuss 6 ways in which organisations appear to be configuring themselves in the face of growing socio-political and investor pressure around climate change, and the emergence of a number of key NGO led carbon disclosure and reporting initiatives such as the Carbon Disclosure project (CDP). Table 7 outlines Kolk & Pinkse (2005) six corporate climate change configurations.

Table 7 Six Corporate Climate Change Configurations adapted from Kolk & Pinkse (2005)

Configuration Type	Proportion of organisations	Description of organisational response
Cautious Planners	31%	Organisations are preparing for action and expecting that they will be required to make GHG reductions in the future. Led by government regulation and not taking action voluntarily.
Emergent Planners	36%	Organisations have begun to set processes in motion, starting with setting energy consumption targets. No reductions yet achieved.
Internal Explorers	14%	Organisations have a strong internal focus setting a combination of targets, implementing improvement initiatives and measuring progress against these. Starting with low hanging fruit such as energy consumption and business travel.
Vertical Explorers	10%	Organisations are moving from an internal to a supply chain focus. Developing initiatives, setting targets and gathering data to measure performance of supply chain participants.
Horizontal Explorers	5%	Organisations are focus on, and open to opportunities in markets outside those of their core business and to collaborations with both expected and unexpected partners.
Emissions Trader	4%	Organisations are focus on, and participating emissions trading and carbon offset projects

As illustrated, some organisations are moving from a position of opposing and slowing action on climate change to recognising the potential organisational benefits of becoming better corporate citizens. No longer are such organisations only preoccupied with the risks posed to them by climate change and in particular how much climate change will cost them, instead many are exploring, and seeking out, the market, investor, business and wider societal opportunities offered by the challenges, and the associated responses (and initiatives), to climate change. Some are even starting to innovate, and adapt their organisational structures and practices in terms of processes, products, markets, human resources and managerial decision making (Kolk and Pinkse, 2005; Okereke, 2007; Kolk*, et al.*, 2008; Schaltegger and Burritt, 2014; Doda*, et al.*, 2015). Environmental NGO's, whose stated mission is to support businesses to measure, report and mitigate carbon emission, have sprung up to support these endeavours. These include the World Business Council on Sustainable development (WBCSD), World Resources Institute (WRI), Carbon Disclosure Project (CDP), and UK-based Carbon Trust. ISO Standards are developing, and voluntary reporting according to Greenhouse Gas Protocol guidelines has become a standard part of the annual reporting system of the world's largest companies with the vast majority of the FT500 companies making partial or full disclosures to the CDP (Kolk*, et al.*, 2008; Doda*, et al.*, 2015). The message to policy makers and governments from business appears clear - *there no need to regulate, business is on board, we recognise our responsibilities and we are doing all we can to clean up our operations and incidentally solve the world's issues as well.* But is everything how it seems. Evidence from a number of recent studies has shone a critical light on the quality of reported data and value of, and progress being made through, voluntary carbon reporting initiatives. Both Kolk, *et al.,* (2008) and Doda, *et al.,* (2015) question the quality, consistency, and comparability of data reported to the CDP and argue that there is little compelling evidence that participation in CDP is having any material impact on reducing emissions for participating firms. Doda, *et al.,* (2015) goes as far as to argue that many of the reported carbon management practices developed are not sufficiently impact oriented and as such it is very difficult to observe any relationship between changes in organisational processes and practice and organisational emissions. They call for greater attention to be placed on measuring the impact of carbon management practices rather than only reporting their existence, which currently happens, and accepting the associated leap of faith made by organisations, policymakers, investors and the wider public that such practices must inevitably lead to better GHG emissions outcomes (Doda*, et al.*, 2015).

Since the term Carbon Foot-printing was first coined in the late 1990s by, its use has primarily been driven by non-academic and scientific stakeholders such as the media, government, industry and NGOs, with academia only recently adopting the term, recognising the limits of their traditional focus on LCA and moving towards a more holistic, interdisciplinary methods and understandings of how organisations could and should response to climate change.

To achieve this, global political, corporate and social consensus is urgently required in respect to: 1. GHG Selection; 2. Reporting metrics; 3. Agreed Methods; 4. System boundaries and scope (including who is responsible for the production, and associated reduction, of GHGs in complex, global supply chains) (Wright et al., 2014).

2.12 Conclusion

A technique that has its origins in the eighteenth century has been developed and expanded by several generations of economists since Leontief's initial formulations, and Stone's vital contribution to the gathering of National Accounts data. The use of input-output analysis has been extended to social impacts and since the early 1970's to the analysis of environmental impacts.

The issue of anthropogenic climate change has driven global policy through a series of agreements that impact on businesses amongst other stakeholders. The response of business to climate change has been discussed, and opens the possibility of new applications for EEIO. The generation of models that have been developed to address these issues, and the development of a new model for carbon foot-printing are discussed in the next chapter.

Chapter 3 Theoretical basis

3.1 Introduction

This chapter documents the implementation of a new EEIO model which is based upon the latest data from the ONS. Firstly, some key EEIO models are described and then the sources of data for the model are considered, along with an introduction to the basics of national accounts, and the assumptions of the model. The development is split into four stages, firstly the derivation of the financial model, secondly the emissions part of the model and then the adjustment for the financial period that is to be analysed. These parts are common to all the EEIO models using this framework. The fourth section is the company specific section, where the mapping process from the organisations purchases to the national accounts sectors is described. The final part of the chapter discusses how the data for the model has changed over the three years of the project and the impacts this has had on building the model each year. The contribution of earlier researchers to the development of Carbon Footprinting is explored in the next sections.

3.2. Introduction to Carbon Footprinting

In response to the issues of climate change, and accepting the challenges set to businesses by the Kyoto Protocol, a number of EEIO models have harnessed the growth of data, and the increase in computing power to provide analysis of carbon flows. Whilst still using the structure originally envisaged by Leontief, they are used to inform policy by considering how globalisation has affected carbon and other environmental impacts.

3.2.1 Wyckoff & Roop

Amongst the first to realise the potential of Multi-regional IO modelling were the OECD on whose behalf Wyckoff and Roop (1994) considered the impact of international trade on the amounts of embedded carbon in imported and exported goods. The concept of embodied carbon was that as products are exported to another country they have already caused the emission of greenhouse gases in the country of production. These greenhouse gas emissions are described as embodied in the products. A measure of the GHG emitted in subsequent operations on those products before being used up in final consumption therefore misses an important part of the emissions associated with those goods produced using imported materials. Wyckoff and Roop (1984) investigated this issue and drew the conclusion that for 6 of the OECD countries including the UK, about 13% of the total carbon emissions of these countries were embodied in imports.

3.2.2 Lenzen

Another innovator stimulated by the Kyoto Protocol and the issue of embodied carbon is Lenzen who has made major contributions to the field of environmentally extended input modelling. This began with a 1998 analysis of energy and greenhouse gases attributable to Australian final consumption (Lenzen, 1998). This is notable for a clear exposition of the model involved and the incorporation of gross fixed capital expenditures into the model. This follows the spirit of Adam Smith's assertion that "consumption is the sole end and purpose of all production" (Smith, 1776)and recognises that capital goods are an input to production as much as the intermediate demand for goods in the production process. Finally the flow of energy in the model is measured in units of energy rather than in financial terms which better allows for the representation of different pricing policies for different consumers of energy e.g. larger consumers drive a better bargain and thereby enjoy lower prices per unit, (Lenzen, 1998).

In his 2001 analysis, he expanded on the notation for IO models, the use of energy multipliers and incorporates a Monte-Carlo analysis of the uncertainty in the emissions multipliers derived from EEIO modelling(Lenzen, 2001b). This consideration of errors builds on his critique of Process Based Life cycle analyses and those based on EEIO modelling in 2000 (Lenzen, 2000; Lenzen and Dey, 2000) which by considering the stages missed by PBLCA estimates the "truncation error" that results from the incompleteness of this method. The truncation error is the total of emissions that arise from processes that are not considered in PBLCA because they seem insignificant when considering system boundaries of a particular product.

Lenzen's other substantial contribution to the field of environmental input-output modelling is the realisation that the Domestic Technology Assumption (DTA) that underlies single region models may considerably underestimate the impacts of consumption in developed economies. He makes substantial contributions along with Wiedmann to the development of multi-regional input-output models (MRIO) that allow a fuller understanding of the environmental impacts of international trade. He was heavily involved in the development of methods for balancing these types of models (Lenzen*, et al.*, 2009)and the implementation of the EORA database for worldwide MRIO that forms a principal resource for this type of modelling and is considered further in chapter 5 of this thesis (Lenzen*, et al.*, 2012; Lenzen*, et al.*, 2013). This is combined with an extension of the multipliers to other aspects of environmental impacts including land-use, water use and bio-diversity.

3.3 Carbon Footprints

There is a reasonably long history of using Ecological Footprint methods to inform local and regional government policymakers, and consumers, of the sustainability impact that their consumption decisions can have. The idea of an Ecological Footprint was invented originally by Wackernagel and Rees (1996), and aimed to communicate the sustainability impacts of, for example, a community, in terms of the land that is required to accommodate the various requirements of the community. It is a concept that seems readily communicable to a wide variety of stakeholders. An early use of the idea of footprints for demonstrating ecological impacts is the study by Barrett & Scott (2001) who consider an ecological footprint of Liverpool. A more sophisticated analysis carried out for the Welsh Assembly, assessing the Ecological Footprint of Wales (Barrett*, et al.*, 2005), shows the power of the approach. That study describes the concept of Consumption Based Accounting (CBA), which is an accounting process to inform those who purchase goods and services of the impact of those services.

Wiedmann, et al., (2006) combine the use of Wackernagel's ecological footprint (Wackernagel and Rees, 1996) with input-output modelling to look at the impact of household consumption in the UK. Wiedmann and Minx (2007) narrow the range of impacts considered to that of GHGs and so come with a definition of Carbon Footprint as a measure of the total amount of CO_2 emissions directly and indirectly caused by an activity or accumulated over the life of a product. They define a Climate Footprint as the amount of GHGs directly and indirectly emitted, and it is this latter definition that is commonly used now. They note two approaches to the problem, bottom up (Process Based Lifecycle Analysis PBLCA), and top down, which involves the use of Input-Output Modelling. A later study by Wiedmann, *et al.,* (2008) constructs a time-series for the UK to calculate the environmental impacts of trade. It is a Multi-Regional Input-Output (MRIO) model and combines data from the Global Trade Analysis Project (GTAP) with UK Office of National Statistics. It is notable in also including a sensitivity analysis. This UK analysis is updated by Wiedmann, *et al.,* (Wiedmann*, et al.*, 2010) to consider the time series 1992 to 2004. The strength of time-series data in showing trends is one of the motivations for constructing a time-series model that can be used in conjunction with UK companies and is outlined from section 3.5 onwards.

"Consumer demand is the central cause of all factor use and environmental pollutants; both directly and indirectly." (Peters and Hertwich, 2004)

Developing the work of Lenzen (1998; 2001a; 2002; 2004) and Wyckoff and Roop (1994) , Peters and Hertwich (2004; 2006a; b; 2008; 2008) consider the questions of the emissions required to sustain final demand in a region, focussing particularly on Norway and extending their analysis to cover international trade. The 1997 Kyoto Protocol had introduced the concept of production emissions and these were what countries were required to report in their Climate Action Plan (CAP).

Production emissions are those emitted by production units within the boundaries of a country and although difficult to measure directly, it is easy to define the system boundary. This method of accounting for emissions may be unfair in that businesses in developed countries frequently have subsidiaries and suppliers in different countries that supply carbon intensive part-finished goods, with relatively low intensity assembly operations taking place in the developed country. To counter this unfairness, it is possible to define another measure that is related to production emissions and termed residency or resident emissions. This being the measure of emissions produced within a country but excluding those emissions for which foreign based entities are responsible and including emissions from domestically owned entities based abroad. Peters and Hertwich (2006b) recognised that a developed economy's responsibility might extend wider than this particularly if it is reliant upon goods and services imported to meet the requirements of final demand particularly those of household final consumption. They are involved in the definition of consumption based emissions which attempts to measure those emissions and requires more data and more sophisticated models to account for the emissions embodied in trade. They describe a model that eschews the domestic technology assumption and considers inter-regional trade and then proposes some simplifications to reduce the burden of data that needs to be gathered to operationalise the model (Peters and Hertwich, 2004). This model is then used to analyse the impact of Norway considering their international trade (Peters and Hertwich, 2006a)

Lenzen had also begun to consider the implications of international trade (Lenzen, 1998; Lenzen*, et al.*, 2004) both in the context of the Australian Economy and also in conjunction with and developing from Munksgaard and Pedersen (Munksgaard and Pedersen, 2001). The subject of multi-regional input-output models is considered in section 3.4.2. The essential development behind the MRIO models is to take into account the trading relationships between regions and allow also for the differing production structures of those countries. With the methodology of SNA being widely applied by national accounts bureaux and increasing international standardisation of classification of industries and products, the construction of models that are representative of different regions but comparable by industry and product sector is possible. This allows for the emissions embodied in trade to be captured for any region of interest and hence allows an estimate of the total footprint of consumption for any of the regions.

3.3.1 Application to estimating the footprint of organisations

Since Elkington (1999) in his memorably titled "Cannibals with Forks" introduced the concept of the triple bottom line, the idea of measuring the environmental impacts of a company and reporting on them, along with social and economic ones, there has been a move towards systematically estimating those impacts of organisations. Much of this work has been based around process based analysis, and the analysis of direct (Scope 1) and indirect (from the supply of electricity, heat or steam, Scope 2) emissions. These emissions are under the control of an organisation, and the measurement of them is conceptually quite easy. For other indirect emissions (Scope 3) the link between financial transactions and impacts that is delivered by EEIO means that there is a role for this technique to be used. The applications of this methodology allow the upstream and direct emissions of an organisation to be estimated. If transportation to customer, in-use and end of life disposal emissions can be estimated then a broad picture can be built up of an organisation's impact.

Wiedmann, *et al.,* (2009)consider the application of EEIO to a small UK company. This provides an early example of the ideas presented in this thesis but differs from it in a number of ways. The national accounts data used are from the UK economy but date from 2000, whereas the model described in this thesis uses the latest account figures. A very broad range of impacts is presented including social accounting measures such as employment, and a very broad range of environmental indicators. This demonstrates the versatility of the input-output approach but the model described in this thesis considers GHG impacts only. The impact of different layers of the supply chain is estimated using Structural Path Analysis (SPA) and the extension of this technique to incorporating supplier provided data is discussed later in this thesis. The analysis is carried out over 76 economic sectors whereas the model described here uses either 110 or 106 sectors depending on implementation date. Some of the weaknesses of using the EEIO technique are discussed e.g. the aggregation of the data inherent to input-output analysis which does not allow product specific foot-printing for example. This model along with the model described in the next section represent the beginning of the use of EEIO with organisations.

3.4 Key EEIO Models and applications to Carbon Footprinting

3.3.2 Berners-Lee et al

Berners-Lee used the technique of EEIO to describe a model that can be applied to small businesses(Berners-Lee*, et al.*, 2011). This combines the use of EEIO with direct emissions data to formulate a hybrid model that can be used to make an estimate of supply chain emissions for a small business and describes the application of the model to a tourism business in the Lake District.

The model is constructed from ONS 2007 figures using a 123 sector representation of the economy and emissions data that is based around a 93 sector model. The model includes Gross Fixed Capital Formation (GFCF) which aligned it with Lenzen's models in the assumption that all production is for consumption. As the economic data were prior to the period in which the model is used, the model is adjusted by using Consumer Price Index (CPI) to deflate the emissions intensities to current prices.

The use of the model gives some insight into how this particular business has an impact on carbon emissions through its purchasing practices and allows for advice to be provided that allow the organisation to effect change. As a one-off exercise, this is of interest but it is the application of the technique over a range of years where greater knowledge can be garnered. In this scenario, the impact of changes can be seen, and also the impact of changes in technology. This requires the model to be updated to include the latest developments in the economy and to be easily updateable to include future changes. Although MRIO data are not used to construct models in this project, a brief overview of the MRIO data is included in the next section.

3.4.1 Introduction

A number of EEIO models have harnessed the growth of data, and the increase in computing power. Whilst still using the structure originally envisaged by Leontief, they include data from international trade. As noted in section 3.2, one of the earliest to use this concept are Wyckoff & Roop (1994) who constructed a 6 region MRIO to estimate the quantities of embodied emissions in imported manufactured products. Their model assumes only bilateral trade.

3.4.2 Data for MRIO

As noted above in section 3.2.2, the development of the System for National Accounting SNA by the United Nations (1953; 1968; 1993; 2008), the data for this type of calculation exist across nations but in general is in a fairly fractured format. Classification systems vary between nations as do the underlying prices used to calculate the transactions. There are issues not only of currency transactions, but also border tariffs. Finally, the issue that of attributing quantities of imports to the different sectors of an economy is challenging as it is usually only the total imports of a commodity that are known, not how they are consumed. This approach (MRIO) does require data collection on a daunting scale but several bodies have collated data and produced MRIO models.

3.4.2.1 Organisation for Economic Co-operation and Development (OECD)

This is an organisation of 34 countries encompassing many of the nations of Northern Europe, Northern America, some of the Pacific States and some South American states (membership at Appendix D). they encompass a number of the developed world's economies and have been gathering data since the formation in 1961. As the name suggests economic co-operation includes data gathering and as a result the OECD is a good position to provide data on its constituent economies. They have some data on non-OECD countries expanding the coverage to 51 countries reporting for the years 1995 to 2011 in a classification based upon ISIC revision 3 and covering 34 industry sectors (OECD, 2015).

3.4.2.2 Global Trade Analysis Programme (GTAP)

This is a research institute based at Purdue University, Indiana and has an extensive database of economic and environmental data that have been gathered since 1993. In addition to data they have developed a model that is intended to link with the data. The model is implemented as a Computable General Equilibrium (CGE) model and covers 113 regions and 57 commodities. The emphasis of the database is on agricultural commodities with 14 of the 57 sectors being agricultural. The data has been used in a UK context by Wiedmann, *et al.,* (Wiedmann*, et al.*, 2008; Wiedmann*, et al.*, 2010) combined with UK ONS data as described above. The data of GTAP has been organised into a MRIO system by Peters, *et al.,* (2011)

3.4.2.3 Exiobase

EXIOBASE is wide ranging database that began life as a European Union funded project to develop an MRIO dataset (Tukker*, et al.*, 2013). It covers 43 countries and 5 Rest of the World Regions. It covers two years 2000 and 2007, so requires the interpolation of data for results between those years. It includes 129 product sectors, and a wide range of environmental impacts data, including Global Warming Potential, the impact that relates to carbon footprinting.

3.4.2.4 WIOD

Timmer, *et al.,* (2015) document this dataset that is designed from the outset to include a time series from 2000 to 2014. Country coverage is reasonably extensive as it covers 40 countries as well as the expected ROW region in 56 sectors. A range of satellite accounts are included that include socio-economic measures, but the dataset is hampered for carbon foot-printing by only having CO_2 emissions available for its 2013 edition, which in turn offers a time-series from 1995 to 2009.

WorldMRIO and EORA

The biggest EEIO database which combines sophisticated algorithms and large datasets to construct a comprehensive, extensive MRIO model of the world with 187 countries covered at a resolution of between 50 and 200 sectors per region (Lenzen*, et al.*, 2012; Lenzen*, et al.*, 2013). This level of sophistication comes at the expense of requiring powerful computers to derive the models. The results are available both in full, and in an aggregated classification and present the most complete and up to date analysis of world trade, and the multiple environmental impacts of that trade. It also includes a statistical analysis on the reliability of the results.

3.4.3 Application of MRIO Data in Footprint estimates

The data collected and analysed by the projects above is available for use by academia, and on payment of a licensing fee for use in commercial applications. However, the modelling process is more complicated than that of a single region model. It requires considerable computing power and efficient implementation as the matrices being manipulated are larger and there are a number of balancing procedures. This means that the financial and emissions parts of the modelling require a skilled team and access to powerful computers. However, for those without such resources it is still possible to use the results of the modelling by using the vector of emissions intensities in place of the one derived in the single region model. This would involve adjusting the emissions intensity to match the financial period of purchasing data, and mapping from purchase categories to the classification used by the MRIO. The GTAP data is slanted towards agricultural commodities having only 43 sectors for the other sectors of the economy and the OECD data is limited to 34 industry sectors. This limited resolution restricts the specificity of the mapping and there may not be the option to form hybrid sectors as described in chapter 5. WIOD as noted, has a limited range of environmental impacts, and quite low country and sector resolution. The WorldMRIO dataset offers a similar resolution to the UK single region model and is more current than the other two. As a result, it would seem to fit better with the intent in this thesis to assess the GHG impact of company supply chains.

However, we still have the issue that the impact of company spending will still be calculated as if it were UK final demand. The other issue is that the model is not transparent to the user of the data. One of the benefits of a simpler, single region UK model is that is possible to understand the interplay between the sectors of the economy, and how that impacts on emissions intensity. In the next section, we consider the development of a single region model based upon ONS data.

3.5 Single Region Model of the UK

The following section discusses the development of an EEIO model based upon the ONS produced National Accounts for the United Kingdom. Although lacking the sophistication of the MRIO, the model has the merits of being relatively simple to understand with all elements of the model being based upon high quality information derived by ONS. The challenges of partial information about imports and exports in MRIO and the concomitant balancing problem that is involved in constructing these models and which can lead to variances between models as will be discussed later, in Chapter 6 is avoided. It is also possible to construct a model from accounts data that is only 2 years old, whereas most of the MRIO not only require balancing between regional account but also adjustment by year. However, it is acknowledged that an advantage of MRIO is the ability to understand the spatial distribution of emissions and this can be more relevant at national level. The model constructed here is intended to provide data for a company – admittedly a large transnational company but incorporated in the UK.

3.6 National Accounts

As has been noted in section 2.4, the United Kingdom was involved in the genesis of national accounts and has continued to produce accounts since that point, although the methods and data used have evolved. Initially the responsibility for National Accounts lay with the Central Statistical Office, but this was merged in 1996 with the Office of Population Censuses and Surveys to form the Office of National Statistics (ONS). The ONS is part of a government independent body – the United Kingdom Statistics Authority (UKSA), and is the current producer of UK national accounts. The national accounts are documented in the "Blue Book" which in its full format is a comprehensive report on the national accounts of a financial year. Quarterly summaries are also published. The key data for constructing EEIO are the supply and use tables which are released in the form of an Excel spreadsheet at the end of October each year and for which the latest data is the financial year 2 years previous, i.e. the October 2015 edition contains supply and use tables up to and including 2013. The precise details of the supply and use tables will be discussed in the construction of the financial model later in section 3.8 of this chapter but first we need to highlight some important assumptions.

3.6.1 Principals of National Accounting

In order for the national accounts to be of use with input-output models, some key assumptions about them are made and these are discussed in the following paragraphs and summarised from the United Stated Bureau of Economic Analysis (BEA) guidance on their Input-Output Models (Horowitz and Planting, 2009).

Principle of Homogeneity

This is the idea that each industry sector's output is produced using a unique set of inputs, i.e. each has a unique production function, and that the inputs is the same for all the various business units in that sector. In practice, because of aggregation each sector produces a variety of outputs and as a consequence requires a variety of inputs, so this is an assumption that can never be completely fulfilled but the objective is to be as close to homogeneity as possible.

Principle of Proportionality

This is the assumption that if demand for a particular good or service increases or decreases then the inputs required for production increase or decrease in proportion. This is a reasonable assumption for small changes in demand as there would be little incentive to change the technology of a given sector. If there is a large change in demand this may mean that the technology used to produce the good or service changes, and so the inputs may change their relative production proportions. If this assumption holds then the model can be used to estimate the impacts of small changes in final demand on intermediate consumption.

Principle of consistency

This is the assumption that the information can be presented under a common classification system which aligns with underlying source data and the national accounts. This allows the easy comparison of industries and commodities within an economy and also the comparison of industries and commodities between periods. One of the difficulties in doing Multi-Regional Input-Output (MRIO) is that the classifications used by nations may differ. There have been attempts to address this issue by using international classification standards such as the International Standard on Industrial Classification of All Economic Activities (ISIC). If this assumption does not hold then conclusions drawn from data classified differently depend partly on how the classification differences are resolved.

The production of the national accounts is important for the management of most developed economies and allows for the analysis of policy decisions as well as providing the statistics by which may countries judge their performance, for example Gross National Product. The discussion of how the national accounts are derived is covered in the next section.

3.6.2 Composition of national accounts

The main use of the national accounts is to estimate the National Income which is of interest both to the government and business, and to a lesser extent the general public. The national income or GDP (slightly different expressions of a similar concept) are interpreted as a proxy for the performance of the nation, with GDP growth being associated with the nation growing wealthier, and the converse suggesting that in some sense the nation is becoming poorer. In general GDP or national income can be estimated in three different ways:

1) The production approach GDP(P), which uses the measure of Gross Value Added (GVA), estimated by the output of goods and services less the intermediate consumption required to produce those goods and services. This estimates the value of the goods produced but avoids over-counting by only adding on the amount of value added. In a product context this can be illustrated by, for example a computer which might comprise £100 worth of electronic parts and require plastic parts (for example a case) costing £50 to assemble, which is then sold to final demand for £200. The Gross Value Added is £50, which is the difference between sale price and the costs of the components. This can be calculated at the industry sector level and is valued at basic prices i.e. with no taxes or subsidies and excluding

distributor's margins. This can be used to estimate GDP (P) at market prices by aggregating the GVA for all sectors, and adding taxes on products and subtracting subsidies on products (Lee, 2011).

2) The expenditure approach GDP (E), which uses the final expenditures in the UK, has several components of which the principal is household final consumption. Other components include: Non-Profit Institutions Serving Households (NPISH); and central and local government final consumption expenditure. There are a range of compnents grouped under Gross Capital Formation (GCF) which includes the expenditure by businesses on goods that last longer than one year, Gross Fixed Capital Formation (GFCF); and expenditure on valuables, which covers goods acquired that have value as a function of their rarity, e.g. works of art. The final part of GCF is changes in inventories, which gives a measure of how stocks for production have changed over the accounting period. The last element of final demand is net exports, that is exports less imports, with the emphasis thereby being on what is spent on domestic production. This is an independent estimate of GDP that does not rely on calculating the GVA (Lee, 2011).
3) The income approach GDP(I), which attempts to estimate GDP by measuring the income of workers, i.e. wages, businesses (profits and rental income), and the income of the self-employed which includes profits taken and also wages (Lee, 2011).

In a balanced economy, these three measures should match: the income should match the expenditure, which in turn should match the value of the goods and services produced. The GDP is commonly mentioned in headlines on the economy, and in general growth in GDP is associated with increasing national wealth (Lee, 2011). In the UK, GDP is one of the most common statistics relied upon. There are slightly different measures which revolve around the terms "National" and "Domestic" and "Net" and "Gross." National includes the output of UK-owned businesses and UK nationals abroad whilst Domestic product/income includes only UK-based businesses and citizens. The distinction between "Net" and "Gross" is that "Gross" implies the inclusion of capital expenditures, that is expenditures on goods that have a useful lifetime longer than the accounting period. Having discussed the components of the national accounts we need to consider how such accounts might be constructed.

Each of the approaches are estimated using different datasets which in principle means that the accounts can be cross-checked. Taking the income approach first, the UK government has an interest in understanding incomes as it from these that a part of government income is determined namely the collection of personal and corporate taxes. In the UK these statistics are collected by Her

Majesty's Revenue and Customs (HMRC). This data then can be used to from an estimate of the income of individuals and business units operating within the UK.

HMRC are also responsible for Value Added Taxes which in the UK are charged upon a wide variety of goods and services. As a result, there are statistics on products that have been sold for final consumption and these can be aggregated to produce an estimate of the expenditure of the nation on goods and services. Finally, HMRC are responsible for imposing import and export tariffs and so have data that relates to these movements of goods and services. It can be seen that with some detailed calculations an estimate of expenditure (approach 2) can be derived.

The first approach, listed above, was that of estimating GDP(I) by calculating the Gross Value Added and this is perhaps the most challenging to estimate. The data for this approach are largely obtained by survey and extrapolation. For example, parts of the data are derived from a survey of the sales and purchases of industries within the economy known as the monthly business survey. This is based upon information submitted by a sample of approximately 30,000 businesses in the production and services sectors (Office of National Statistics, 2012). The sample is drawn from the approximately 2.1 million businesses that are registered on the Inter-Departmental Business Register (IDBR). This data feeds into the Index of Production (IoP) and Index of Services (IoS) which then is combined with data from Retail, Construction and Financial sectors to build the picture of inter-industry transactions. The data are presented in the form of input-output tables which, as the name implies, show both the destination of goods produced by an industrial sector (the output) but also the production requirements for that industrial sector (the input). The reason for the generic nature of EEIO becomes apparent, as the model is based around industry sectors that are producing similar but not identical products. Currently in the UK the economy is divided into 106 industry sectors, but in previous publications of the national accounts there have been 110 industry sectors(ONS, 2012a), and 123 sectors(ONS, 2007). The ONS publishes data on the industries represented in the UK, and other statistical bureaux produce data on the industries that are applicable within the boundaries of their region. In order to allow cross-comparison between countries a common standard of classification is important. Most EU bureaux use NACE (**N**omenclature statistique des **A**ctivités économiques dans la **C**ommunauté **E**uropéenne) codes to classify economic activities such as industry and products. This standard is in turn derived from the UN classification ISIC (International Standard Industrial Classification).

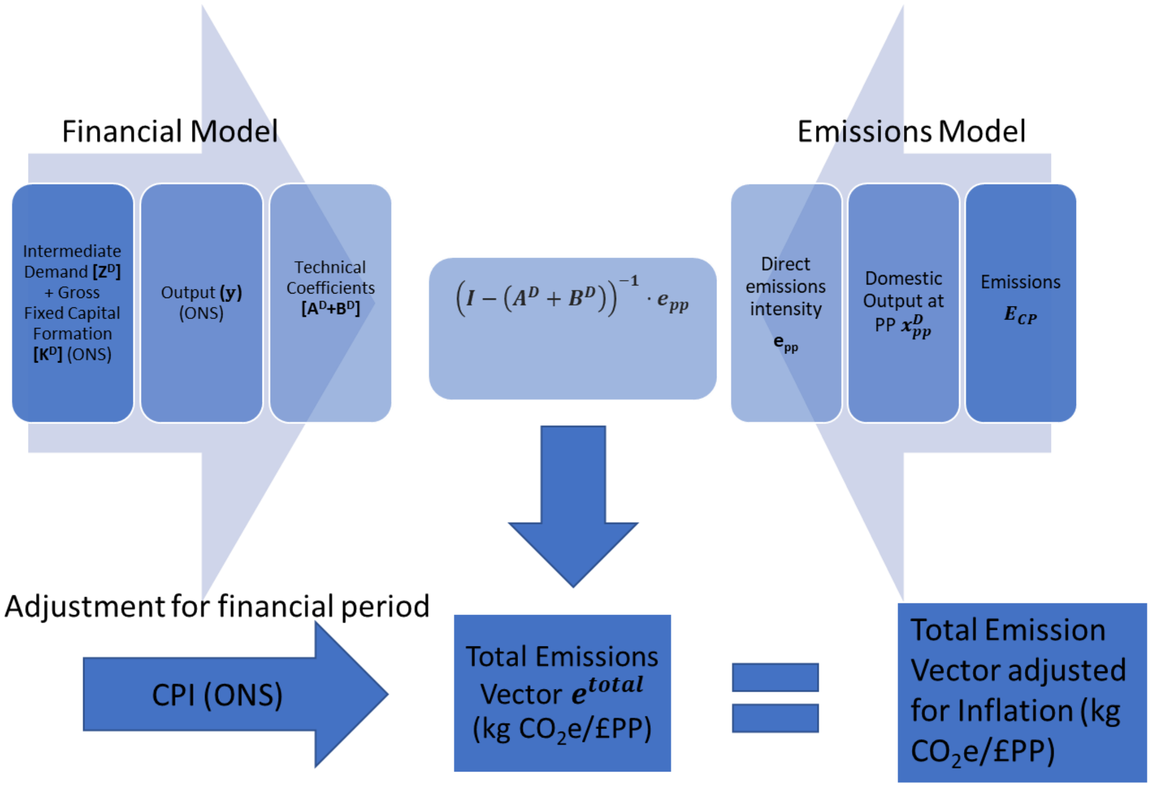
Pricing Bases

The prices in the national accounts are given under two different definitions, pricing at basic prices, and purchaser's prices. Basic prices are prices calculated before taxes (net of subsidy) on products, and distributor's trading margins. Purchaser's prices are the prices after taxes less subsidy on products, and distributor's trading margins have both been added. The intermediate demand is calculated in purchaser's prices. In the text below the pricing bases are abbreviated BP – basic prices, PP – purchaser's prices.

3.7 Method

The model is split into several sections and is described in detail below. A schematic of the structure is at Figure 1. The financial model (section 3.8) is derived from the intermediate consumption of the supply and use tables of the national accounts. This is a matrix detailing the inter-industry transactions, the rows showing where the products of each industrial sector are sold, the columns showing the production requirements of each industrial sector. This is added to the matrix of Gross Fixed Capital Formation (GFCF) which also constitutes part of the national accounts. This matrix accounts for the products transactions between industry sectors for capital goods, that is infra-structure, stocks, and valuables. The final parameter required is total output, which is the sum of intermediate consumption (those products consumed by industry to produce the goods for final consumption) plus value added, which comprises taxes, remuneration of employees, and profits and mixed income. This data allows the formation of a Leontief Inverse as described for example by Miller & Blair (2009), which is the basis of the financial model.

Figure 1 Schematic of Model



The emission module (section 3.9) is based on data of the various emissions associated with each industry sector, which are estimated in six categories and summarised as a total of tonnes CO_2 equivalent where the totals of the different gases are aggregated using their global warming potentials (GWP). This gives a figure for the impact of direct emissions on the atmosphere measure in a common unit. Also required is the domestic supply of goods by each sector adjusted to basic prices and purchaser's prices. A direct emissions intensity for each industry sector is derived from the ratio of GHG emissions measured in CO_2 equivalents to supply of goods in pounds at purchaser's prices. This is an estimate of the CO_2 equivalents released by the final consumption of one pound's worth of the goods or services of any given sector.

In the UK, as noted above, the national accounts take time to compile and as a result are usually two years out of date. In applying the model to an analysis of organisations footprint an adjustment to the relevant financial period is required (section 3.10). In this model, a correction can be applied using pricing information which is compiled by ONS and measures the changes in prices across a basket of goods. The correction implemented in this model is simply to adjust intensities using consumer price index (CPI) information.

A crucial part of the process of applying this modelling to organisations is an understanding of the relationship between the structure of that organisation's finances and the structure of the national accounts that are used to build the financial model. This understanding has to be built during a process of consultation with the organisation and results in the mapping from the purchase ledger of the organisation being assessed to the sectors of the UK economy (section 3.11). The assumption is made that once this mapping has been undertaken, the expenditures of the company can be used to stimulate the model as a vector of final demand (Berners-Lee*, et al.*, 2011). The mapping is used to translate purchases as delimited in the company accounts into purchases in the sectors of the national accounts. We can now consider the aspects of the model in greater detail.

3.8 Financial Model Generalised Input-Output Models

The type of input-output model used to model the emissions from the UK, is what Miller & Blair (2009) characterised as a "generalised product by industry input-output model", which includes capital expenditure. In this instance, the term "product by industry" means that the model is derived from the quantities of each product sector output used by each industry sector to produce one unit of output. As each product and industry sector are comprised of heterogeneous products and industries, the amounts of products used by industry sectors are quoted in financial terms. Capital expenditures (Gross Fixed Capital Formation) are normally part of final demand but capital may be expended to provide e.g. machinery or premises that are used in the manufacture of goods or provision of services. This capital requires replenishment on timescales longer than the year which is used for intermediate demand, but it presents a more complete picture of the resources used in an economy to take the use of capital into account. Balanced against that, capital may contribute to several years of production so allocating it in one year overstates its impact on production. The sole exclusion is that capital used to replenish housing is not included in the derivation of the model.

The inclusion of GFCF is common in this type of model. For example, Lenzen (2001b) argues that all production is for consumption and that so the formation of capital should be included along with intermediate consumption. However, Peters and Hertwich (2004) point out that there are two categories of capital: that which is intended to replace goods worn out in use and also includes production of goods for stock (inventory); and that which is used to finance expansion of an industry. The former could be regarded as part of production but being used outside the timescales of intermediate consumption, which is goods consumed in one year. Therefore, in estimating impacts of production it is reasonable to include this element. Expansion of capital stock to increase production capacity may not reflect the actions of a year to year change in final demand and so should be excluded (Peters and Hertwich, 2004). In this thesis, it is assumed that both uses of capital should be included in assessing the impacts of production and hence the financial model incorporates all GFCF.

Turning to the specifics, an EEIO model based upon the UK national accounts is outlined below. In the discussion that follows a bold capital letter (e.g. ***A***) is used to denote a matrix, a bold lowercase letter (e.g. ***y***) is used to denote a vector. The element of a vector or matrix will be denoted by italic lowercase with subscripts representing the row and column respectively of the element within the matrix, such that a_{ij} represents the *j*th element of the *i*th row of ***A***.

Table 8 Table of variables Used in IO Model (BP = valued at Basic Prices, PP=valued at purchaser's prices)

Label	Description	Type	Units
$\boldsymbol{x^D}$	n x 1 vector of Domestically produced output	Data (ONS)	£(BP)
$\boldsymbol{Z^D}$	n x n matrix of Intermediate Industrial Consumption	Data (ONS)	£(PP)
$\boldsymbol{K^D}$	n x n matrix of Gross Fixed Capital Formation	Data (ONS)	£(PP)
$\boldsymbol{y^D}$	n x 1 vector of domestic final demand	Data (ONS)	£(PP)
$\boldsymbol{y^D_{HH}}$	n x 1 vector of final consumption by Households	Data (ONS)	£(PP)
$\boldsymbol{y^D_{NPISH}}$	n x 1 vector of final consumption by NPISH	Data (ONS)	£(PP)
$\boldsymbol{y^D_{RG}}$	n x 1 vector of final consumption by Regional Government	Data (ONS)	£(PP)
$\boldsymbol{y^D_{CG}}$	n x 1 vector of final consumption by Central Government	Data (ONS)	£(PP)
$\boldsymbol{y^D_{GFCF}}$	n x 1 vector of Gross Fixed Capital Formation (GFCF)	Data (ONS)	£(PP)
$\boldsymbol{y^D_V}$	n x 1 vector of changes in Valuables	Data (ONS)	£(PP)
$\boldsymbol{y^D_I}$	n x 1 vector of changes in Inventories	Data (ONS)	£(PP)
$\boldsymbol{y^D_{ex\ GFCF}}$	n x 1 vector of final domestic demand less GFCF	Data (ONS)	£(PP)
$\boldsymbol{A^D}$	n x n matrix of technical coefficients of the Industry intermediate consumption per unit of domestically produced output $\boldsymbol{x^D}$	Parameter calculated from Data (ONS)	£(PP)/£(BP)
$\boldsymbol{B^D}$	n x n matrix of sectoral flows of fixed capital per unit of domestically produced output $\boldsymbol{x}^D$	Parameter calculated from Data (ONS)	£(PP)/£(BP)
$\boldsymbol{i}$	$n\times1$ summation vector which on post multiplication of a $n\times n$ matrix gives a $n\times1$ vector where the ith entry is the total of the ith row of the matrix	Summation vector	None

Consider the $(n\times 1)$ vector $\boldsymbol{x^D}$ (see Table 8 for definitions of variables in the following) of the domestic output of the UK economy in n sectors, this can be related to the $(n\times n)$ matrix $\boldsymbol{Z^D}$ of Intermediate Industrial Consumption and the $(nx1)$ vector $\boldsymbol{y^D}$ of domestic final demand from the n sectors of the UK economy then the output of the economy can be related to the other terms using a summation vector $\boldsymbol{i}$:

$$\boldsymbol{x^D} = \boldsymbol{Z^D i} + \boldsymbol{y^D} \qquad (3.1)$$

that is the domestic output of the ith sector of the UK economy is given by $\sum_{j=1}^{n} z_{ij}^{D} + y_i^D$ the sum of the intermediate industrial consumption and final consumption.

We then assume that intermediate industrial consumption is a linear function of $\boldsymbol{x^D}$ using the second principle of national accounting of proportionality, and introducing a $(n\times n)$ matrix of technical coefficients $\boldsymbol{A^D}$, which is the direct requirements of each industry in purchasers prices per pound sterling of output in basic prices.

$$\boldsymbol{Z^D i} = \boldsymbol{f}(\boldsymbol{x^D}) = \boldsymbol{A^D x^D} \qquad (3.2)$$

so substituting in equation (3.1) gives,

$$\boldsymbol{x^D} = \boldsymbol{A^D x^D} + \boldsymbol{y^D} \qquad (3.3)$$

We can decompose $\boldsymbol{y^D}$ into its components, as described in

,

$$\boldsymbol{y^D} = \boldsymbol{y^D_{HH}} + \boldsymbol{y^D_{NPISH}} + \boldsymbol{y^D_{LG}} + \boldsymbol{y^d_{CG}} + \boldsymbol{y^D_{GFCF}} + \boldsymbol{y^D_V} + \boldsymbol{y^D_I} \qquad (3.4)$$

We assume that the Gross Fixed Capital Formation is also a linear function of $\boldsymbol{x^D}$, introducing a $(n \times n)$ matrix of GFCF coefficients $\boldsymbol{B^D}$, which is the direct GFCF requirement in purchaser's prices per unit of financial output in basic prices.

$$\boldsymbol{y^D_{GFCF}} = \boldsymbol{f}(\boldsymbol{x^D}) = \boldsymbol{B^D x^D} \qquad (3.5)$$

and then using $\boldsymbol{y^D_{ex\,GFCF}}$ to gather the other elements of final demand, $\boldsymbol{y^D}$ can be written as

$$\boldsymbol{y^D} = \boldsymbol{B^D x^D} + \boldsymbol{y^D_{ex\,GFCF}} \qquad (3.6)$$

Substituting for $\boldsymbol{y^D}$ from (3.5) into (3.4),

$$\boldsymbol{x^D} = \boldsymbol{A^D x^D} + \boldsymbol{B^D x^D} + \boldsymbol{y^D_{exGFCF}} \qquad (3.7)$$

Collecting terms in $\boldsymbol{x^D}$ on the LHS and factorising,

$$\left(\boldsymbol{I} - \left(\boldsymbol{A^D} + \boldsymbol{B^D}\right)\right)\boldsymbol{x^D} = \boldsymbol{y^D_{ex\,GFCF}} \qquad (3.8)$$

Pre-multiplying by the inverse of $\left(\boldsymbol{I} - \left(\boldsymbol{A^D} + \boldsymbol{B^D}\right)\right)\boldsymbol{x^D}$,

$$\boldsymbol{x^D} = \left(\boldsymbol{I} - (\boldsymbol{A^D} + \boldsymbol{B^D})\right)^{-1}\boldsymbol{y^D_{ex\,GFCF}} \qquad (3.9)$$

Where $\left(\boldsymbol{I} - (\boldsymbol{A^D} + \boldsymbol{B^D})\right)^{-1}$ is referred to as the Leontief inverse $\boldsymbol{L}$ **(Miller and Blair, 2009)**and summarises the total requirements of intermediate demand and GFCF over all industries in coefficients that are the total amount in purchaser's prices of each product per unit of output in basic prices of each industry. Rewriting our equation using the Leontief inverse, $\boldsymbol{L} = \left(\boldsymbol{I} - \left(\boldsymbol{A^D} + \boldsymbol{B^D}\right)\right)^{\boldsymbol{-1}}$,

$$\boldsymbol{x^D} = \boldsymbol{L y^D_{ex\,GFCF}} \qquad (3.10)$$

The outcome of this algebraic manipulation is the relation of output of the economy $\boldsymbol{x^D}$ to domestic final demand $\boldsymbol{y^D_{ex\,GFCF}}$ by a constant matrix $\boldsymbol{L}$. By the assumption of proportionality, we can calculate the output $\boldsymbol{x}^*$ or change in output $\boldsymbol{\Delta x}^*$, in financial terms, that arises from a final demand $\boldsymbol{y}^*$ or change in final demand $\boldsymbol{\Delta y}$ provided that the magnitude of the change in demand is not large.

A subtlety of the model is that by our inclusion of fixed capital in the Leontief inverse, the final demand element represented by GFCF should not be included when using this model. We now have the tools to estimate the financial impact of changes in final demand, but for Carbon foot printing we need a means of connecting financial impacts with GHG emissions. In the next section, we consider the emissions that are associated with industry sectors and calculate the quantity of emissions per unit output.

3.9 Emission Model

In order to link the financial model with the emissions, the assumption is made that the emissions made by an industry sector scale with the output of that sector. This is a substantial assumption to make as the structure of the sector could change and the impact of that change in structure may not vary the emissions of that sector in a linear manner. The basis of the emissions model is to derive a relationship between the emissions of that sector and the output of the sector at purchaser's prices which then aligns with the measurement of the industry requirement in purchaser's prices per unit of output.

We need the total domestic output of goods at purchaser's prices. The ONS provide data on supply of goods and emissions and these are summarised in Table 9 below:

Table 9 Supply Data from ONS (table 1 of SUT)

Label	Description	Type	Units
$\boldsymbol{x^D}$	$(n\times 1)$ vector of Domestically produced output	Data (ONS)	£(BP)
$\boldsymbol{M_G}$	$(n\times1)$ vector of imported goods	Data (ONS)	£(BP)
$\boldsymbol{M_S}$	$(n\times1)$ vector of imported services	Data (ONS)	£(BP)
$\boldsymbol{D}$	$(n\times1)$ vector of distributor's margins	Data (ONS)	£(BP)
$\boldsymbol{T}$	$(n\times1)$ vector of taxes less subsidies on products	Data (ONS)	£(BP)
$\boldsymbol{E}$	(131×24) vector of total greenhouse gas emissions from 131 sectors of the UK economy from 1997 to 2011 (ONS, 2012b))	Data (ONS/Ricardo AEA)	Tonnes CO_2 eq.
$\boldsymbol{E_{CP}}$	$(n\times1)$ vector of total greenhouse gas emissions aggregated from $\boldsymbol{E}$ and representative of the financial period analysed in the financial model	Data (ONS/Ricardo AEA)	Tonnes CO_2 eq.

$\boldsymbol{S_{PP}}$	$(n\times1)$ vector of the supply of goods in the UK at purchaser's prices	Data (ONS)	£(PP)
$\boldsymbol{S_{BP}}$	$(n\times1)$ vector of the supply of goods in the UK at Basic Prices	Calculated	£(BP)
$\boldsymbol{x_{PP}^{D}}$	$(n\times1)$ vector of the domestic output of goods in the UK	Calculated	£(PP)
$\boldsymbol{e_{PP}}$	$(n\times1)$ vector of direct greenhouse gas emissions per pound of output	Calculated	kg CO_2eq/£(PP)
$\boldsymbol{e^{total}}$	$(n\times1)$ vector of total (direct and indirect) greenhouse gas emissions per pound of output	Calculated	kg CO_2eq/£(PP)

The vectors of domestic output, imported goods and services, distributors margins and taxes less subsidies on products are summed to give the vector of total supply at purchaser's prices.

$$\boldsymbol{S_{PP}} = \boldsymbol{x^{D}} + \boldsymbol{M_{G}} + \boldsymbol{M_{s}} + \boldsymbol{D} + \boldsymbol{T} \qquad (3.11)$$

Subtracting the items of distributors margins and taxes less subsidies on products, give us the total supply at basic prices.

$$\boldsymbol{S_{BP}} = \boldsymbol{S_{PP}} - \boldsymbol{D} - \boldsymbol{T} \qquad (3.12)$$

and multiplying the elements of total domestic output of goods at basic prices by the ratio of supply at purchaser's prices to supply at basic prices for each industry gives an estimate of domestic output at purchaser's prices. This assumes that imports and domestic output attract proportionally the same amounts of distributors margins and taxes less subsidies on products.

$$the\ ith\ element\ of\ \boldsymbol{x_{PP}^{D}}\ is\ given\ by\ x_{PP_i}^{D} = x_i^{D} \times {}^{s_{PP_i}}/_{s_{BP_i}} \qquad (3.13)$$

The total greenhouse gas emissions of 131 industry sectors in units of tonnes carbon dioxide equivalents are obtained by summing the emissions of CO2, CH4, NO_2, HFC, PFC, SF_6, and NF_3 multiplied by their individual Global Warming Potential (GWP). The emissions from the 131 sectors are aggregated as required onto the n sectors of the financial model to give a $(n\times1)$ vector $\boldsymbol{E_{CP}}$ which is the total emissions for the year for each sector analysed in the financial model. The total emissions for each sector are divided by the domestic output at purchaser's prices to give the emissions intensity vector $\boldsymbol{e}_{PP}$ where the ith element is the amount of GHG emitted by industry i per pound sterling of domestic output at purchaser's prices.

$$e_{pp_i} = 1000 \times \frac{E_{CP_i}}{x^D_{pp_i}} \qquad (3.14)$$

The aviation sector has an additional factor of 1.9 applied owing to the increased effect of releasing emissions at altitude (Rogers*, et al.*, 2002).

So therefore the ith element of the vector of total greenhouse gases, $\boldsymbol{g}$ associated with total output $\boldsymbol{x}^*$ can be written as

$$g_i = e_{PP_i} \times x_i^* \qquad (3.15)$$

It is also useful to derive a $(n \times 1)$ vector $\boldsymbol{e^{total}}$ of total greenhouse (direct and indirect) gas emissions per pound of final demand which can be obtained by post multiplying the Leontief inverse $\boldsymbol{L}$ by $\boldsymbol{e_{pp}}$,

$$\boldsymbol{e^{total}} = \boldsymbol{Le_{PP}} \qquad (2.16)$$

This links the financial and emissions model such that the impact of changes in final demand on total greenhouse gas emissions can be estimated. However, the data that is used to form these two elements of the model is usually two years out of date so in the next section we consider how to adjust so the data can be used in other time periods.

3.10 Adjustments for financial period and to exclude exports

The model, as described above, was derived from the UK National Accounts published in in a given year (say $\boldsymbol{Y1}$) and this does not always coincide with the year for which an estimate of GHG emission may be required. In order to be useful for estimating emissions in years other than the reported year a process of adjusting the emissions intensity is required. Prices of products in product sectors change over the course of the years and a simple way of adjusting for reporting in different financial years is to use CPI to adjust the emissions intensity from year $\boldsymbol{Y1}$ to year $\boldsymbol{Y2}$. This is complicated by the fact the ONS do not use the same classification for CPI as they do for the Supply and Use Tables (SUT). This means that a mapping is required from the CPI classification to the national accounts structure to obtain the $(n \times 1)$ vectors of CPI by national account code.

Table 10 Variables for Financial Period Adjustment (ONS)

Label	Description	Type	Units
$\boldsymbol{CPI_{Y1}}$	$(n \times 1)$ vector of inflation indices for Year $\boldsymbol{Y1}$	Data (ONS)	Index, base year 2005 = 100

$\boldsymbol{CPI_{Y2}}$	$(n\times1)$ vector of inflation indices for Year $\boldsymbol{Y2}$	Data (ONS)	Index, base year 2005 = 100
$\boldsymbol{I}_{[\boldsymbol{Y1},\boldsymbol{Y2}]}$	$(n\times1)$ vector of the ratio of the CPI in $\boldsymbol{Y1}$ divided by CPI in $\boldsymbol{Y2}$	Parameter derived from ONS Data	Ratio of indices
$\boldsymbol{e_{Y1}^{total}}$	$(n\times1)$ vector of total emissions intensities for year $\boldsymbol{Y1}$	Variable derived from financial and emissions model	$kgCO_2$ eq/£(PP)
$\boldsymbol{e_{Y2}^{total}}$	$(n\times1)$ vector of total emissions intensities for year $\boldsymbol{Y2}$	Variable derived from financial and emissions model	$kgCO_2$ eq/£(PP)

Let $\boldsymbol{e_{Y1}^{total}} = \boldsymbol{Le_{pp}}$ (for descriptions of variables in this section see Table 10**)** be a vector of total emissions intensities for a base year $\boldsymbol{Y1}$, and let $\boldsymbol{Y2}$ represent the year of interest for the model. Let $\mathbf{I}_{[\mathbf{Y1},\mathbf{Y2}]}$ represent a $(n{\times}1)$ vector of inflation factors, the vector being constructed from two $(n{\times}1)$ vectors $\boldsymbol{CPI_{Y1}}$ and $\boldsymbol{CPI_{Y2}}$ of ONS CPI figures constructed by matching the ith industry sector in each with an appropriate CPI sector (see Appendix A). Then

$$the\ ith\ element\ of\ I_{[Y1,Y2]_i} = \frac{CPI_{Y1_i}}{CPI_{Y2_i}} \qquad (3.17)$$

Then we can express our vector of emissions intensity for year $\boldsymbol{Y2}$ as

$$\mathbf{e}_{\mathbf{Y2}}^{\mathbf{total}} = \mathbf{I}_{[\mathbf{Y1},\mathbf{Y2}]} \cdot \mathbf{e}_{\mathbf{Y1}}^{\mathbf{total}} \qquad (3.18)$$

Then the total emissions for year $\boldsymbol{Y2}$ may be expressed as the product

$$E = \mathbf{e}_{\mathbf{Y2}} \cdot \mathbf{y}_{\mathbf{Y2}} \qquad (3.19)$$

Where $\boldsymbol{y_{Y2}}$ is the final demand in the year $\boldsymbol{Y2}$.

We now have the ability to estimate an emissions intensity and hence total emissions for a financial period $\boldsymbol{Y2}$ which is different to, and more recent than the financial and emissions models derived from data for period $\boldsymbol{Y1}$. Now we can consider the application of the model to estimating the emissions of an organisation.

3.11 Organisational Model

In order to use the model to estimate emissions in the supply chain of an organisation there are several steps that must be carried out in conjunction with the organisation. In general, organisations will report accounts on an annual basis, and although statutory accounts do not require details of purchases, many organisations will keep a purchase ledger that records details of financial transactions with suppliers. Typically for management purposes there will also be a categorisation into purchase types or categories. This will vary from organisation to organisation but typically might start at a high level of aggregation, e.g. major capital acquisitions, which are then disaggregated into finer level of details, e.g. capital acquisition – Trucks; capital acquisition- plant and machinery etc. These categories may correspond precisely with the SIC used for the UK national accounts but it is also possible that they will overlap several categories. A process that must be carried out before the use of the model will be a mapping of the organisation’s purchase categories to the SIC.

This is likely to be an iterative process that is carried out in conjunction with the organisation, particularly with either purchasing team or purchase ledger team. This mapping allows the expenditures of the company to be mapped to a vector of final demand that can be used to stimulate the model and produce an estimate of emissions based on the organisational spend in a given financial period or periods. Similarly aggregating an organisation's purchases with a supplier into a final demand vector to simulate the model can highlight suppliers with disproportionate amounts of emissions that could also be targeted for improvement.

In general, a purchase category can be mapped to one or more industry/product sectors of the SIC 2007 classification. There might be a direct match, particularly as the UK industrial sectors are quite highly aggregated. For example, sector 29 covers the manufacture of motor vehicles, trailers and semi-trailers so anything that relates to the purchase of cars, lorries, vans etc. can be attributed to this industrial sector. Another possibility is to split a purchase category over two or three industrial sectors. This can happen for example in computer and IT purchases where there is quite often a hardware and a software element. This purchase category could be assigned in proportions to sector 26 "manufacture of computer, electronic and optical products" and sector 62 "Computer Programming, Consultancy And Related Activities", with the exact proportions being decided in consultation with the organisation.

Provided that the organisation's purchase ledger structure remains fairly stable, this mapping process need not be carried out every time the model is used. This opens up the possibility of being able to compare the organisation's footprint over a number of financial periods. It is also a quick process: even for large organisations it can be carried out in a couple of days, and usually only requires a day or so of work each time the report is prepared to check the current allocations and add in any new purchase categories. Changes in the classification of the industrial sectors by the ONS can complicate this process so evolution of classification systems is preferred to revolution.

With a complete list of the categorisation carried out by any organisation it is possible to derive a mapping from the categories used to characterise their spend onto the product/industry sectors of the input output model. On post-multiplying the spend vector by the mapping matrix, a vector of spend by input-output category is obtained. This then can be multiplied by the vector of emissions intensity. The cross product will give an estimate of the total emissions arising from the company's spend, and element-wise multiplication of the vectors will give a sectoral estimate. Using the mapping matrix to transform this leads to a breakdown of emissions by purchase category which may be useful feedback to the organisation on how their spending impacts upon their total emissions. A diagram of an idealised mapping process is shown at Figure 2

Figure 2 Illustration of mapping process from Purchase Ledger to Input-Output Sectors

Purchase Ledger

Transaction	Supplier	Amount	Purchase Category
1	ABC	S_1	Capital Purchase
2	CDE	S_2	Office Supplies
…	…	…	…

Purchase Category	Weight IO Sector 1	Emissions Intensity IO Sector 1	Weight IO Sector 2	Emissions Intensity IO Sector 2	…	Composite Purchase Category emissions intensity
Capital Purchase	w_{CP_1}	e_{pp_1}	w_{CP_2}	e_{pp_2}	…	$e_{Capital\ Purchase} = \Sigma w_{CP_i} \times e_{pp_i}$
Office Supplies	w_{OS_1}	e_{pp_1}	w_{OS_2}	e_{pp_2}	…	$e_{Office\ Supplies} = \Sigma w_{OS_i} \times e_{pp_i}$
…	…	…	…	…	…	…

Mapping of Purchase Category to IO sectors

Carbon Emissions by Purchase Category and Total Emissions

Purchase Category	Emissions
Capital Purchase	$S_1 \times e_{Capital\ Purchase}$
Office Supplies	$S_2 \times e_{Office\ Supplies}$
…	…
Total	Sum of emissions

3.12 Use of the model

We have now the elements of a complete model that can be applied to the purchasing data of an organisation, and produce an estimate of the greenhouse gas footprint of that organisations spending. This is part of the organisation's Scope 3 data, there are other elements, e.g. End of Life Processing, In-Use Emissions etc. There are a number of other elements included in the total footprint and it has been the aim of this project to integrate as many of these other elements as the management of the organisation wishes. These elements are considered in the next sections.

3.12.1 Use of Direct and Indirect emissions data

For many organisations, they may have made more accurate estimates for their use of energy directly, either by direct combustion, e.g. in vehicles, or plant and equipment or for heating. The use of electricity may be obtained by the use of recordings of meter's or from the electricity supplier(s) themselves. The EEIO model provides an estimate of these emissions from purchases from the energy sectors, but in many cases accuracy will be improved by using estimates of GHG emissions derived from the amounts of energy used, multiplied by an appropriate emissions intensity. The EEIO model can be used to include the upstream Scope 3 elements of power generation, or production of fuels for direct combustion. The Scope 3 emissions that are calculated from direct measurements can then be added into the final results. A method for doing this is described below.

From the emissions model above we have two vectors $\boldsymbol{e_{pp}}$ and $\boldsymbol{e_{total}}$, representing respectively the direct emissions intensities and total emissions intensity for each sector. Using these, we can calculate a ratio of total emissions intensity to direct emissions intensity for any given sector i,

$$ratio\ total\ emissions\ to\ direct\ emissions\ for\ sector\ i = \frac{e_{total_i}}{e_{pp_i}} \qquad (3.20)$$

By using an appropriate industry sector e.g. "Land transport services and transport services via pipelines, excluding rail transport" for road transport, an estimate of the scope 3 emissions E_{scope3} arising from direct emissions E_{direct} can be calculated from,

$$E_{scope3} = E_{direct} \times \left(\frac{e_{total_i}}{e_{pp_i}} - 1 \right) \qquad (3.21)$$

These scope 3 emissions estimates can then be used to provide an estimate of the total impact of travel and transport.

3.12.2 Estimates of Business Travel/Commuting

Other Scope 3 emissions such as those estimated under the GHG protocol categories of "employee commuting" and "business travel" and possibly also from upstream transport and distribution may also be calculated using a more process based method. For example, passenger kilometres travelled also include an upstream Scope 3 element that is not necessarily captured using the standard factors provided by for example DEFRA. By a calculation similar to that above (equation 3.21) these Scope 3 emissions estimates may be added to the footprint estimate.

3.12.3 Use of Process based Data

There may be other areas of an organisation's operations where the organisation has carried out a process based analysis of their operations which allows them to make a more relevant estimate of their emissions than that offered by EEIO modelling. In these instances, an estimate of the upstream scope 3 impacts may be made by resorting to a calculation similar to that described above in 3.12.1

System Boundaries to avoid Double Counting

In the instances described above, care must be taken to avoid double counting of emissions arising. For example, if direct emissions arising from transport are estimated using a process based method then if purchases of fuels for vehicles are included in the purchases made by the organisation, the results arising from EEIO modelling will overlap with those from the process based analysis. The organisational mapping will need to be adjusted to exclude purchase categories that are relevant to operations where the emissions are estimated by a process based method.

3.13 Evolution of the Model

The model described by Berners-Lee *et al.* (2011) was based on 2007 data which was presented in the form of supply and use tables where the number of product/industry sectors n was 123. As has been noted previously, the ONS publish the national accounts of the UK annually. It is advantageous when developing the input-output model that is to be used in estimating the footprint of an organisation to have the most up to date information from the ONS. The most important outcome of this project is that the Berners-Lee *et al.* (2007) model has been replaced by a model that uses the most up to date data. There have been a number of changes in the underlying datasets and these are discussed in the next section.

3.13.1 Sector Classification

The evolution of the EEIO model is driven by the data available from the ONS. Although the general format of the accounts has remained broadly unchanged, there have been a number of amendments since the project began. The model described by Berners-Lee *et al.* was based on the Standard Industry Code (SIC) 2003 for industry sectors and the Classification of Products by Activity (CPA) 2002 for the product sectors which resulted in the supply and use tables consisting of 123 sectors for both product and industry (Berners-Lee *et al*, 2011). Over the course of time the ONS updates the national accounts and also introduces new methods and new ways of reporting the data. This has an impact on the structure and use of the model. There was a significant change in the economic sectors classification in 2012. In 2012, for the first time, the accounts were produced using SIC 2007 and CPA 2008 classification schemes. The composition of the economic sectors changed somewhat so that accounts produced before 2012 are difficult to compare with those produced after 2012. In addition to a change in the subsectors that comprise the industry and product sectors, the total number of sectors decreased from 123 to 110. The ability to use the most up to date data was the main reason for producing a new model.

From 2013 and reflecting changes in some of the industry sectors, a number of sectors have been merged. The construction sectors 41, 42 and 43 have been merged into one, sectors 59 and 60 which previously dealt separately with “Motion picture, video and TV programme production services, sound recording & music publishing” and “Programming and broadcasting services” have been merged. Finally, sector 87, “Residential care services”, and 88, “Social work services without accommodation”, have been merged. This means a net reduction in economic sectors from 110 to 106.

3.13.2 Changes in presentation of GFCF

As noted above, we include GFCF in our model by incorporating the GFCF transactions amongst sectors with the intermediate demand. It should be noted that GFCF does not necessarily occur in all sectors of the economy and also that GFCF is formed in two sectors "Dwellings" and "Transfer costs for land etc." which are not industry sectors and so do not appear in the tables for intermediate consumption. The first model that was developed was based upon the 2012 Bluebook, which was the first supply and use tables produced using the SIC2007/CPA 2008 classifications with the number of sectors (n) being 110. For this edition, the GFCF matrix was released in the form of (110×112) matrix which matched the intermediate industrial consumption matrix when the two columns for dwellings and transfer costs were removed. This allowed a straightforward addition of the two to produce the matrix including capital flows which is subsequently used to calculate the technical coefficients.

As noted above, in 2013 the number of sectors (n) decreased to 106. The GFCF matrix however is presented as a (44×84) matrix. This means that 44 products are used to form GFCF in 82 industry sectors. Some sectors have been removed as the capital flows to them are insignificant and others have been aggregated. This means that an adjustment of the GFCF matrix is required in order to calculate the sum of the Intermediate Consumption (Table 2 of SUT) and GFCF (Table 4 of SUT), in order to form the technical coefficients matrix. This calculation is made using the 2012 capital matrix which was produced in 110 sectors to estimate the disaggregation where necessary. As the GFCF can change from year to year, using this structure is likely to become increasingly unrepresentative. Although in general GFCF flows are relatively small by comparison with intermediate consumption flows, it is more significant in some sectors e.g. construction, machinery etc. After adjusting the GFCF such that it is available in (106×106) matrix the addition to intermediate consumption can be undertaken as described above.

3.13.3 Calculation of Time Series

The earliest models as described in 2010 were derived from a single set of supply and use tables and used CPI to adjust for time periods other than 2007. The drawback to this is that any changes in structure of the economy are not reflected in the model. Since 2012 the ONS have been producing a time series of Supply and Use tables from 1997 up to the year of interest. This allows the construction of a time series of input-output models based upon consistent data. Over the course of the project this has been utilised to allow estimates dating back several years rather than a simple comparison between current year and previous year. Although involving extra work in constructing the models, the classification system remains consistent, which means that the mapping of the organisational purchase categories onto the national accounts sectors allows the time series to be used with spend data going back several years.

3.14 Conclusion

This chapter has discussed the composition of the national accounts of the UK as used in the construction of EEIO models for estimating organisational footprints. The construction of an EEIO model has been broken down into four stages: the financial, emissions, time period adjustment, and tailoring to the organisation for which it is to be used. Some general comments have been made as to how the model can be modified to work with process based data. Finally, the evolution of the model over the life of the project has been discussed. In the next chapter, the implementation of the models with a large international company is discussed.

Chapter 4 Application to Business

Case Study of Organisational Supply Chain Emissions

4.1 Introduction

With the cooperation of Small World Consulting Ltd., it has proved possible to use the revised and updated model in conjunction with a UK based telecommunications company to provide an estimate annually of their carbon footprint. As noted above this required access both to their account structures and account details, and also to their data on scope 1 and 2 emissions. This chapter provides an example of the real world application of EEIO models over three years with a large organisation, and the impact of initiatives taken by them can be shown in the model. The model has been updated each year to reflect the data that was being released by ONS. Over the course of the three years a number of smaller projects have arisen from the analysis and have been amenable to using some of the techniques that an input-output analysis allows. Some of the smaller projects are examined in more detail in sections 4.4.3, and 4.4.4 and two more substantial modifications are discussed in detail in chapter 5.

4.2 The Company

4.2.1 Overview of the Company

The company is a large UK based provider of international telecommunications services. The core of its business is associated with connecting national and international calls, providing broadband and it also has responsibility for installing copper and fibre cabling. The company's customers span a full range from individual households to large companies. The company has diversified into providing digital TV content which represents a step in a different direction.

The company undertakes a wide range of purchasing but their major purchases are those of telecommunications services, engineering materials associated with their installation of copper and fibre cabling, TV rights, and Customer Premises Equipment (CPE), e.g. switchboards, handsets etc. Of course, there are the usual range of purchases associated with a large company, e.g. vehicles, assets, IT etc. The opportunity to study this type and size of organisation has not been noted in the literature before so this presents a novel application of EEIO. It has also been possible to study the organisation over three years, and have access to spend data from the year immediately preceding the three years of study so that four years in total can be analysed.

4.2.2 Environmental Reporting and Activity

The company set its first carbon target in 1992 and therefore has been at the forefront of environmental reporting and has for fifteen years issued reports about scope 1 and 2 emissions. In 2011, they undertook a project with SWC to measure their supply chain scope 3 emissions and have included this as part of their reporting since then. They work with several non-profit organisations such as the World Business Council for Sustainable Development (WBCSD), Carbon Trust (CT) and Carbon Disclosure Project (CDP). With the aid of these organisations they have led on policy issues, extended their scope 3 reporting to include in-use and disposal emissions and encouraged their supply chain to participate in reporting their emissions. Representatives of the company have attended the recent COP and made presentations about their efforts on sustainability. They feel that they are suppliers of a range of technologies that may encourage consumers and businesses to conduct businesses according to new paradigms that involve reduced transport, and streamlined information sharing.

4.2.3 Scope of SWC Ltd. Work

SWC undertake an analysis of upstream supply chain emissions which is mainly estimated using EEIO methods. An initial project had been undertaken in 2011, using a model like that described by Berners-Lee *et al.* (2011). This thesis documents the application of the model described in chapter 3 which uses the latest available data from ONS and the new classification SIC 2007/CPA 2008. Some categories that are amenable to a more process based approach have been identified by the hotspot analysis discussed later in the chapter (section 4.4.4). This has led to the development of a hybrid estimate for the digital TV content and the inclusion of supplier provided data, both modifications are described in chapter 5. The final element of SWC analysis is the estimation of the upstream element of scope 1 and 2 emissions, and of business travel and commuting.

4.3 Implementation of the Model

The organisation is a large one and has several subsidiaries and component companies. Their revenue is in excess of £18 billion and they have over 100,000 employees. As a result, they have a complicated accounts structure. With the diverse range of services offered, they also have purchasing requirements over a wide spectrum of suppliers. For their financial reporting they consolidate their accounts, and it is these data that are used for EEIO analysis. For their scope 1 and 2 emissions etc. the company have their own carbon model, and the estimates arising from this model are passed to SWC who make an evaluation of the scope 3 emissions arising from those. As noted in chapter 3 one of the most crucial aspects of the foot-printing process is to understand the mapping from purchases to national accounts. This is discussed in the next section.

4.3.1 Accounts Structure

The first use of EEIO with this company covered the period 2011-2012. The organisation in question provided data at quite a high level of aggregation, in 56 "spend categories" and a mapping from those spend categories to the 123 sectors of the national accounts. The second period (2012-13) for which an estimate was prepared also used this mapping. However, in 2013-14, the model that is the subject of this thesis was available and as noted, this used the new classification scheme, which split the economy into 110 sectors. As a new mapping was required, enquiries were made as to whether the spend data were available in a more granular form. It turned out that there was a lower level of aggregation of 421 "purchase categories" and as the mapping exercise had to be undertaken again it was decided to use the more granular spend data with the new industry classifications. Although the national accounts classification changed slightly for 2014-15 (reducing to 106 sectors) it was relatively easy to amend the mapping to match the aggregated sectors. The company has continued to add "purchase categories" to aid their financial analysis so the mapping has been updated and agreed between the two parties each year. The details of accounts structures and related EEIO models are in Table 11.

Table 11 Company Accounts Structure and EEIO model reference

Company Financial Year	Account Structure	EEIO model	CPI adjustment required
2011-12	56 Spend Categories	Model based on Berners-Lee 2010 using 2008 ONS data and 123 sectors	3 years
2012-13	56 Spend Categories	Model based on Berners-Lee 2010 using 2008 ONS data and 123 sectors	4 years
2013-14	421 Purchase categories (37 top level categories)	Model as described in this thesis using 2010 ONS data and 110 sectors	3 years
2014-15	526 Purchase Categories (37 top level categories)	Model as described in this thesis using 2012 ONS data and 106 sectors	2 years
2015-16	565 Purchase Categories (39 top level categories)	Model as described in this thesis using 2013 ONS data and 106 sectors	2 years

Purchase categories represent a lower level in the accounts hierarchy and hence are more closely related to products and services purchased. The 565 purchase categories in the 2015-16 ledger are grouped within 37 top level categories. The "top level category" is mainly used for reporting but the use of lower level purchase categories allows a “drill-down” into areas of interest. Associated with each purchase line is a supplier, transaction type and amount in GB pounds excluding VAT. The first part of assessing the footprint is how the purchase category can be mapped onto national accounts. Although in principle a purchase category could be split over all n sectors of the economy, in practise an upper limit of 3 national account sectors were mapped onto each purchase category with a varying proportion to be allocated according to the assessment of the purchase category. In this example, there only three purchase categories that required mapping onto three sectors of the EEIO but 46 (8%) of the total are mapped over two EEIO sectors. The mappings onto this allocation are of course generic for the purchase category and may not represent each transaction within the purchase category precisely. The allocation of purchase categories was done in conjunction with the organisation and agreed by them at the end of the process. For an example of the mapping allocations see Appendix B.

For the purposes of footprint estimation, it proved easier to calculate the aggregated emissions intensity for each purchase category. Thus, for a purchase category P_i, the amounts were allocated across national account sectors with a weighting coefficient w_{ij}, to give a purchase category emissions intensity e_{P_i}, as a function of total emissions intensity e_j by national account sector as per the following:

$$e_{P_i} = \sum_{j=1\ to\ n} w_{ij} \times e_j \qquad (4.1)$$

And of course,

$$\sum_{j=1\ to\ n} w_{ij} = 1 \qquad (4.2)$$

with typically the total number of coefficients w_{ij} being one or two and not exceeding three (by design choice) for any purchase category. So emissions for each purchase category E_{p_i} could be calculated by multiplying the spend in that purchase category S_{P_i} by the composite purchase category emissions intensity e_{P_i}.

$$E_{P_i} = S_{P_i} \times e_{P_i} \qquad (4.3)$$

The total emissions from the supply chain spend can then be found by summing over all purchase categories:

$$E^{total} = \sum_{i=1\ to\ m} S_{P_i} \times e_{P_i} \qquad (4.4)$$

$$m\ being\ the\ number\ of\ purchase\ sectors$$

The emissions E_{P_i} were aggregated for reporting purposes back into “top_level_category” but underlying results were made available when required. Having considered how the supply chain footprint may be estimated, it is appropriate to move onto the hybrid nature of the model and how system boundaries may be set.

4.3.2 System Boundaries

There are several areas within the organisation when EEIO is not used to calculate emissions. The organisation collects data on commuting and business travel (Scope 3), electricity (Scope 2) emissions, direct emissions either from commercial vehicles, stationary combustion or releases of refrigerants Scope 1 emissions. These emissions are included in calculations of the organisation’s footprint but what is not taken into account are the supply chain implications of those emissions. for example, the use of commercial vehicles incurs scope 3 emissions arising from the production and transport of the fuels to be burnt. The direct emissions of commuting are supplemented by the requirement to purchase, insure, maintain and repair the vehicle used in commuting. This aspect is dealt with in the model by using EEIO to estimate the supply chain emissions arising from those direct emissions. This is added to the supply chain scope 3 footprint of the organisation.

For these areas, the purchase categories were identified that apply to purchases in those areas and then the purchase category emissions intensity, e_{P_i} was set to zero in order to avoid double counting.

The company uses a third type of classification known as transaction types which are also used to identify transactions that should be disregarded. The company carries out some internal trading and transactions of this type are disregarded in the model. Also disregarded are the payments of tax and rates. The transactions covered are purchases from suppliers, commissions and payments to charities. In terms of the purchase categories used the organisation uses PBLCA methods to estimate business travel, commuting, fleet vehicle usage, stationary combustion and scope 2 emissions of electricity. The EEIO model is used to estimate supply chain scope 3 emissions for these activities in a method that has been described in section 3.8.1 and 3.8.2 but the purchases in these categories are not considered to avoid double counting.

4.3.3 Reporting Requirements

As discussed above, once the purchase category emissions intensities and spend are combined, then the total supply chain footprint can be estimated readily. It is clear also how the emissions for any given purchase category may be calculated, and by a process of aggregating purchase category totals for each top level category, how totals for these may be assessed. This is clearly of interest to any organisation and may be the only reporting required for some. However, the data can be aggregated in other ways that might also prove interesting. Usually an interesting area for businesses is how much of their footprint arises with a particular supplier or set of suppliers. Typically, the organisation buys goods from a given supplier in a number of different purchase categories which will be a subset of the full list. For a supplier X, who supplies goods and services in subset $T = \{P_j, P_k \ldots\}$ then the total supplier emissions E^X arising from spends with supplier given by $\{S^X_{P_j}, S^X_{P_k}, \cdots\}$ is given by:

$$E^X = \sum_{\{T\}} S^X_{P_T} \times e_{P_T} \qquad (4.5)$$

Again by focussing on individual product categories, the report can be refined.

Finally, as mentioned the organisation is a member of the WBCSD and was interested in reporting on emissions by GHG protocol scope 3 category (World Resources Institute, 2011). This information is not easily assessed from either purchase category or supplier although given the scope of the modelling it is likely that most of the emissions will arise in the upstream scope 3 category "Purchased goods and services". However, in the same way that a mapping can be carried out from purchase category to national accounts sector, a mapping can be carried out to GHG protocol scope 3 category. Thus, for each purchase category P_i a set of weighting coefficients are defined, $g_{ik}, k \in \{1,2,\cdots,15\}$ such that each coefficient represents the proportion of emissions in purchase category P_i that should be assigned to GHG protocol k. Then the total emissions E_{G_k} for each GHG protocol are given by:

$$E_{G_k} = \sum_{i=1\ to\ m} E_{P_i} \times g_{ik} \qquad (4.6)$$

To ensure that all emissions for a purchase category P_i are assigned to a GHG protocol category then:

$$\sum_{k=1\ to\ 15} g_{ik} = 1 \qquad (4.7)$$

Thus, we have established the basis of reporting emissions footprints in categories that are useful for businesses, that is by purchase category, by supplier and by GHG protocol category. By changing the order of the summation it is also possible to report by supplier within purchase category, and purchase category within supplier. We now describe the implementation of the model.

4.3.4 Data Formats and software packages used

Although input-output modelling can be computationally expensive particularly for multi-regional models, in this instance the data from the ONS is aggregated such that the matrices involved are not very large. However even inverting small matrices can only be done using some form of automation. There are specialised packages, and linear optimisation tools for more generalised maths packages such as MATLAB or R that can undertake this task. However, Microsoft's Excel now includes matrix operations such as calculating the inverse, and has the capacity to deal with the small matrices that result from the UK SUT. The ONS provide all their data in the form of Excel worksheet so it was easy to integrate this data. So in this instance where ease of use and compatibility with business reporting tools is useful, the decision was taken to undertake all of the modelling in Excel. One of the minor innovations used during the implementation phase was the extensive use of the range naming facility and matrix algebra facilities provided by this package. This provided a further element of defence against inadvertent altering of small sections of the model and also ensured that the matrix formulation of the model continued into the actual figures themselves,

The organisational spend of the participating company was also made available in Microsoft Excel format. Also included were the other emissions data such as scope 1&2 data, business travel and commuting. This was more challenging to obtain, as it was not part of the purchase ledger department remit and the company's sustainability team undertook an initial analysis and consolidation of the data before passing it on in an aggregated format in units of tonnes CO_2 eq. The purchase data comprised in the region of 50,000 to 60,000 lines of purchase information in pounds sterling and the overall size of the spreadsheets was in the region of 35 to 50 megabytes. This proved feasible to run on standard desktop computers although files of this size are challenging to operate with over a distributed network. Future implementations could be done in a more suitable matrix modelling package such as Matlab, but in general it is felt that the business community's lack of familiarity with these types of tools would mean that reporting would continue to be in Excel.

Ultimately of course integration into the organisation's financial and purchasing software would allow business managers both to be aware of the impacts of purchasing decisions instantly, and also to use their current reporting tools to include carbon footprint estimates as part of their regular reporting. This might help to elevate carbon footprint from an annual audit exercise to key performance indicator for the managers of the business with concomitant impacts. What gets measured gets managed and many financial packages these days allow for the easy integration of other information that may be useful in the decision making process.

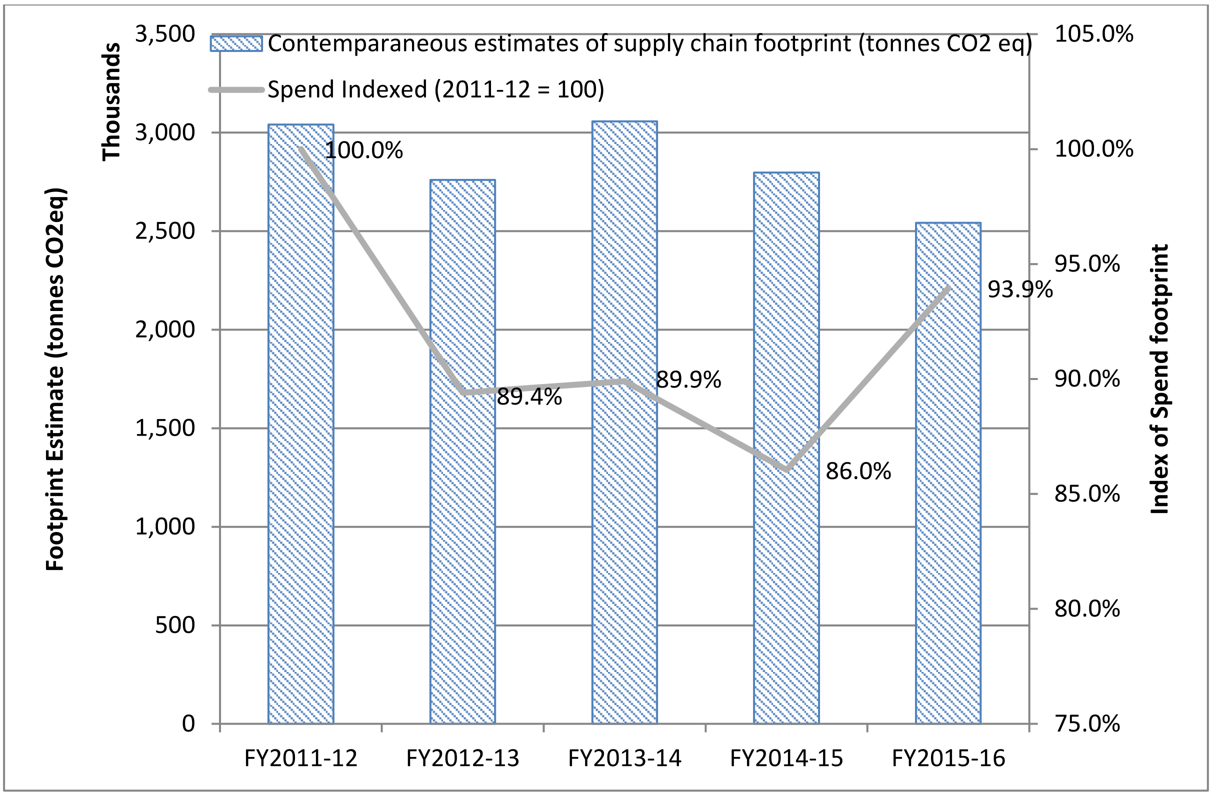
4.4 Results of the analysis

Whilst the full co-operation of this organisation has been invaluable to this study, clearly some information has commercial implications so the results are discussed in a general manner. There is an evolution in the analysis of their supply chain footprint available to the organisation, and two new developments which are outlined in chapter 5 and which attempt to address one of the chief weaknesses of this type of modelling - that of generic sectors. The measures taken to understand the impact of both a change in the classification of the national accounts and the increased granularity of the mapping are also described.

4.4.1 Total Footprint

The headline figure is that of an organisation's total footprint. However, this is not necessarily so easy to define and even the WRI standard is not too prescriptive allowing companies to opt to report scope 3 emissions(Ranganathan*, et al.*, 2004). A figure that is comparable over the years and is directly relevant to this thesis is that of supply chain footprint, those scope 3 emissions arising from spend with suppliers. Two time-series are available, the first being the figure calculated contemporaneously and the second calculated from the most up to date national accounts but using spend data from previous years. Figure 3 below, shows the absolute estimate of the footprint and indexed purchase spend of the organisation from the first estimate of the footprint.

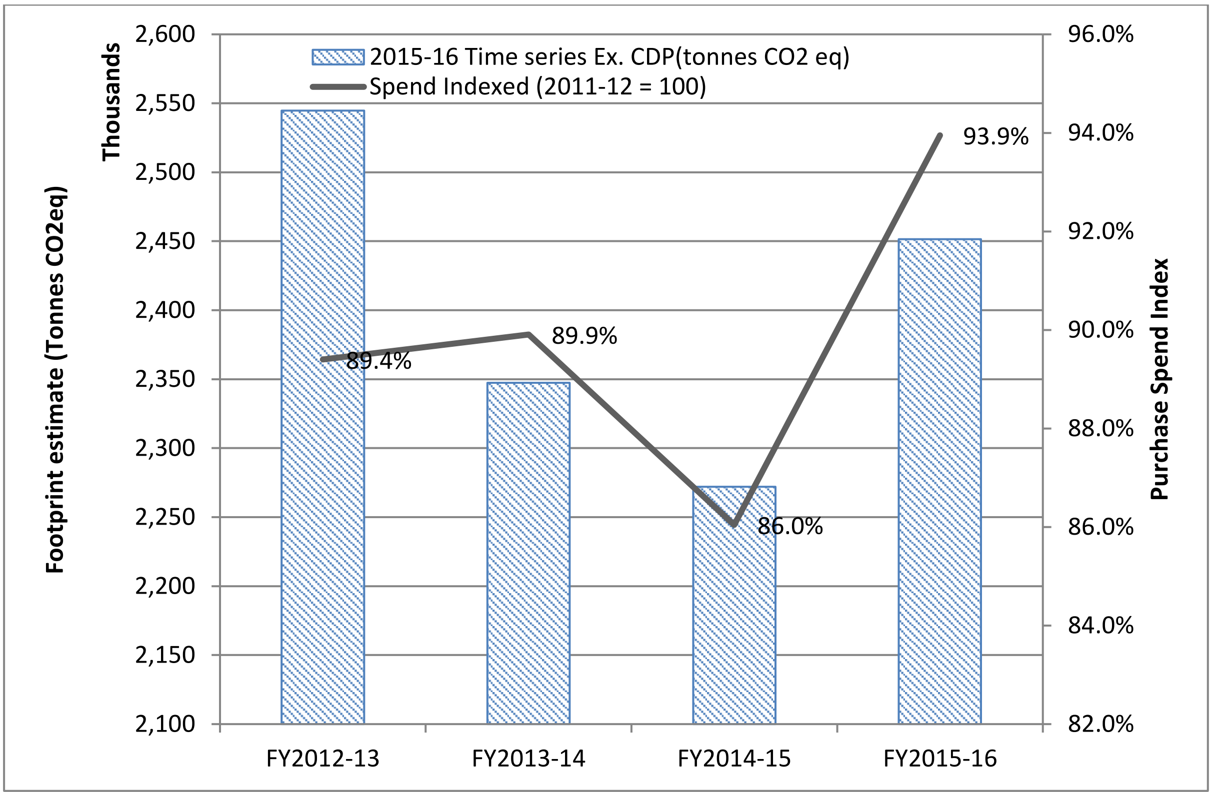
Figure 3 Footprint Time-series Contemporaneous and Indexed Spend



Summarising the initial position in FY2011-12, the organisation had reporting on its supply chain emissions at an aggregated level based upon the 123 sector model using 2008 data. As explained in chapter 3, these data have to be adjusted using consumer price index (CPI) data to match it to the reporting year of the organisation. This means that the data do not reflect any changes in the structure of the economy that would be reflected in more up to date input-output tables, although the CPI will provide some indication as to how pricing for the product group has changed over the course of the intervening period. In FY2012-13 the same ONS data were used with the same spend categories and adjusting using CPI for 4 years. In FY2013-14, the new model using the most up to data (at the time 2010 National Accounts) was introduced, along with a revised mapping. The emissions footprint increases markedly by 9.8% for broadly the same spend up by 0.5%. With two radical changes to methodology it is difficult to unpick which has the most effect, but validation modelling carried out at the time gave an indicative estimate for FY2013-14 that was 2.4% higher (based on the 2008 ONS data) than FY2012-13. This would indicate that the mapping changes accounted for a minor part of the change and most of the change was due to the new ONS data on the economy. In the following financial year FY2014-15 the footprint follows spend in a downward trend and again new ONS data (2012) has been used to make the EEIO model. Finally, in FY2015-16 spend and footprint follow opposite trajectories owing to modifications in modelling that are described in chapter 5. To summarise briefly here, these involve a specialised treatment of one purchase category identified as a result of hotspot analysis, and a change in the adjustment for financial period to use the Purchaser's Pricing Index (PPI) rather than CPI.

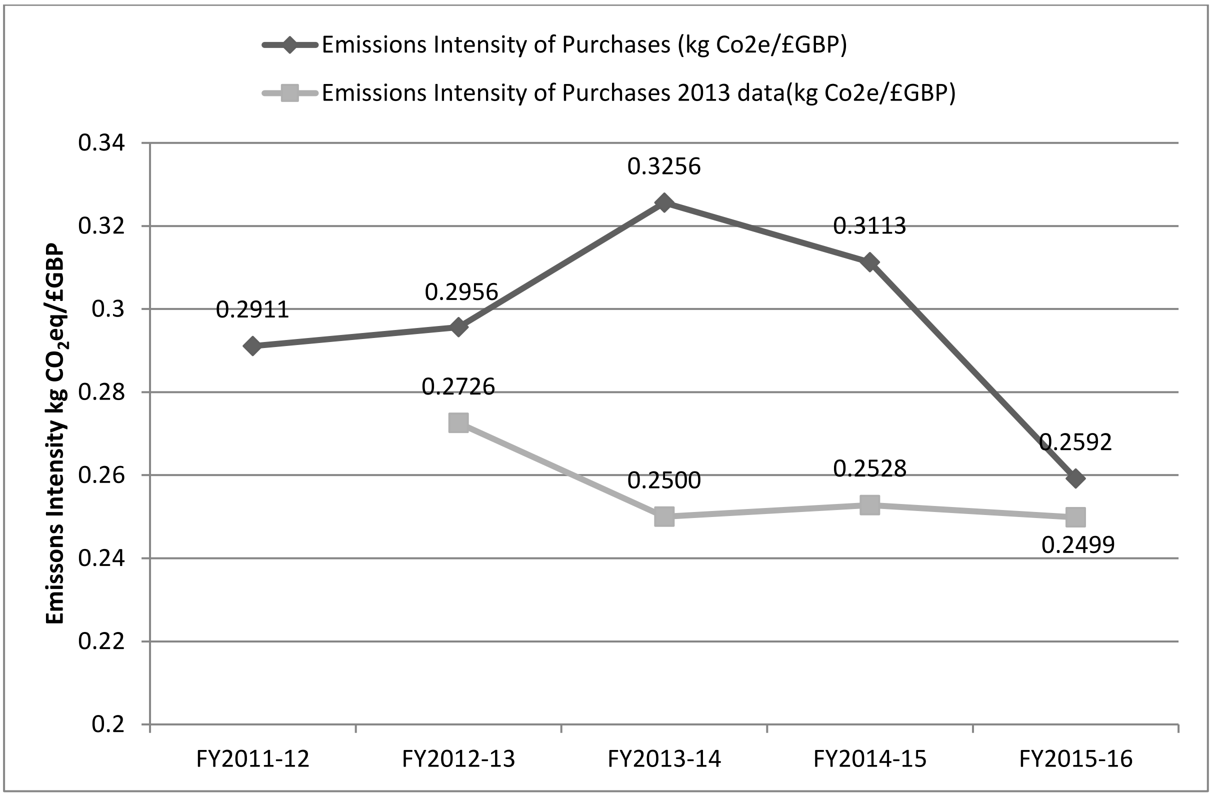
As a time-series of EEIO models are now available it is possible to consider how the footprint changes based upon the most up to date national accounts in 2013. This is presented in Figure 4.

Figure 4 Footprint estimate for FY2012-13 to FY2015-16 using 2013 Data and excluding CDP data



This separates out the differences between the data and from FY2013-14 onwards shows a closer correlation between spend and footprint. in FY2012-13 the mapping is from 56 purchase categories to the 106 sectors of the national accounts and this might have some impact. However, a greater factor is possibly a change emphasis of spending. Between FY2012-13 and FY2013-14 the organisation began spending around 5.1% of the qualifying spend in a newly created top level category called "TV content" where the majority of spend was assigned to either categories 59 "Motion picture, video and TV programme production services, sound recording & music publishing", 60 "Programming and broadcasting services", or 77 "Rental and leasing services". Sectors 59 and 77 have medium to low carbon intensities in the range 0.31 to 0.35 kg CO_2eq/GBP, with 60 being around 0.17 kg CO_2eq/GBP. This was found to be replacing spending that had previously been assigned to sector 26 "Computer, electronic and optical products" which had an intensity considerably higher than the others at 0.42 kg CO_2eq/GBP. Hence there is a considerable difference between the two years in the contemporaneous time series which other than that shows a close link between spend and footprint which can be seen more clearly in a graph of purchase emissions intensity, an aggregate statistic of the total supply chain emissions divided by the total spend and is shown in Figure 5.

Figure 5 Comparison of Emission intensity using contemporaneous data, and time series calculated using 2013 ONS data



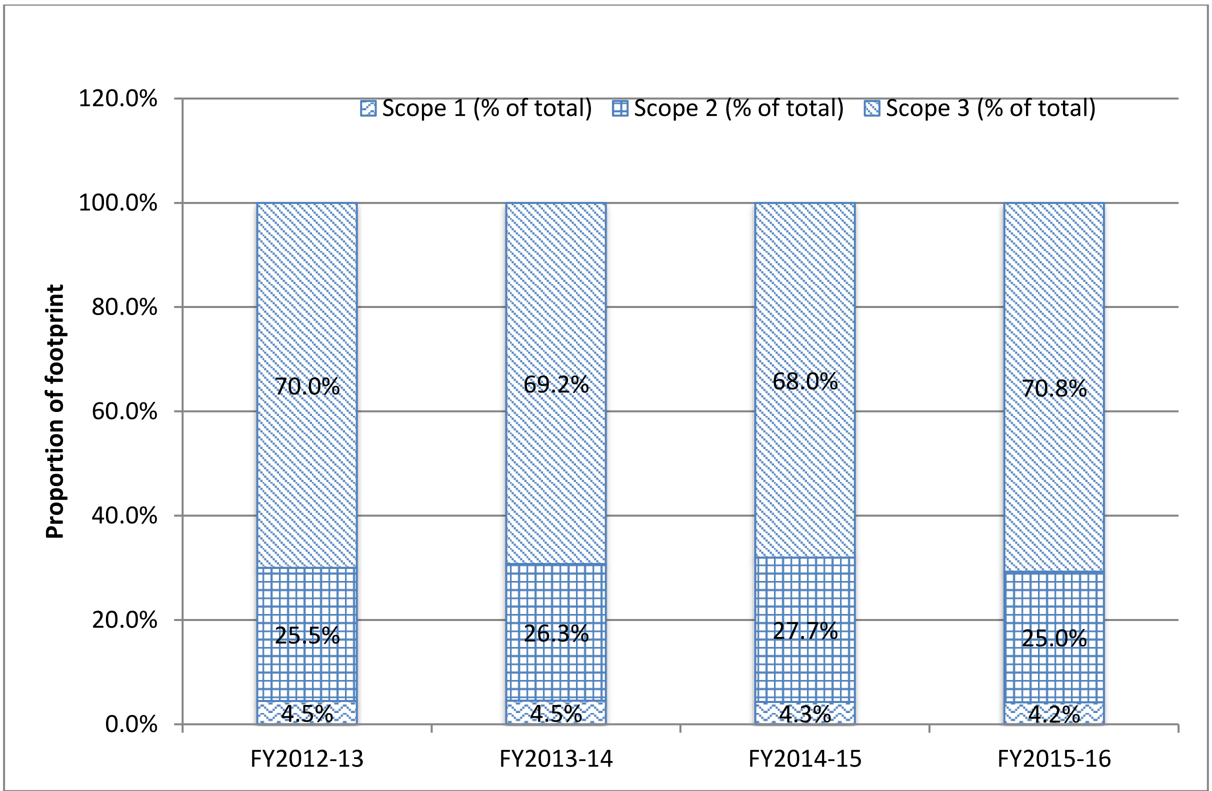
The influence of inflation is that emissions intensities tend to decrease over time – the effect is to decrease the amount of emissions bought with each pound. However, CPI reflects changes in consumer spending and thus might not reflect the changes that business purchasers experience. As this organisation is good at controlling costs, and striking good deals, it is likely that its spend does not go up with CPI. They enjoy therefore an automatic reduction in emissions footprint provided that inflation occurs. However, in a zero to negative inflation period such as the UK has endured through 2014 – 2016, this performance "improvement" is no longer guaranteed, so better visibility of the company's supply chain performance on carbon emissions reduction arises. This effect can be seen in Figure 5, where the emissions intensity barely changes between FY2013-14 to FY 2014-15 to FY2015-16 which have a CPI adjustment of one and two years respectively. This can be a disappointment for the organisation, but the use of up to date data offers the best estimate.

The current policy of ONS is to publish the national accounts with balanced accounts available for two years previous. The latest version of the Blue Book, as this information is commonly referred to, was released in 2015, and contained a balanced set of accounts for 2013. This is the data that were used for the most current estimate made in 2016 for FY2012-16, the CPI data being used where necessary to deflate those figures. The information is only two years old as opposed to the calculations in 2012 and 2013 which were based upon 2008 data deflated to February 2011, and September 2012 respectively and thus were at best three years behind. If the ONS remains on this schedule then the calculations for any given financial year will be based on data that are only 2 years old which will reduce the possibility for CPI to have an inordinate effect on emissions estimates.

4.4.2 Breakdown by Scope

Although this is a company that provides mainly services, it also has scope 1 and scope 2 emissions. The relative proportions of the Scope 1,2, and 3 emissions are presented at Figure 6.

Figure 6 Proportion of Scope 1,2 and 3 Emissions



As will be noted the proportions vary little over the time series, but the significance of the supply chain emissions is evident. It should also be noted that the company makes purchases of renewable electricity to offset its use of electricity so its net scope 2 emissions are less than 1% of its footprint. The possibility of influencing the supply chain and thus reducing its scope 3 emissions is one of the challenges undertaken by this organisation. There have been a number of approaches to this challenge, many of which have been aided by the use of EEIO modelling. An early approach to understanding the impact of products on the supply chain footprint is discussed in the next section.

4.4.3 Analysis of Plastics and Paper in Supply Chain

The organisation was interested in understanding the impact of trying to impose supply chain product related policies with its suppliers. Accordingly, two areas that are commonly associated with high emissions intensities were selected: 1) use of paper; and 2) use of plastics. An analysis was carried out to model the impacts of policies such as ensuring that the supply chain use only recycled paper products or should include a percentage of re-cycled plastic in plastic products.

In order to make these estimates, a brief foray is needed into the toolbox of Input-Output Modelling to explain how these calculations can be made. First we consider how the impact of different levels of the supply chain can be calculated.

4.4.3.1 Taylor Series Expansion

In the early years of Input-Output analysis when inverting large matrices was computationally difficult, a technique was developed that allows a more straightforward calculation and also provides insight into how the supply chain contributes to the total emissions intensity. Following Miller & Blair (2009), consider the following equation:

$$(\boldsymbol{I}-\boldsymbol{A})(\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\cdots+\boldsymbol{A}^N) \quad (4.8)$$

Where $\boldsymbol{I}, \boldsymbol{A}$ are the identity and technical coefficients matrices, and N is an arbitrary but large number. Note also:

$$0 < a_{ij} < 1 \qquad (4.9)$$

which means that $\boldsymbol{A}^N \rightarrow \boldsymbol{0}\ as\ N\ increases$. Then expanding equation (3.8) gives:

$$\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2\cdots+\boldsymbol{A}^N-\boldsymbol{A}-\boldsymbol{A}^2-\cdots-\boldsymbol{A}^{N+1}=\boldsymbol{I}-\boldsymbol{A}^{N+1} \qquad (4.10)$$

So:

$$(\boldsymbol{I}-\boldsymbol{A})(\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\cdots+\boldsymbol{A}^N)=\boldsymbol{I}-\boldsymbol{A}^{N+1}\approx \boldsymbol{I}\ for\ sufficiently\ large\ N \quad (4.11)$$

By comparing with the definition of an inverse matrix:

$$(\boldsymbol{I}-\boldsymbol{A})(\boldsymbol{I}-\boldsymbol{A})^{-1}=\boldsymbol{I} \qquad (4.11)$$

We reach the following:

$$(\boldsymbol{I}-\boldsymbol{A})^{-1}\approx(\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\cdots+\boldsymbol{A}^N) \quad \text{(Miller and Blair, 2009)}$$

The economic interpretation of this, is that the inverse $(\boldsymbol{I}-\boldsymbol{A})^{-\mathbf{1}}$ known as the Leontief can be estimated by summing the successive powers of $\boldsymbol{A}$ and this also gives an estimate of the input required at each level of the supply chain. Combining this with equation (3.16) from chapter 3 gives:

$$\boldsymbol{e}^{\boldsymbol{total}} = \boldsymbol{L}\boldsymbol{e}^{\boldsymbol{pp}} = (\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{e}^{\boldsymbol{pp}} \approx (\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\cdots+\boldsymbol{A}^N)\boldsymbol{e}^{\boldsymbol{pp}}$$

Multiplying out the bracket gives

$$\boldsymbol{e}^{\boldsymbol{total}} \approx \boldsymbol{e}^{\boldsymbol{pp}} + \boldsymbol{A}\boldsymbol{e}^{\boldsymbol{pp}} + \boldsymbol{A}^2\boldsymbol{e}^{\boldsymbol{pp}} + \cdots + \boldsymbol{A}^N\boldsymbol{e}^{\boldsymbol{pp}}$$

this can be seen as showing the vector of total emissions intensity $\boldsymbol{e}^{\boldsymbol{total}}$, being made up of the vector of direct emissions intensity plus a contribution from tier 1, tier 2 up to tier N suppliers. Hence the contribution of different layers of the supply chain can be estimated. In the second excursion into the toolbox, we decompose the emissions intensity for an industry sector into the contributions of each of the industry sectors.

4.4.3.2 Industry Emissions Intensity Analysis

Consider an intermediate stage in the calculation of $\boldsymbol{e}^{\boldsymbol{total}} = \boldsymbol{L}\boldsymbol{e}^{\boldsymbol{pp}}$, the calculation of the ith element of $\boldsymbol{e}^{\boldsymbol{total}}$ given by:

$$e_i^{total} = \sum_{j=1\ to\ n} l_{ij} \times e_j^{pp}$$

And explicitly, writing the series out:

$$e_i^{total} = l_{i1} \times e_1^{pp} + l_{i2} \times e_2^{pp} + \cdots + l_{in} \times e_n^{pp}$$

Which could be crudely expressed in words as the total emissions intensity of sector i is the sum of emissions per unit output of each industry sector j. Hence the emissions contribution of any sector j to any other sector i can be calculated and is given by:

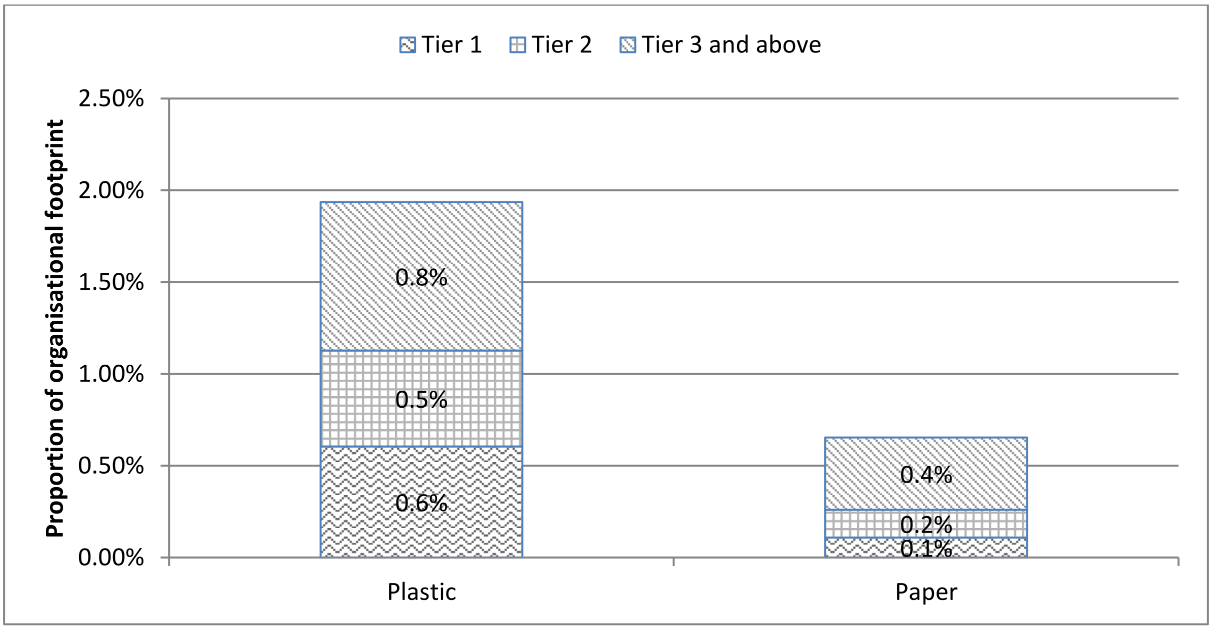
$$e_{ij}^{total} = l_{ij} \times e_j^{pp}$$

These manipulations of the technical coefficients matrix $\boldsymbol{A}$, Leontief Inverse $\boldsymbol{L}$ and the direct emissions intensity $\boldsymbol{e}^{\boldsymbol{pp}}$ allow the decomposition of emissions intensity both by tier of supply chain and industry sector and can be used with the adjustments for financial period, and the organisational model to investigate the impact of particular product sectors within the footprint of an organisation.

4.4.3.3 Results of the Analysis

As noted above the organisation wanted to assess what the possible policy impacts might be of imposing rules such as only using recycled paper down the supply chain. The analysis was intended to put some bounds on the reductions in footprint that might be expected. The process for estimating the carbon footprint for both of the areas is similar. On examination paper can be considered to comprise 2 of the sectors of the UK economy – one comprising “Pulp, paper & paperboard” and the other “Paper & paperboard products”. Similarly, plastic can be considered to comprise 2 sectors “Plastics and Synthetic Resins etc.” and “Plastic Products”. From the section above we have seen how an industry sectors emission intensity can be decomposed into the contributions of each of the other industry sections. So we can derive an emissions intensity vector that comprises just the contributions of the two sectors for paper (or plastic) for each of the industry sectors. We can then use our mapping from industry spend categories to UK national accounts categories to calculate spend in national accounts category. Then multiplying these spends by the decomposed emissions intensity vectors allows us to estimate the total of emissions arising from either paper products or plastic products. Using the Taylor series expansion, we can calculate the amounts of emissions that occur at each level of the supply chain. The results of the analysis are presented in Figure 7.

Figure 7 Total and Breakdown by supply chain tier Proportion of Plastic and Paper to Organisational Footprint



Firstly, it will be noted that the two categories actually represent a reasonable proportion of the supply chain, but of the two products, plastic dominates. Secondly that quite a high proportion of the emissions associated with these products are at Tier 1 and Tier 2 of the supply chain and hence are potentially within the influence of the purchaser. This analysis allowed the organisation to make an appraisal of the upper bound of the improvement offered by the imposition of supply chain policies. Clearly there are some weaknesses in this analysis, for example it reflects the technology a number of years before the analysis owing to the nature of the modelling. In addition, the aggregated nature of the sectors conceals a level of complexity about how exactly improvements in emissions might be made. Plastics for example are complicated, as all the different types of plastic products are gathered together, with possibly a wide range of options to change processes. Finally, the analysis is weakened by having no mechanism for feeding back the effectiveness of policies implemented as it is based on national accounts data only.

The approach does illustrate however how policy areas can be quickly assessed, and areas that are likely to be fruitful for supplier action identified. The organisation can focus in on areas where their efforts are likely to result in greater reductions in emissions. Another slightly different approach is considered in the next section.

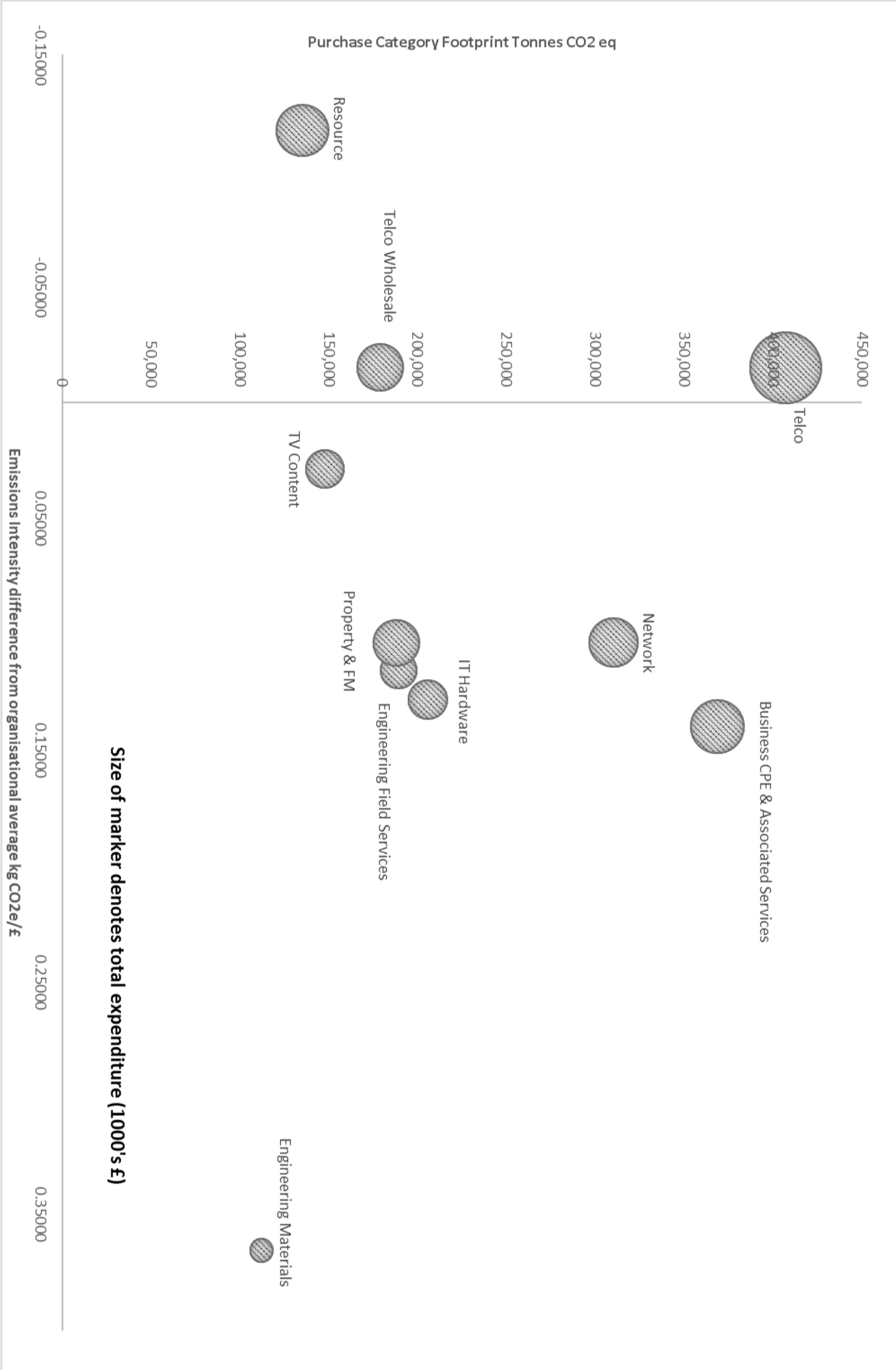
4.4.4 Hotspot Analysis

From the preceding section, we have seen how it is possible to analyse an organisational footprint through a lens that relates to particular products. This cuts across the departments of the company and highlights those products in the supply chain everywhere they may occur. This requires the implementation of a companywide policy which may be difficult to enforce. The company naturally organises its purchases by top level category and these are administered by specialist purchasing teams. If a top level category can be identified that is responsible for high levels of emissions, then the purchasing team for that area can be tasked with seeking improvements. From above we note that there are two factors in total emissions, spend and emissions intensity. Accordingly, an analysis was carried out that considered emissions by top level category combining data on footprint, spend and emissions intensity. The results are presented in Figure 8, where the top 10 top level categories by size of footprint are plotted against the Emissions Intensity (EI) difference from the unweighted organisational average. This highlights by horizontal position how emissions intensive a particular purchasing area is, and by vertical position the significance of the footprint of that category. From this analysis it is possible to pick out "Engineering Materials" as a possible prospect for investigation on the grounds that any improvements in material use would have a substantial impact on footprint without impacting too highly on spend. Other areas are highlighted as being fruitful but the categories "Telco", "Telco Wholesale" and "Resource" could be considered lower priority than categories to the right of the vertical axis as they are less than the company average. Clearly though there may be room for improvement in these sectors as they are significant contributors to the total.

Some limitations of the EEIO modelling apply to this approach, for example generic nature of the sectors limits the detail, for example the “Telco” and “Telco Wholesale” purchase categories are assigned to sector 61 “Telecommunications services” of the national accounts which is representative in general of the purchases made in this sector but may not reflect the difference implied by the use of the word “Wholesale”. Again, the caveats about the technology being slightly behind the report and the lack of feedback to the model for efficiency improvements implemented apply.

This shows the power of the dataset of spend and emissions intensity combined. It is also possible but not shown here for reasons of confidentiality to analyse suppliers’ contribution to footprint in a similar way. Further analysis was undertaken to intersect product category and supplier which potentially provides very targeted information. The company knows the suppliers it needs to involve in efficiency programmes and furthermore can indicate product categories that should be fruitful.

Figure 8 Bubble Chart of top 10 Top Level Categories, x axis is Emissions Intensity difference from organisational average, y axis is Purchase Category Footprint, Bubble size Spend in £,000s



4.5 What was the impact on the focal organisation

The organisation that was the focus of the case study had already invested substantially in sustainability, reported the results of GHG emissions, and had explored several of the common strategies, for example: It had established a sustainability policy that was implemented and overseen by the board, and included commitments to:

1) Measure end to end emissions, including emissions arising from the use of products and services, and report on them annually;
2) Using electricity from renewable supplies,
3) Setting targets for energy efficiency in devices, and for the supply chain.
4) Encouraging users to substitute telecommunications services for more carbon intense activities.

The company derived a strategy that compared the emissions saved using the services offered by the organisation and compared them with the supply chain (Scope 3) emissions with a view to maintaining a positive ratio and increasing this ratio so that the impact of the organisation was compensated by those using its services. The ongoing estimation of supply chain scope 3 emissions forms part of the evidence that the company is progressing towards its objective.

The analysis of hotspots within the company chain allowed estimates to be made of the impact of potential changes in purchasing policies. The incorporation of supplier provided data (discussed in chapter 5) provided the opportunity to engage with suppliers – which the company encouraged by forming an association of suppliers, which meet to discuss best practices. The results of our analysis have been fed back to purchasing managers and to the Vice President of purchasing.

4.6 Conclusion

Currently the major contribution of EEIO modelling to this organisation is to facilitate the reporting of a substantial part of their footprint, supply chain carbon and the upstream supply chain elements of their scope 1 & 2 emissions. As part of their financial reporting they include and update their sustainability report which in turn depends upon an environmental audit. The level of trust the company have in the results of analysis are reflected in three ways:

1) They are willing to share sensitive financial data with Small World in order to undertake the analysis;
2) They are willing to allow the work to be audited by a third party:
3) The analysis forms a substantial part of their public statement of the company's sustainability.

The use of EEIO modelling has other advantages to businesses, it is flexible in its use and can be adapted to allow the use of other methods of estimation. This can be accommodated as long as the boundaries of the methods can be established to minimise or avoid double counting. This flexibility means that the company has often approached us for sophisticated ad-hoc analyses, knowing that the tool that we use can usually be adapted to provide an answer to their request.

As the reporting of the footprint is aligned with accounts, it is easy to make the estimates available in terms that the company already understands and which are regarded as significant by the company. As a result, they can target their efforts precisely. Furthermore, when the sustainability division is reporting to main board or other areas of the company they have a common framework within which to work.

Over the years, the footprint has been calculated using the best available model and data available. The company relies upon the model to understand the differences between years. With the model updated to use the most recent Standard Industry Code (SIC) and Classification of Products by Activity (CPA) classifications, the full UK accounts time-series is accessible for modelling purposes. The most recent iteration of the model that uses this time-series provides a consistent presentation of the footprint over a period of 4 years where previously shifts in methodology had impacted on their reporting. In future, a rolling 5 year estimate of the footprint will be provided.

The final, and most significant aspect of how the foot-printing tool is regarded by the company, is that they have used their contacts with Carbon Disclosure Product, to make the product available to their suppliers. The wider implications of the method for business sustainability are discussed in chapter 7.

In the next chapter, the hybridisation of the model to deal with particular details of reporting is described.

Chapter 5 Hybridisation of the Model

5.1 Introduction

The previous chapters have outlined the process for constructing a single region input-output model based upon the UK economy. The application of this model to the estimation of the emissions of organisational supply chains has been illustrated and discussed. The input from the organisation in this process is that of providing financial data, data on direct emissions, and commuting and business travel. The organisation also has to cooperate in deriving an understanding of how the purchasing categories of the business are reflected in the mapping to input-output classifications. The types of analyses discussed in the previous chapter have highlighted that often a substantial proportion of a company's footprint may arise from specific groupings of purchases. The first part of this chapter (section 5.2) discusses the investigation of a top level category, and the subsequent modifications in the application of the model. The modifications involve the decomposition of the emissions intensities by national account category and the definition of a hybrid category using EEIO modelling and process based data. This combination is used to refine the footprint estimate of the organisation.

The second part of this chapter (section 5.3) discusses the involvement of suppliers in providing information about their processes and how this might be utilised in improving footprint estimates. By definition scope 3 emissions of an organisation are beyond the direct control of that organisation. However, there is a significant dialogue between organisation and their supply chain. This can be facilitated by membership of non-profit bodies such as the Carbon Disclosure Project (CDP). This body exists to allow the interchange of sustainability data between companies in a standard format. With this data the model can be extended to include supplier specific data and provide a mechanism for supply chain improvement to be included in footprint estimates.

5.2 Modification of Purchase Categories

The type of analysis outlined in the previous chapter allows the identification of areas within an organisation that are associated with either high total emissions or high emissions intensity. These areas might prove a fruitful area for further analysis, perhaps leading to supply chain initiatives or other measures. The organisation analysed in the previous chapter had introduced a new top level category reflecting an important new strategic area for the company. This top level category "TV content" comprised a number of purchase categories that were mapped to a variety of national account sectors and accounted for 8.2% of spend, and 8.1% of emissions in the supply chain. The breakdown of spend and emissions by purchase category is shown in Table 12.

Table 12 Breakdown of Top Level Category "TV Content" FY2015-16

Breakdown of Top Level Category “TV Content” FY2015-16		
Purchase Category	Proportion of spend	Proportion of emissions
TV Content.Licence/Royalties.Acquired Rights Creditor Settlements.	78.91%	80.26%
TV Content.Production.Sports Production Services.	6.64%	5.66%
TV Content.Licence/Royalties.VOD.	2.41%	2.45%
TV Content.Content.All.	2.79%	2.38%
TV Content.Licence/Royalties.Sports Conditional Access fees.	2.34%	2.38%
TV Content.Playout & Capacity.Satellite and Uplinking.	1.39%	1.42%
TV Content.Licence/Royalties.Recurring Licence costs.	1.15%	1.17%
TV Content.Production.Sports Studio Production Facilities.	0.63%	1.07%
Purchase categories responsible for less than 1% of emissions omitted for clarity.	3.75%	3.20%

One purchase category is responsible for the majority of emissions and spend that of “TV Content.Licence/Royalties.Acquired Rights Creditor Settlements.” When mapping to UK national accounts, reference is made to the detailed breakdown of CPA2008 which lists the thousands of products and how they are related to the aggregated sectors that are used in the national accounts(Eurostat, 2009). In the detailed breakdown of CPA2008 it is not clear what IO category this type of activity should be assigned to. It does not sit in the category of “59 Motion picture, video and television programme production, sound recording and music publishing activities” as this sector is concerned with production and not acquisition of rights. The acquisition of rights is mentioned in the CPA code “77.40 Licensing services for the right to use intellectual property and similar products, except copyrighted works” and this is included in IO category “77 Rental and leasing services”. This sector was selected to be the mapping for this purchase category and used in the contemporaneous estimates made in 2013-14 and 2014-15. The weakness of using generic sectors is evident as this IO category also includes high emissions intensity areas such as plant and vehicle hire although as will be noted from the results presented previously the remapping did lead to a reduction in overall emissions intensity. Further analysis of the area was requested, and as the dataset includes supplier information it proved possible to identify the suppliers associated with the services provided.

From an analysis of the suppliers in this area, it became apparent that the royalties were paid for sporting events such as football and rugby. So, it could be argued that a better mapping would be to Sector 93 “Sports Activities and Amusement and Recreation Activities”. However, this sector covers a wide variety of sports and leisure activities. In this the sports being covered were large stadium sports. It was decided to analyse the construction and energy expenditures for these types of events. There had been a recent study carried out by Hedayati *et al.* (2014) which analysed the footprint of the construction and operation of an Australian Rules football stadium. The Millennium Stadium in Wales provides an inventory of materials used in construction on its website so it was possible to calculate an estimate of the construction emissions arising from this stadium using Inventory of Carbon and Energy (ICEv2) figures. Finally, the UK government encourages businesses to join the Carbon Reduction Commitment (CRC) project whereby they record details of their carbon emissions relating to energy use. The method used is outlined below.

As discussed above the royalties purchase categories are to be mapped to sector 93 “Sports Activities and Amusement and Recreation Activities” rather than sector 77 “Rental and Leasing” in order to derive the emissions intensity. The results of the EEIO emissions modelling are to be modified by considering two sectors in greater detail – construction of stadia, and use of energy (Scope 1&2 emissions).

5.2.1 Emissions Intensity of Construction

There has been quite considerable work done on the PBLCA of building but little that has been aimed at the construction of stadia. The results in this Hedayati *et al.* (2014) study considered the footprint per match day attendance of building and operating the stadium but did not quote a total footprint of construction. In addition, the study was carried using Australian LCA figures. This provided some idea as to how a footprint of construction could be calculated in a UK context. The Millennium Stadium in Wales provides an inventory of materials used in construction on its website. It was possible to estimate the construction emissions arising from this stadium and an outline of this is shown at Table 13.

Construction Material	Unit	Quantity	Emissions Intensity (kgCO2e/tonne)	Reference	weight (tonnes)	Emissions (tonnes CO2e)
concrete	tonnes	40,000	107	ICE v2.0		4280
structural steel	tonnes	12,000	1530	ICE v2.0		18360
Steel reinforcement	tonnes	4,000	1400	ICE v2.0		5600
Block Work	m^2	34,000	107	ICE v2.0	3817	408
Steel tubing	km	22	1450	ICE v2.0	20.54	29.8
Stainless steel tubing	m	560	6145	ICE v2.0	0.53	3.2
galvanised tubing	km	5	1540	ICE v2.0	4.67	7.2
Cast Iron Piping	km	15	2032.24	ICE v2.0	446.77	907.9
wash handbasins	unit	640	1610	ICE v2.0	3.2	5.2
toilet pans	unit	760	1610	ICE v2.0	15.2	24.5
Total						29,626

Table 13 Structural Elements of Millennium Stadium Cardiff, (http://www.millenniumstadium.com/information/facts-and-figures.php#.VnGe7jYrFOI)

5.2.2 Estimate of Stadia Energy Use

The use of stadia is characterised by relatively low energy use for long periods, punctuated by short periods of high energy use when the stadium is in use. Within the UK, it is a requirement for large energy users to be registered with the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme. As part of this process, these users are required to notify their carbon emissions associated with energy by calendar year. Several football clubs and arena operators are listed with CRC, and hence it was possible to obtain information about their energy related carbon emissions in 2012-13, and 2013-14. The estimates of absolute emissions, associated with construction and energy use, can be combined with information about the revenues of stadium operators to estimate an intensity figure.

5.2.3 Revenues of Sports Organisations

The Football Association and Rugby Football Union produce detailed financial statements that allow an assessment of their revenue to be made. The Premiership clubs produce accounts and it is also possible to ascertain the revenues of these clubs by consulting the websites of the clubs.

5.2.4 Calculations of emissions intensity

A construction emissions intensity figure was calculated by amortising the construction footprint of the Millennium stadium over 30 years and normalising to the seat capacities of a sample of Premiership football teams. This per-annum figure was then divided by the revenue of the operators of the stadia to derive an estimate of the construction emissions intensity of $e_{93}^{pblca} = 0.0039067$ kgCO2e/£. For five premiership or championship football clubs, and for the Rugby Football Union Stadium at Twickenham, the CRC emissions figures were divided by revenue to derive an estimate of Scope 1 and 2 emissions energy intensity of $e_{93}^{CRC} = 0.039157$ kgCO2e/£ (based on 2013-14 season). These figures were substituted for the EEIO calculations of "Construction" emissions intensity and the direct and scope 2 emissions intensity of the "Sports Activities and Amusement and Recreation Activities" sector to obtain an estimate of the emissions intensity which should be applied to sport royalties payments.

To summarise the calculation of the emissions intensity associated with these purchase categories we need to use some of the techniques outlined in chapter 4. Recall that the Leontief inverse $\boldsymbol{L}$ can be approximated by a Taylor Series Expansion (section 4.4.3.1):

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \approx \boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \cdots + \boldsymbol{A}^N, for\ some\ suitably\ large\ N$$

And that therefore, total emissions intensity can be written:

$$\boldsymbol{e}^{total} \approx \left(\boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \cdots + \boldsymbol{A}^N\right)\boldsymbol{e}^{pp} \qquad (5.1)$$

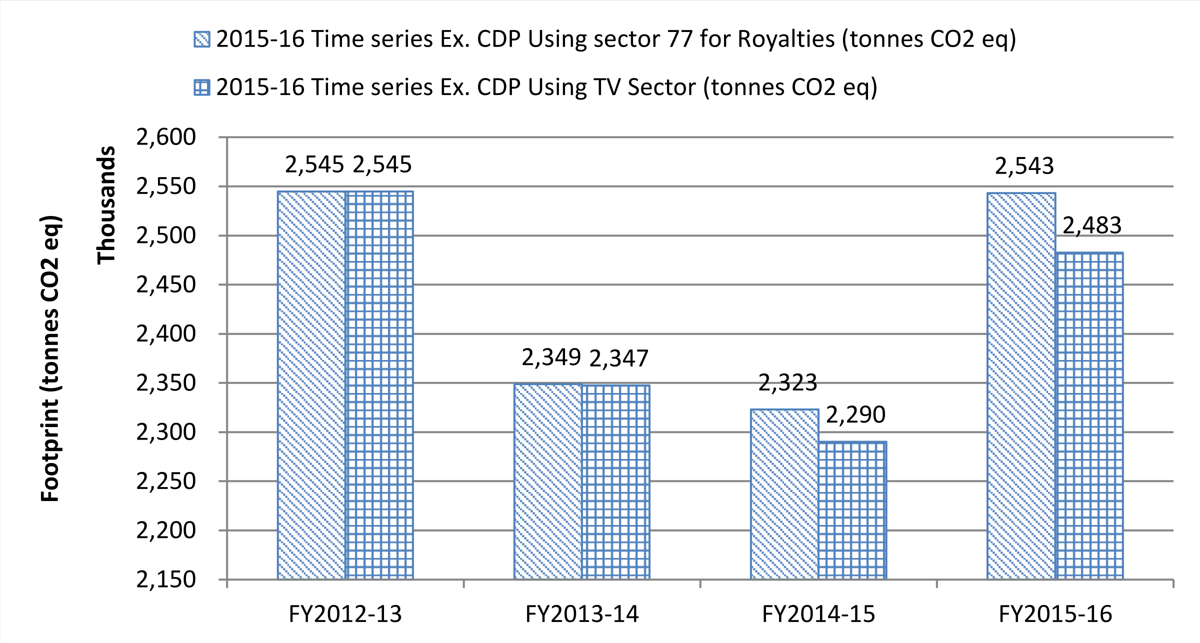
where $\boldsymbol{e}^{pp}$ is the vector of direct emissions intensity for the n industry sectors, then considering the element e_{93}^{total}, the total emissions intensity for sector 93, this is calculated by:

$$e_{93}^{total} = e_{93}^{CRC} + e_{93}^{pblca} + \left(\sum_{j=1\ to\ n} a_{93,j} \times e_j^{pp} + \sum_{j=1\ to\ n} a_{93,j}^2 \times e_j^{pp} + \cdots \right) - \left(a_{93,35.1} \times e_{35.1}^{pp}\right) - \left(a_{93,(41,42,43)} \times e_{(41,42,43)}^{pp}\right) \qquad (5.2)$$

In this ungraceful equation, e_{93}^{CRC} represents the scope 1 and 2 energy intensity calculated from CRC figures and e_{93}^{pblca} the emissions intensity of construction derived from PBLCA. The first bracket represents the tiers of the supply chain. The second bracket represents scope 2 emissions being the emissions arising from sector 35.1 "Electricity, transmission and distribution" in tier 1 of the supply chain. Finally, the third bracket represents the contribution from sector 41,42 & 43 "Construction".

Applying the revised sector results in small decreases in FY2013-14, increasing through FY2014-15 and FY2015-16 reflecting increased spend in this area. The results are presented at Figure 9.

Figure 9 Bar chart of the impact of using "TV Content" hybrid sector in footprint Estimation



This modification attempts to address one of the issues identified with EEIO modelling in the assessment of supply chain carbon emissions which is that the financial model used is highly aggregated. With modern organisations buying many thousands of items it could be argued that the use of an aggregated model with perhaps 106 or 110 sectors is not sufficient. However, as previously noted, organisations do not tend to carry out financial analysis at the individual product level. Their financial information is typically at product category level, i.e. how much money is spend on capital goods, perhaps split into for example motor vehicles, computers etc. The organisations would probably find it quite difficult to quantify their purchases below this level but even if they could do so, it is unlikely that Process Based Life Cycle Analyses exist for all the products and services bought so there must be some use of generic analysis simply to reduce the resources required to manageable levels. The approach in this section allows some use of PBLCA to be used in conjunction with EEIO. In the next section, we move to considering how information from suppliers can be integrated with EEIO.

5.3 Supplier Provided Data

This section investigates the combination of data on direct (scope 1) and scope 2 emissions from the suppliers to the company with existing modelling. This combination of supplier information and EEIO modelling is novel and illustrates another method for improving footprint estimates using hybrid modelling. The methodology and some initial results were presented at the International Input-Output Association (IIOA) 2014 Conference and the paper is included in Appendix D. This section shows how the supplier scope 1&2 emissions intensity, $\epsilon_{scope1\&2}^{(CDP)}$ is integrated into the model described above, provides an update on the data, and presents the results from three years of analysis.

5.3.1 Integration into Hybrid Model

In section 4.3.1, we described the construction of a Purchase Category emissions intensity e_{p_i} from a weighted average of emissions intensities (e_i^{total}) derived from the UK accounts. In the previous section we have discussed how a national accounts emissions intensity can be decomposed into a series consisting of the direct emissions intensity, e_i^{pp}, and a Taylor series:

$$e_i^{total} = e_i^{pp} + \sum_{j=1 \; to \; n} a_{i,j} \times e_j^{pp} + \sum_{j=1 \; to \; n} a_{i,j}^2 \times e_j^{pp} + \cdots \qquad (5.3)$$

where the summations in the equation above represent the impacts at successive levels of the supply chain. This allows the separation of scope 1 emissions, e_i^{pp}, and scope 2 emissions, $(a_{i,35.1} \times e_{35.1}^{pp})$. By subtracting the scope 1 & 2 emissions from the total, we can derive a scope 3 emissions intensity:

$$e_i^{Scope\ 3} = e_i^{total} - e_i^{pp} - \left(a_{i,35.1} \times e_{35.1}^{pp}\right) \qquad (5.4)$$

This allows the Purchase Category emissions intensity e_{p_i}, to be split into two elements

$$e_{P_i}^{Scope\ 3} = \sum_{j=1 \; to \; n} w_{ij} \times e_j^{Scope\ 3} \qquad (5.5)$$

And bundling the other two emissions intensities together we can define:

$$e_{P_i}^{Scope\ 1\&2} = \sum_{j=1 \; to \; n} w_{ij} \times \left(e_j^{pp} + \left(a_{j,35.1} \times e_{35.1}^{pp}\right)\right) \qquad (5.6)$$

with of course,

$$\sum_{j=1 \; to \; n} w_{ij} = 1 \qquad (5.7)$$

So then for suppliers who have reported to the CDP, emissions per unit revenue, or sufficient information to allow it to be calculated, we can calculate the emissions arising from expenditure with them. Consider a supplier Y, who has provided such data and for whom an emissions per unit revenue figure has been determined for a particular financial year and the supplier provides goods in a set $U = \{P_i, P_j, \cdots\}$ of purchase categories, with spends in each purchase category of $\{S_{p_i}^Y, S_{p_j}^Y, \cdots\}$ then total emissions for that suppler, E^Y are given by:

$$E^Y = \sum_{\{U\}} S_{P_U}^Y \times \epsilon_{scope1\&2}^{Y(CDP)} + \sum_{\{U\}} S_{P_U}^Y \times e_{P_U}^{Y(Scope\ 3)} \qquad (5.8)$$

The emissions for suppliers who have not disclosed sufficient information can be calculated as described in Chapter 4.

5.3.2 Data Update

There has been a process of dialogue between SWC and the CDP about the quality of the data and particularly the frequent miscalculation by suppliers of the Scope 1&2 emissions per unit revenue. As the scope 1&2 total emissions forms part of the CDP data, it is possible to cross-check the Scope1&2 Emissions intensity by dividing the total by revenue that is publicly quoted. This can sometimes be non-representative as the scope 1&2 emissions may only apply to a subsidiary or subsidiary group of a supplier. As of 2015 an additional data field is requested from suppliers which is that of revenue so that the emissions per unit revenue figure can be checked, or re-calculated if it fails sense-checking.

5.3.3 Results

From the beginning of the project there have been some issues with data quality from the respondents in the survey, so part of the process has been cleaning the data and encouraging good practice amongst suppliers. This seems slowly to be having an effect as can be seen from the data presented at Table 14.

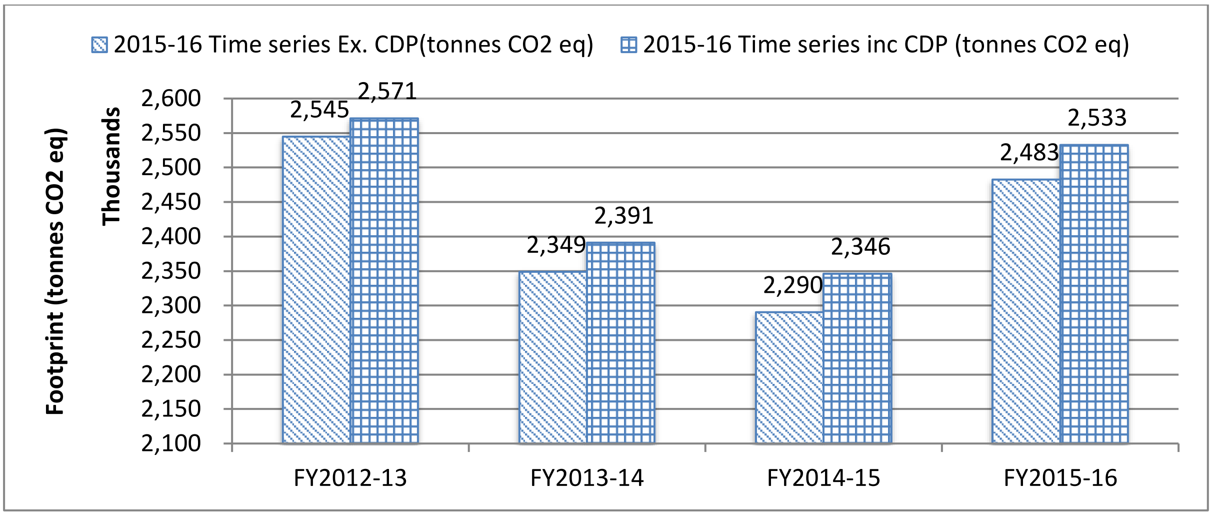
From this it can be seen that both participation and usable data rates are rising. The data from these suppliers covers 37.2% of the supply chain emissions and 5.3% of the supply chain emissions footprint. Recent calculations showed that if all suppliers could be persuaded to report Scope 1&2 emissions intensity then 13.4% of the company’s scope 3 emissions would be covered by supplier provided information.

Table 14 Data Quality Analysis of suppliers reporting to CDP

	Number in 2013	Number in 2014	Number in 2015
All Company suppliers reporting to CDP	100	131	150
Suppliers whose names could not be not matched to Company purchase ledger or have 0 Company spend		2	3
Suppliers whose emissions are excluded from the EEIO based part of the supply chain analysis		9	9
Suppliers whose emissions are included in EEIO-based part of supply chain carbon analysis	100	120	138
Suppliers whose intensity figures pass simple sense checks and are assumed to be usable in the model	37	59	55
Suppliers whose intensity figures are thought to contain error factors of three or more orders of magnitude and are assumed to be usable after this has been corrected.	41	37	42
Suppliers whose intensity figures are not reported or are thought to contain error but have been derived by researching their revenue figure.	9	5	13
Suppliers for whom it is possible, after any necessary corrections and amendments, it was possible to use data reported to CDP to substitute emissions estimates into the Company supply chain model.	87	101	110
Suppliers for whom intensity figures were not supplied and could not be derived since a revenue figure was not available.	13	19	28

The effect of including supplier provided information is shown at Figure 10. Overall the effect of is to increase the estimate of supply chain footprint by between 1% and 2.4%. It is interesting to note that use of supplier provided data indicates that the suppliers are in aggregate, less energy efficient than the UK industry sector(s) that represents the goods and services supplied. This may be for a variety of reasons: the suppliers used may represent the energy intensive end of the spectrum of a generic category; an international supplier may not be well represented by estimates based on the UK; the mapping onto UK accounts sectors may be unrepresentative; or they may be poorly performing in their energy use. Investigating the reasons for differences can improve the footprint estimate, or improve supplier performance. In both of these cases we have a mechanism for incorporating the improvements in the model.

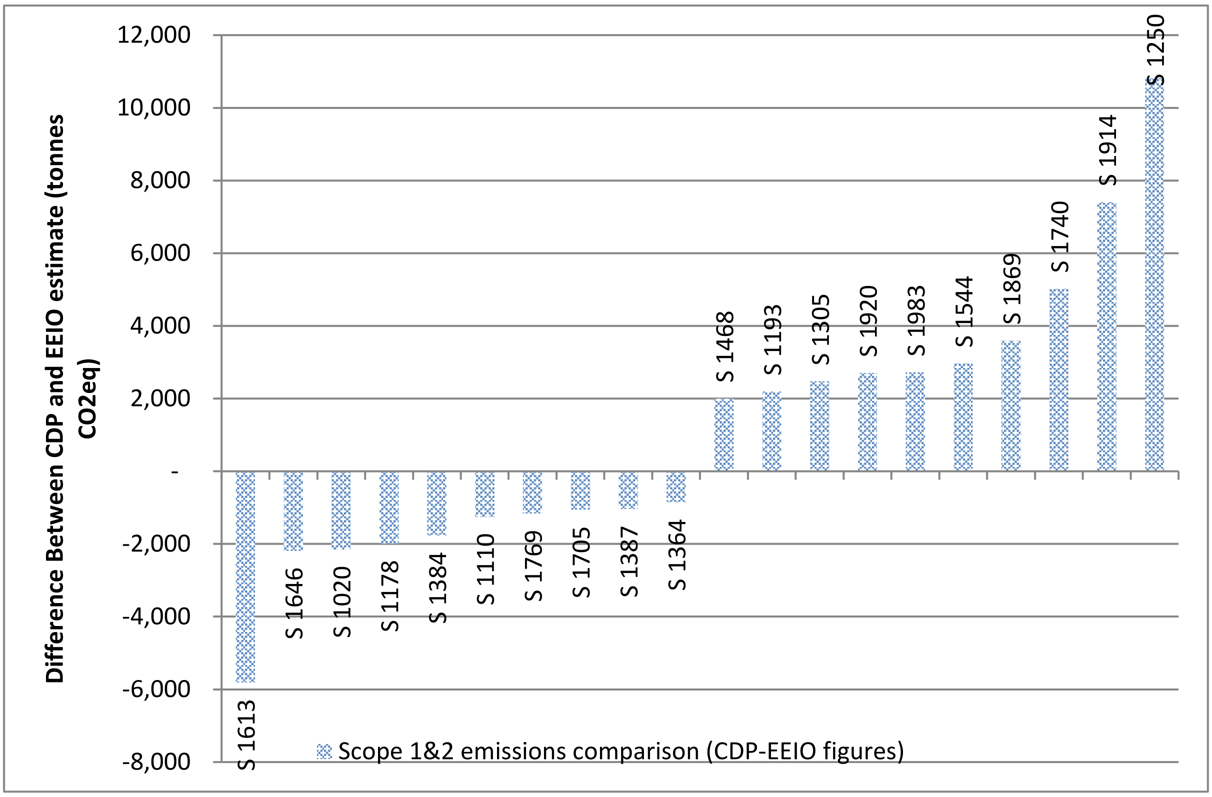
Figure 10 Comparison of the impact of Supplier Provided Data on Footprint estimate (2013 Data on Time Series)



It is instructive to compare the supplier on their scope 1& 2 emissions performance as reported and as estimated using the EEIO model. A breakdown of the suppliers shows that there are variations in performance and these results (anonymised) are presented at Figure 11. On the left hand side this shows the top ten suppliers whose CDP-reported scope 1&2 emissions are lower than those estimated using the EEIO model. These suppliers might then be leaders in the field of energy efficiency and their good practices could be shared with others. The converse applies to those suppliers on the right hand side whose CDP reported emissions exceed those estimated by EEIO. As noted above this may not necessarily be attributed to poor emissions performance but both ends of the spectrum would reward investigation.

The use of supplier provided data can provide insights that are not available from the EEIO modelling. The integration of the two data sources allows an appraisal of supplier performance against their industry sector, albeit in a UK context rather than an international one. This combination of data can be used to begin a dialogue with suppliers about how emissions reductions may be pursued. It also gives suppliers an incentive to participate as any improvements will be incorporated when they report their results to CDP.

Figure 11 Comparison of Suppliers Scope 1&2 Emissions CDP less EIO



5.4 Conclusions

In this chapter, we have demonstrated two ways to hybridise the EEIO model to address some of the weaknesses identified in chapter 4. The first section of the chapter provided an insight into a purchasing area that is significant in terms of its impact on emissions. A modification to the purchase category has been undertaken that potentially represents the services that are purchased under this spending head. From the analysis in chapter 4, several other possibilities for investigation have been identified.

In the second section, we have considered the use of an alternative dataset to provide information on supplier scope 1&2 emissions, and shown how these can be integrated on a supplier by supplier basis. The results of the analysis provide potential examples of best practice, and candidates for discussion about their emissions performance. The modification allows for the results of any changes in practice to be reflected in the results of the footprint estimation as soon as they are reported to CDP, or sooner if the data demonstrating it can be verified. There is nothing to preclude the use of both methods together if necessary.

The results have shown a reduction of 60,000 tonnes CO_2 eq. in the estimate of the 2015-16 footprint by using the hybrid sector, and a slight increase of 50,000 tonnes CO_2 eq. using supplier provided data.

Chapter 6 Critique of EEIO modelling for Supply Chain Footprinting

6.1 Introduction

The technique of EEIO modelling in supply chains offers a considerable strength in that it uses a top-down technique, that in principle, captures emissions from the whole of the supply chain. The nature of the model, and the way that it is used, lead to a comparison with the financial accounts of the organisation. These are audited and balanced throughout the process of compilation and publication, so that the figures may be trusted by those who use them. The footprint estimate arising from this model is often presented as a point estimate perhaps to emulate the certainty offered by financial accounts. This kind of precision is unwarranted given the underlying uncertainties of the model. This chapter discusses the causes and impacts of the uncertainties in this estimation technique.

Unfortunately, it is not the case that GHG emissions are recorded by invoices raised, and credits received, as is the case for the financial accounts. The basis of this technique is attributing a physical effect (e.g. the emission of GHGs) to a financial transaction. There is no exact process for a supplier providing a product or service to count the amount of GHGs emitted or absorbed during their delivery of it. There is no way to exactly account for the GHGs that have been emitted or absorbed by the inputs to their processes. In short, despite being linked by the model, the estimation of emissions and the accounts of money flows differ in a fundamental way. The accountant will be used to balancing the books to the penny; the footprint estimator has no comparative process. However, being aware of where the uncertainties lie in the models, and having an idea of their significance means that an opinion can be formed as to the validity of the estimate.

There are a variety of areas where uncertainties arise in the derivation of the models used to estimate organisational supply chains. These are subdivided for the purposes of this chapter into three main areas:

1) Dataset Errors, that is the potential for uncertainty in the data underlying the models;
2) Implementation Issues, a consideration of the weaknesses in the way the models are implemented;
3) Theoretical Errors, deals with the possibility that the theoretical approach that is selected is not appropriate even if implemented correctly.

These are considered in order.

6.2 Dataset Errors

This section discusses the uncertainty in the data that underlies the models. Although beyond the control of the modeller, it is important to understand where uncertainty may arise, and how it may affect the models that are constructed from them. The models described in this thesis depend upon a range of data-sources: however there are three broad areas of data to consider; which are discussed below.

6.2.1 ONS Data

All the data for the EEIO model are reported and collated by the ONS. The ONS is the official statistics office for the UK government and is considered authoritative on the economic statistics of the UK. They provide wide information on the methodology used to construct the national accounts and include as a matter of course, details on coherence adjustments which acknowledge the uncertainty in their data. With the complexity of the processes, and in common with other national statistics authorities, it has been claimed that the actual error statistics are virtually unquantifiable (Penneck and Mahajan, 1999). This means that any estimate of uncertainty is based upon uncertainty to begin with. This is not to say that compiling the statistics is done carelessly, but that a consequence of the methods of collection and collation make it impossible to calculate errors in the data. We consider the sources of data individually in the next paragraphs.

The SUT use a wide variety of data sources in order to cover the whole of the economy and provide data for the three measures of GDP – income, expenditure, and production. There are a wide range of business surveys that investigate the purchasing and sales of UK businesses. Information is drawn from HMRC on incomes, profits and taxes and also data on imports and exports. Data are required from households and other final consumers on their purchasing habits. These data are combined to produce the tables of inter-industry demand, value added, supply, and final demand, and the disaggregation of GFCF. By design there is a cross-checking process with the national accounts in that the three separate measures of GDP are estimated and must be reconciled. This however can only operate at the aggregate level. The transactions recorded in the SUT can only be regarded as estimates of the flows. Berners-Lee, *et al.* (2011) draw upon an earlier assessment of uncertainty in the UK accounts by Wiedmann, *et al.* (2008), to estimate that the uncertainties arising in the technical coefficients matrix are in the range 0% to 20% with a mean of 7%. However, there are further data required to compile the EEIO model, which are the environmental data that are used in the calculation of emission intensity.

It is difficult to estimate the environmental impacts of a sector given the diversity of products within a product sector, and the difficulty of estimating GHG emissions for a single product let alone for the whole sector. For large point sources such as power stations, it is possible to measure the flows of greenhouse gases but that leaves much of industry unmeasured. Estimates of the Greenhouse Gas Inventory (GHGI) are produced by Ricardo-AEA on behalf of Department of Energy and Climate Change (DECC)[2] (as was) who are (were) the single responsible body for reporting greenhouse gas emissions to UNFCCC. A wide variety of methods are used to make the estimates dependent on the processes involved. Wherever possible the estimates are derived from physical measurements such as animal population data, combustion models etc. There is also validation of the estimates using high precision high-frequency observations of greenhouse gases from Mace Head in the Republic of Ireland and then using a Lagrangian dispersion model to estimate the amounts of GHG emissions that can be attributed to UK, and those which are from mainland Europe (Ricardo-AEA, 2014). Three further sites are now included in north Scotland, Norfolk and Herefordshire to improve the quality of the estimates. There is still the issue of assigning emissions to industry sectors, which is done using input-output modelling so there is a circularity in the data used. Berners-Lee, *et al.* (2011) estimates that if the uncertainty in the distribution of greenhouse gas emissions to industry sectors matches that of the financial accounts (i.e. 10%) then the mean uncertainty in their calculation of emissions intensities is 12%, with a maximum of 23%.

The final element of data that is used in the model is CPI which is produced by the ONS, and frequently used as a barometer of the economy. The CPI is based upon data gathered from retailers on a monthly basis based on a basket of 700 items. The data are classified under a different system to the national accounts which as noted previously requires a mapping from CPI sector to national account sector. There is little information on the uncertainties in this data, although given the frequency of observation leading to a high volume of sample points and the importance of this measure it is likely to be low. A cautious estimate might be less than 5%, and given the linear relationship between deflated emissions intensity and inflation, this might result in an uncertainty slightly higher than that for the emissions intensity alone.

The reduction of these uncertainties is difficult to address as the collection of data is not under the control of the modeller or even the ONS. The best that can be hoped for is an understanding of the possible errors and the impacts upon the footprint estimates. However as noted in the introduction, this information no matter how limited is not explicitly communicated to client companies nor necessarily understood fully by those using the data.

[2] In recent governmental re-arrangements DECC has been absorbed into the department of Business, Energy and Industrial Strategy (BEIS)

6.2.2 Organisational Data

In applying the model to an organisation, the organisation is requested to supply financial and other data that might be relevant to the footprint estimation process. The uncertainties in this data are difficult to assess and will vary between organisations. In the case of the large company that forms the subject of the case-study the accounting function could be anticipated to be strong but it is certain that they use a degree of automation to produce their accounts. An error in an automatic journal may lead to purchases being accrued to an inappropriate purchase category and there is always the possibility of one-off transactions being miscategorised. There will be checks to try and catch these errors but from personal experience they can be difficult to trace. There is also the possibility that the organisation may categorise spends in certain categories because it is advantageous to the company to do so. Again, the modeller is not in a position to assess or audit the accounts and in general for the purposes of this thesis it is assumed that the uncertainties associated with this data are sufficiently low to be negligible.

6.2.3 Supplier Provided Data

The final significant data used are that of scope 1 & 2 emissions that are provided by suppliers to the organisation. These are collated by Carbon Disclosure Project (CDP) but the submission of questionnaires is voluntary and is self-audited. From the results in chapter 5, in 2015, 83 suppliers of 138 (60%) failed to calculate an emissions intensity that passed a simple sense check of being less than 1 tonne CO_2eq per unit currency. However, this arithmetical error can be alleviated by cleaning the data. The scope 1 and 2 emissions total upon which the emissions intensity is based are estimated or measured by a variety of means dependent upon the supplier and their processes. Part of the questionnaire requests information concerning the methodologies used to assess scope 1 and 2 emissions, whether the estimates are audited, and the level of uncertainty in the results. Most suppliers have formal methodologies, are audited and quote low levels of uncertainty typically 1% to 10%. Tentatively the uncertainty in this area of the model might be around 5% but it only applies to a limited subset (around 8% in 2015) of the scope 3 emissions, so it does not impact the overall uncertainty by much. In the case of an individual supplier though the results would be expected to be more accurate than those arising from EEIO modelling alone.

This section outlines the major datasets used and the uncertainties within them. At times other data sources have been used, for example DEFRA factors, and ICEv2 factors for construction materials. These are used in areas of the model that are limited in scope, so unless very different in uncertainties than the ONS data are unlikely to increase or decrease the overall uncertainty of the model as used. Across the whole of the model therefore, the uncertainty is estimated to be 10% to 21%, although for assessment of suppliers who report to CDP this uncertainty should be lower. The implications of this uncertainty are discussed further in chapter 7 but now we consider errors arising from implementation issues.

6.3 Implementation Issues

This section considers how choices made in the implementation of the model might impact on the results. These can be considered to affect the model in a number of ways and to occur in different areas. The implementation issues may increase the uncertainty in the estimate but they may also systematically under- or over-estimate the footprint by comparison with other implementation options. Firstly, the impact of adjusting emissions intensity to allow for changes in time period is discussed.

6.3.1 Method of adjustment for time period

It is inevitable that the models will use of out of date data as the national accounts for the UK take two years to produce. This means that the model does not incorporate changes in technology or trading patterns that take place between the time the data was collated, and the time it is used. An adjustment is made to intensities that reflects change in the prices of goods and services. The method and the data used to carry out this process can lead to errors which are difficult to estimate.

Currently the emissions intensities are adjusted by using CPI and this means that the changes that are reflected in the figures are those linked to prices of goods and serviced bought by the final consumers. It might be more appropriate to use an index that reflects the inflation experienced by companies. The ONS produce two Purchaser Price Indices (PPI) one for industry input prices and one for industry output prices. Although the sectors are aggregated, and not all of the sectors of the UK accounts are represented, the use of PPI could present a more defensible choice when analysing large companies. Adopting this method would probably not affect the uncertainty of the model overall although it is more difficult to calculate what industry is paying and would probably result in a slight over-estimation of the footprint by comparison with using CPI as inflation in the input prices is lower than that experienced by final consumers.

Considering only the final prices of goods, also ignores that the structure of the economy may also be affected by the changes in pricing. It is possible to extend the use of price indices to the inter-industry transactions table, a method known as double deflation (Miller and Blair, 2009). This involves deflating the transactions, and the outputs of the national accounts. This process usually results in the tables being out of balance, so a re-balancing process has to be undertaken. These revised tables will result in a different technical coefficients matrix $\boldsymbol{A}$, and hence different Leontief $\boldsymbol{L}$. It would also be possible to adjust the direct emissions intensity $\boldsymbol{e}^{\boldsymbol{pp}}$so that all of the elements of the model reflected pricing changes. The balancing process is computer intensive and requires a linear solver that is not included in Excel. With the UK accounts data available within two years of the period measured, this methodology has not been implemented. It would remain an option if for some reason older data needed to be used.

6.3.2 Errors in application of the model

In the example used in this thesis, the organisation uses several methods of calculating its footprint some of which supersede the EEIO model. Even the calculation of scope 1 and scope 2 emissions by process based methods means that some areas of the EEIO model should not be used, for example those concerned with estimating the footprint arising from fuel purchases and electricity. There are other areas of spend that are typically omitted, e.g. salaries, rates and taxes. With parts of the EEIO model being switched off, one of the strengths of it is diminished that is coverage of the entire supply chain. These errors are difficult to isolate and may affect the footprint estimate either by double counting or omitting emissions. The only solution is vigilance and systematic review of those purchase categories which are set to zero.

A smaller issue is that of spend to which no purchase category has been assigned, either through neglect or because the spend is difficult to categorise. These expenditures should be captured, and a catch-all purchase category is defined for them. This purchase category is a weighted average of all the other purchase categories for which there are spends.

6.3.3 Errors in hybridisation

The EEIO model has been selected for use in this application because it is easy to hybridise the model. This has been demonstrated both in the construction of a hybrid product sector to apply in the purchases of TV rights, and by the incorporation of supplier provided data. When making modifications of this nature it is possible to introduce errors. There may be a simple error in the calculations of the elements that replace EEIO elements, although there is the possibility of validating against the EEIO data. Obviously exact correspondence would be unexpected but if there are differences of an order or magnitude or more, then caution should be exercised. This size of change would require strong evidence that it was appropriate. There is also a danger of cherry-picking the areas where the hybridisation is undertaken to systematically over or under estimate the footprint. Finally, there should be checks to ensure that the scopes of the elements being interchanged are matching. For example, a calculation of construction emissions intensity to substitute into a national accounts sector might use PBLCA and EEIO, so incorporation at only one tier of the supply chain would be inappropriate.

Alleviating these types of methodological error is challenging and requires detailed checking and validation at all stages. There is an argument that they should be independently verified.

6.3.4 Errors in mapping data between classifications

There a number of different classifications of data that arise during the construction and application of this model. In all cases where this occurs, a mapping from one classification to another must be constructed. The most critical of the mappings that take place is that from purchase category to national accounts category but there are also mappings from the industry sectors used for emissions of greenhouse gases, and from CPI to national sectors. The mapping for greenhouse gases is based on SIC2007 but uses 131 sectors and thus matching categories is straightforward and uncontentious, only aggregation is required to match the 110 or 106 sectors of the national accounts. Some details are lost in emissions intensive industries. An alternative solution would be to disaggregate the national accounts sectors involved but this requires a considerable amount of bespoke data collection to understand the inter-industry transactions of these sectors.

The classification for CPI is very different to that for the national accounts. There are 125 categories in total but many of these are aggregates including obviously the headline aggregate overall CPI rate. The mapping is one to one but selection of CPI category is subjective, and the mapping arrived at by one modeller may not match that proposed by another. There are considerable differences in CPI rate, in April 2015 the indices quoted ranged from 11.8 to 244.3 (with the 2005 index defined as 100) but groups of products and services tend to be more closely aligned. Furthermore, it is not the absolute value of the CPI that is used but rather the proportional change. The change over 12 months (i.e. compared with April 2014) showed a range of 74% to 110%. There is clearly room for an incorrect mapping to have an impact on total emissions intensity, $\boldsymbol{e^{total}}$ that would affect footprint estimate if CPI adjustment is required. The only solution to this is documentation of the mapping, and this mapping being freely available to those who use the model. See Appendix A Mapping of National Accounts sectors to CPI sectors.

The area where there is the most possibility for a methodological error to have an impact on the estimate of the footprint is the mapping from purchase category to UK national account sectors. This is a mapping arrived at in conjunction with the organisation but is again subjective and complex. There are two possibilities: one is that a purchase category is mapped to one or more UK accounts sectors that do not represent the goods or services being purchased; the second possibility is that the weighting of UK accounts sectors to a purchase category is not representative of the goods or services purchased. The latter case is less severe unless the purchase categories differ by a considerable margin. It is also unrealistic to expect an exact match as the ratio of purchases probably changes year by year so the weightings are a long term estimate.

The mis-mapping of purchase category to national accounts sector is potentially more serious particularly if it occurs in areas of high expenditures. This type of error may occur because of a faulty understanding of the UK accounts sectors that are applicable to a purchase category which can be solved by a discussion between modeller and organisation and remapping. There is also the case discussed in chapter 5 where none of the sectors is considered representative of the purchase category. In this case and as demonstrated, a hybrid category may provide a solution.

This section has discussed a variety of implementation issues that may and have occurred. It has also discussed some methods to avoid or alleviate these implementation issues, but the adaptations tend to introduce issues of their own. The uncertainties introduced by these methodological errors are impossible to quantify. A culture of vigilance, and review, preferably by someone independent of the modelling goes a long way to curbing the impact of them and particularly to avoid issues associated with cherry-picking data.

6.4 Theoretical Errors

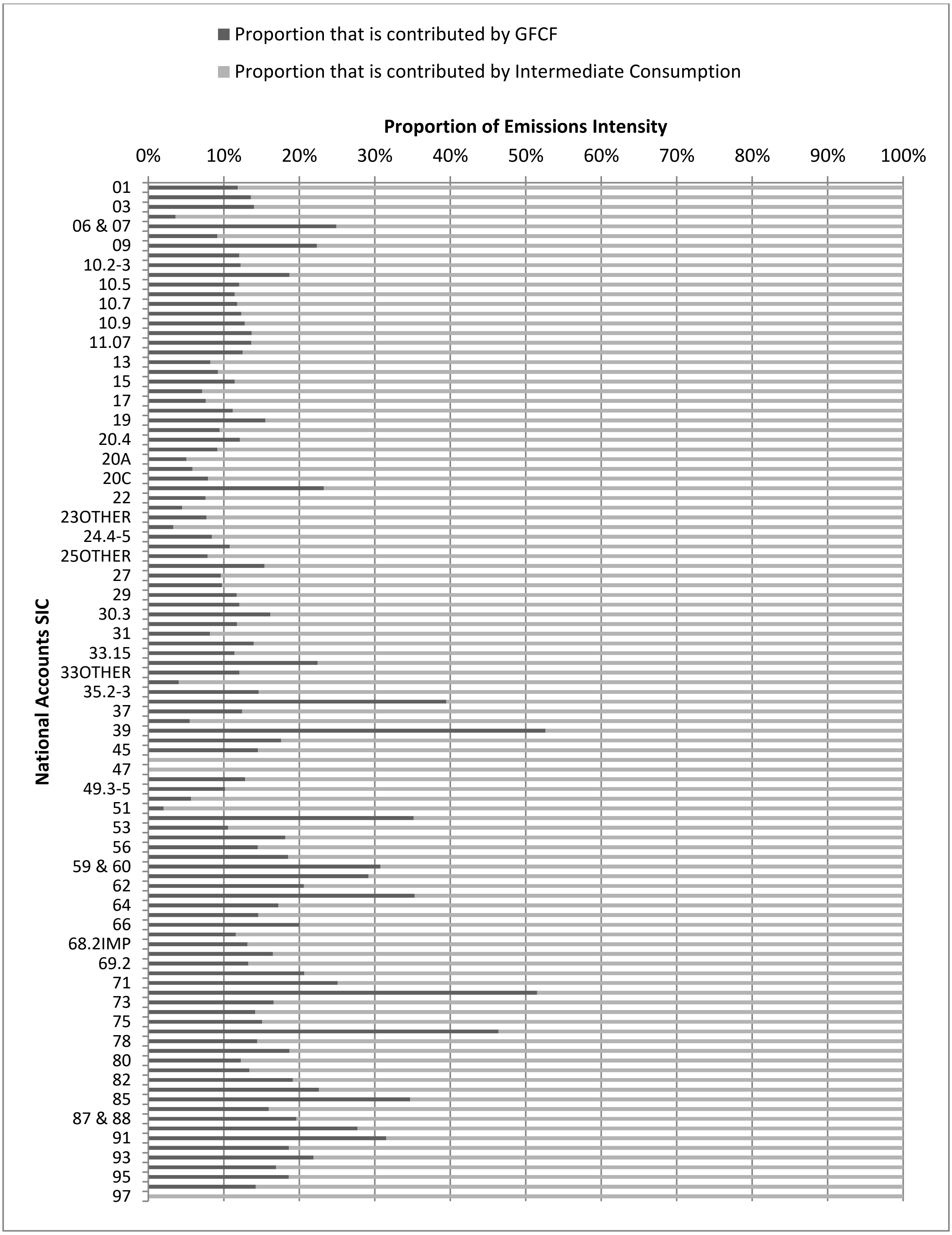
This section considers at a more theoretical level the relevance of using the methodology that has been outlined above. This section goes beyond highlighting implementation errors and discusses whether the philosophy of the method used is appropriate. It also analyses some of the assumptions that are made in the course of constructing the model.

6.4.1The inclusion or exclusion of GFCF

The inclusion of GFCF was discussed in chapter 3, and in this case the example of Berners-Lee *et al.* (2011) and Lenzen (2001b) was followed with an appeal to Adam Smith's assertion that "consumption is the sole end and purpose of all production". Peters and Hertwich (2004) demur and argue that it is possible to identify two aspects to GFCF, that which is used to replace for example worn out machinery, thus is part of production and therefore should be included. The other GFCF is for the expansion of industry and should not be included. They also point out that in an export dependent economy, GFCF may go to the industries that support export and thus should not be considered in the context of domestic final demand.

The decision to include or exclude GFCF will lead to slightly different intensities being calculated for the industry sectors. GFCF also introduces challenges in that, in the UK, the GFCF data are produced in an aggregated form and so the distribution of the GFCF amongst some of the industry sections has to be inferred. However, it is easy to assess the impacts of GFCF on total emissions intensity and the results are presented below, in Figure 12.

Figure 12 Proportion of Emissions Intensity contributed by GFCF



As can be seen from the chart the component contributed by GFCF to total emissions intensity varies quite widely, although the arithmetic mean of the proportion is 14%. In the telecommunications sector (61) however, the proportion contributed by GFCF is 29% which reflects the amount of infrastructure they are installing, e.g. copper and fibre cabling. The amended emissions intensities have not been used with the organisational model but it is likely that the exclusion of GFCF would lead to a reduction in the footprint estimate of between 14% and 29%.

Although the exclusion of GFCF would lead to an underestimate of footprint by comparison with the current model, it is likely that if that if the method was changed and retrospectively applied that the trends between the years, and differences between sectors would remain similar. Thus the numbers might change but the recommendations for action, and the analysis would probably remain the same.

6.4.2 Representing Organisational Purchasing by a Final Demand vector

In the financial model, the independent variable is final demand. When assessing the impact of the organisation, one way of considering the modelling process is that we construct a vector of final demand that represents the organisation's purchases by national accounts sector, then use our model to predict the emissions arising from that vector. In previous studies, undertaken by Wiedmann*, et al.* (2009), and Berners-Lee*, et al.* (2011) this has been in essence the calculation used. This might seem appropriate when working with relatively small businesses which are perhaps the final supplier to final consumption. However, the subject of this case study is a substantially sized company that supplies industry perhaps more than final consumption. In this case it could be argued that purchases made by this company are not modelled well by a vector of final demand. It might be more appropriate to reflect its purchases in inter-industry transactions, by creating an additional sector and putting the purchases in the industry column as inputs, and carrying out some research as to destination of the outputs of this industry which would be included in the outputs row. We would then end up with a $(n+1)\times(n+1)$ technical coefficients matrix, and similar dimension Leontief. From information supplied by the company we could calculate its direct emissions intensity. Finally, some research with the company could establish a figure for final demand for this company's products and services. Then a calculation could be undertaken of UK total consumption based emissions, including and excluding this sector. This would provide an alternative estimate of the company footprint.

The main drawback about using the model in this format, is that the results generated would be classified under national accounts classification. One of the major advantages of the formulation used is that the results can be presented in classifications that the company understand, e.g. by purchase category, and that we can break down the emissions intensities by level of supply chain and industry contribution. However, it would be interesting to compare the total footprint obtained by the separate approaches.

6.4.3 Is a national economy representative of international company purchasing?

Another of the potential limitations in the modelling presented in this thesis is that the financial and emissions modules are based upon the UK accounts. The company that is the subject of the case study is a UK based one, but it has both subsidiaries and supply chains that are outside the UK. It could be argued that therefore that the economy within which this company trades is not represented well by the economy of the UK. It may be that a supra-regional model would be more relevant to its operations. This could be implemented in two different ways. The first and potentially the simpler would be to construct a model derived from a single SUT, but with the transactions in the SUT being those of a bloc of countries, for example EU, OECD or global. The datasets for the first two examples already exist and largely use the same classification system though with some national variations so there would be a process of reconciliation and consolidation. This process is made more difficult because the differing economies will have different structures and so the supra-regional model may end up with a greater number of sectors than the one based on the UK ONS data alone. The model would also have to be modified to take into account intercountry transportation costs, and also customs tariffs. Economies that are outside the trading blocs mentioned could also be included if data could be gathered and converted into the SIC 2007/CPA 2008 classification. There is also the issue of converting the currencies used into pounds sterling. This would constitute a substantial amount of work, and would require as decision as to what currency rate to apply, for example Market Exchange Rate (MER); Purchasing Power Parity (PPP); or another. The end result would be a more complex model but one that should mesh closely with the current model. It is potentially more representative but still not exactly the environment in which the company operates. However, it could also be applied to other companies that operated in similar environments including companies from outside the UK and thus would have a more general application. All of the analysis that is used in this thesis could also be used with a model that is constructed within the same framework. This model would still miss the intricacies of international trade, and the means to tackle that is discussed in the next section.

6.4.4 International Trade

We have discussed one possibility of reflecting the international scope of company supply chains. However, the use of supra-regional bloc as the basis of the model averages the differences between national economies, and does not allow for the interplay of exports and imports. It might also miss the trend towards carbon leakage, which according to (Felder and Rutherford, 1993), leads to the transfer of energy intensive processes to other economies particularly those in the developing world. One approach is to deal with first order transfers i.e. those countries that are the immediate suppliers to the UK. This approach is described in the next section.

6.4.5 Environmentally Extended Bilateral Trade

The single region model implemented and used in the case study has several limitations of which one is that it uses the Domestic Technology Assumption (Miller and Blair, 2009). This is the assumption that imports into the UK are treated as if they were made using the same technology as the UK. As the structure of economies varies, and also the mix of fuels they use for energy, the total emissions intensities derived using this methodology may be less accurate than they could be. One way to extend the methodology is to use environmentally expanded bilateral trade (EEBT). This provides analysis at the first level of trade, so the emissions that are imported from and exported to direct trading partners are calculated. The single region model accounts for exported emissions but in order to extend the model, information is required about the emissions associated with imports. This would require an understanding of where a region's imports come from, and into which sectors of the economy they are imported. These emissions can then be added to the domestically produced emissions to provide an assessment of the embodied emissions of a product or sector.

Whilst this begins to answer the issue, it does not really reflect the full complexity of modern supply chains. For example, vehicles produced in Germany and exported from Germany to the UK will have a proportion of embodied emissions from the assembly that takes place in Germany. However, the components for the car may come from other economies, and in particular the extraction of raw materials, which tends to stimulate the production of large quantities of emissions, may well take place elsewhere. Tracking the imports through the sectors of the economy may also be difficult. Common components such as nuts, bolts and screws may be used in a wide variety of sectors and establishing where the products are used is prone to large estimation errors. A possible way to overcome the first of these issues is to extend the model beyond the immediate trading partners of the region. The next paragraphs discuss how this might work.

6.4.6 Multi-Regional Input-Output Modelling

If the data are available to assess the trade between two trading regions, then it should be possible to collect trading data for a range of blocs or regions. The UN, through its System for National Accounts (SNA) (United Nations Department of Economic and Social Affairs, 1968; 1993; 2008), has provided a framework for all nations to produce national accounts and for those accounts in principle to be compatible. In order for countries to effectively administer their nations, they must produce accounts. As part of the national accounts, import and export figures are produced even if only to ensure that tariffs are collected where appropriate. In this case then we can imagine a single regions national accounts extended to show not only its domestic production but also its imports from and exports to other areas. In an analogous way to the single region model this can be either solved or inverted to produce a Leontief inverse that applies across a trading block or indeed across the globe. Combined with emissions data, and making similar assumptions to the single region model then the effects of a small change in final demand in any one region can be modelled. Furthermore, not only can the magnitude of the change be estimated but also the spatial location of the emissions. The sources of data for these models were discussed in chapter 3, and several models using this data have been constructed. It is a complicated exercise, and usually undertaken as a collaborative exercise, combining expertise in modelling, informatics and high-performance computing. Though this would be beyond the scope of this project, the emissions intensity by industrial sector are available from a number of the models, and could be used to form an estimate of an organisational footprint. MRIO modelling is also the source of much of the recent literature in uncertainty in EEIO modelling and this is discussed in the next section.

6.5 Uncertainty in EEIO modelling

Miller and Blair (2009) describe a wide variety of input-output models and methods including EEIO modelling; however they provide only a limited discussion that describes sensitivity or uncertainty analysis. A small section of chapter 12 is dedicated to the identification of Important Coefficients citing work by Quandt (1958, 1959) which in turn was based on the work by Sherman and Morrison (1949, 1950) and Woodbury (1950). Sherman and Morrison (1949,1950) and Woodbury (1950) investigated how changes to elements of a matrix impacted upon the inverse of that matrix. Building on this work, and with some minor mathematical adaptions, Sonis & Hewings (1992) investigated the fields of influence of a coefficient and came up with the concept of inverse-important coefficients, i.e. those coefficients have the greatest influence upon the inverse when changed. These calculations are quite labour intensive without the assistance of computers but can give insights into how changes in the technical coefficients matrix $\boldsymbol{A}$**,** effect the inverse, and hence, multipliers derived from the inverse.

Lenzen, *et al.* (2010) note "a dearth of environmental MRIO studies where an uncertainty analysis is undertaken" although this is partially remedied by their analysis of the uncertainties in an MRIO model applied to the analysis of the UK carbon footprint (Wiedmann et al. 2010). They identify the issue in using a method of error propagation to analyse uncertainty is that the base equation of input-output modelling, $\boldsymbol{y} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{x}$, that relates final demand $\boldsymbol{y}$, to output $\boldsymbol{x}$, and the technical coefficients $\boldsymbol{A}$ cannot be differentiated with respect to the coefficients $[a_{ij}]$. Thus, Monte-Carlo simulation has become the usual method of uncertainty estimation applied (Bullard and Sebald, 1977; 1988). This includes the assumption that coefficients are independent, and normally distributed, an assumption which is questioned by Rey et al. (2004). Furthermore, the use of Monte-Carlo techniques depends upon a considerable amount of computing power being available, as typically the multipliers need to be calculated thousands of times, which involves inverting large matrices each time (Lenzen*, et al.*, 2010).

Weber and Matthews (2007) perform an analysis of the Emissions Embodied in Trade (EET) for the United States and undertake an uncertainty analysis of their time-series. They estimate a range of 0.5 Gt CO_2 (note this is CO_2, not CO_2eq) to 0.8 Gt CO_2 in 1997, and 0.8 Gt CO_2 to 1.8 Gt CO_2 in 2004. The range expressed as a proportion of the mean is 46% in 1997, and 77% in 2004. They cite a number of areas of uncertainty including aggregation and allocation, but draw the conclusion that most of the uncertainty derives from currency conversion of prices. They note that the latter along with the uncertainties involved in estimating the ROW region are issues that are unqiuely associated with MRIO.

Lenzen et al. (2010) identify six datasets, which have varying uncertainties. The financial part of the model draws upon input-output data for the UK and 3 other regions. They note that no uncertainty information is available for UK input-output data, a situation that remains true in 2016. They use data from the Annual Business Inquiry (ABI), now the Annual Business Survey (ABS), to calculate a regression of absolute standard errors to estimate the Standard Deviations (SD) of transactions in the Supply and Use Tables. Input-Output data for the 3 other regions in the MRIO are drawn from the GTAP database and the difference between fitted and unfitted data is used to estimate SD. The emissions data for the UK is drawn from the UK Environmental Accounts. This data is in turn calculated from the UK GHG inventory as reported to UNFCC which provides uncertainty estimates at an aggregated sectoral level that were regressed to provide estimates for the individual sectors. The same regression coefficients are applied to International Energy Agency (IEA) CO_2 emissions data which are used for the other regions of the model. They also note the mismatch in the availability of GTAP data, e.g. in the UK Input-Output data is available at the 123 sector level whereas GTAP data is only available at 30 sector resolution. Producer Prices Index (PPI) from OECD is used to deflate the GTAP data, which was only available for two time points – 1997 and 2001, and a Relative Standard Deviation (RSD) of 10% was calculated for this data. The final datasets were import data obtained from UK SUT and regressed using the formula for SD of the UK input-output data.

The results of this comprehensive analysis are presented by considering the consumption emissions, which show a minimum RSD of 3.0% in 1994 to 5.1% in 1999 and 2001. Considering carbon footprint, the study concludes that there is a probability of 93% that the carbon footprint was greater in 2001 than in 1994. The time series is from 1992 to 2004 and the estimate that takes in the full range has a probability of 89% that 2004 emissions are greater than 1992. The estimates for RSD in embedded emissions in imports (EEI) varies from 5.5% in 2000 to 8.5% in 1995, with estimates for RSD of embedded emission in exports (EEE) ranging from 3.6% in 2000 to 5.9% in 1997 and 1998. The authors observe that there are some systematic errors that may have been missed for example:

1. Changes in the structure of foreign input-output data as only 2 points are available for the GTAP data.
2. Changes in how imports are used within the UK economy as there is only one time point for this data.
3. Over, or under, estimation of CO_2 intensities of foreign industries owing to a mismatch between UK and GTAP data.
4. Choice of currency conversion factors (Purchasing Power parity or Market exchange rate).

Finally, the authors note that although aggregated results show relatively low RSD, there is considerable sectoral variation.

It is clear from the analysis of Lenzen et al. (2010) that there are several areas where environmentally extended MRIO may demonstrate uncertainty. Several studies since then have investigated different aspects of these systematic and dataset uncertainties and these are discussed in turn below.

Owen, *et al.* (2014) note that the datasets and methods of construction can lead to differences in results reported and aimed to develop a systematic measure of how the different elements of a MRIO model can contribute to the overall uncertainty of the system. They used Structural Decomposition Analysis (SDA) to analyse three databases – Eora (Lenzen*, et al.*, 2013), World Input Output Database (WIOD) (Timmer*, et al.*, 2015) and EXIOPOL (Tukker*, et al.*, 2013) – at a point in time, 2007, when all overlap. The analysis was carried out for emissions of CO_2 arising from fossil fuel burning, neglecting other emissions sources. At first sight, the range of the total global carbon footprint from the three databases seems quite wide (see Table 15), so the authors treated the total global emissions as an independent variable in their calculations. In addition, they created a common classification system onto which all the models could be mapped.

Table 15 Global Emissions CO2 from Table 2, Owen et al. (2014)

	Eora	GTAP	WIOD
Total CO_2 Global emissions 2007 ($kTCO_2$)	28,237.228	22,800, 300	25,261,657

The objective of this study was not to quantify the uncertainties within MRIO databases but to understand how the sources of emission data and financial trade contribute to the uncertainty. The study considered 6 different decompositions of the Leontief equation, which provide increasing insight into the effects of the elements of the model. The results of the simplest decomposition showed that 95% of the uncertainty in the model is attributed to the vector of CO_2 per unit output (the industry sector emissions intensities) and the balance is contributed by the product of the Leontief and final demand $\boldsymbol{Ly}$. Further decompositions drew out the effect of the Leontief $\boldsymbol{L}$ and total emissions vector $\boldsymbol{f_t}$ in positive contributions in the footprint estimation counterbalanced by a negative contribution of the inverse of output $\boldsymbol{x^{-1}}$. The distribution $\boldsymbol{f_p}$ of the emissions over production sectors played a lesser part.

Steen-Olsen, *et al.* (2014) consider the effect of aggregation of industry sectors on the outputs of models. Their literature review identifies a variety of impacts as sectors are aggregated with, as might be intuitively expected, an increase in the coefficient of variation of as the sectors are aggregated from 4-digit Standard Industrial Code (SIC) (coefficient of 31%) to 3 digit (37%) and 2 digit SIC (45%) (Kymn, 1977). Lenzen, *et al.* (2004) found significant errors when aggregating from 118 to 10 sectors per region for Denmark. Su, *et al.* (2010) noting that 40 sectors were sufficient to capture the majority of embodied emissions in the exports of China. The results of Steen-Olsen *et al.* (2014) are based upon the analysis of 4 MRIO (Eora, EXIOBASE, GTAP and WIOD), where they investigated the impact on CO_2 multipliers, and of aggregation to a common classification (CC) scheme of 40 sectors and 17 regions that were common to all 4 databases. The general conclusions drawn are that the greater the detail in the original database, the larger the error in multiplier in the aggregated version.

Stadler, *et al.* (2014) consider the effects of the construction of the Rest Of World (ROW) in MRIO used to calculate global warming potential (GWP) footprints, i.e. the impact of emissions in terms of Gt CO2eq. In MRIO modelling, it is usual to consider a focal region, i.e. the one that is being investigated, and other regions that form the bulk of the trade with the focal region. The ROW region is intended to capture the trade that is carried on with regions not represented explicitly in the model. As this region is, in effect, a conglomeration of regions, its economic structure is very difficult to define but is usually modelled by a region that is thought to broadly represent it. Stadler *et al.'s* contribution is to model how sensitive the ROW is to the country used to represent it. They find that for GWP footprints there is little sensitivity to the country chosen to represent the ROW region.

Moran & Wood (2014) note that the general approach to calculating Carbon Footprints does not differ, and is summarised as the use of a Leontief model with money based financial tables, and an environmental stressor vector. However, the datasets used to estimate the footprints do differ, and so they seek to answer three questions:

1) How different are the estimates for each MRIO datasets?;
2) Do these estimates lie within the variance bounds of the others – are the differences possibly explained by chance?;
3) How the different elements of the models contribute to the uncertainty?

They adopt a model that relates the footprint C, to the environmental stressor $\boldsymbol{F}$, a measure of direct impact by sector, the structure of the economy $\boldsymbol{Z}$, and the demand $\boldsymbol{Y}$. In this study they hold $\boldsymbol{F}$ constant and investigate how changes in $\boldsymbol{Z}$ and $\boldsymbol{Y}$ affect C. They assert that $\boldsymbol{F}$ is the variable showing the greatest variance owing to the wide range of data used in estimating environmental impacts, and the challenge in calculating direct impacts for heterogeneous industry sectors. A novel approach of this paper is to perturb the inter-industry flows, rather than the technical coefficients matrix $\boldsymbol{A}$. The method used is to compare the models under 5 different scenarios which are summarised in Table 16. The datasets compared are: Eora (full resolution and aggregated to 26 sectors), Open-EU based upon GTAP, EXIOBASE (full resolution and aggregated to 15 Sectors), and WIOD.

Table 16 Summary of Table 1 Scenarios considered (Moran & Wood, 2014)

Scenario	F harmonised	Regime for Relative Standard Error σ
1&2	No	1) $\sigma = 0.1$, 2) Uses log regression (Lenzen, 2010)
3	Yes	Uses log regression (Lenzen, 2010)
4	Yes	$\sigma_F = \sigma_Z = 0.1, \sigma_y = 0.3$
5	Yes	$\sigma_F = 0.1, \sigma_Z = 0.3, \sigma_y = 0.1$

The results of this study are quite illuminating, with the results under scenario 1, before the environmental stressor is harmonised, showing an average relative maximum difference (RMD) between models amongst the countries of 20% for Production Accounts figures. There is considerable range of maximum differences, with the UK estimate of ≥ 50% range for this measure. Using the Consumption Based Accounts in general increases the maximum difference between models, as the effects of inter-industry flows, and final demand are considered, although for the UK the inter-model difference reduces to the low 40%. Post harmonisation, the maximum differences are considerably reduced with a range of 5% to 30%, and the UK around 11% difference. The paper concludes that it is important to get emissions accounting to a similar standard to the financial accounting, and that harmonisation of the environmental stressor is not sufficient to reduce the variance to below the inter-year variance, hence it is difficult to draw statistically valid inferences about the inter-year variance. The authors also conclude that qualitatively the models agree, but further work is needed to deliver quantitative agreement.

Geschke, *et al.* (2014) consider the method of construction of MRIO and the impact that the various methods may have on the results obtained. They consider three databases EXIOBASE v1 and v2 (Tukker *et al.* 2013) and Eora (Lenzen *et al.* 2013) and use the initial estimates (IE), constraints and reconciliation processes of the three databases to understand the impact of these processes on the final result. The reconciliation method that is applied to all three initial estimates and constraints sets is that used by Eora which is automated using a software called AISHA. The outputs of this reconciliation process are then compared with the MRIO prepared from the original data and using the original reconciliation process. The methods are complex, and the results can be summarised as:

1) It's a very complicated process to construct MRIO models but that they are a good Initial Estimate on the quality of the final product.
2) The methods of constructing and balancing the data during the process of building the MRIO model can make a significant difference to calculations that use it.
3) Automation of the processes, using software like AISHA, can produce close approximations of MRIO Models that were originally constructed in a step-wise manner.

Arto, *et al.* (2014) consider the use of two databases, namely GTAP-MRIO and WIOD, specifically for the purpose of Carbon Foot-Printing of Nations. They criticise the use of single country models using the Domestic Technology Assumption for this purpose as not reflecting the emissions embedded in trade, but rather giving an estimate of the "…emissions avoided through international trade". The selection of the two databases for this study is justified by them being the most widely used in policy analysis. The paper aims to analyse the differences between the databases after harmonising the databases to 15 sector industrial classification, and using the 41 regions of WIOD. They develop a new measure of the similarity of matrices, the Weighted Relative Percent Difference (WRPD), with the relative percentage difference (RPD) being the difference between the estimate of Carbon Footprint for a country from a given dataset and the mean of the two estimates. This adds new insights into the analysis of input-output systems and the difference between the databases were found to be in the order of 20-25%.

The range of studies illustrate the diversity of sources of uncertainty in environmental MRIO modelling. From the above studies, we can identify the following as contributors to uncertainty:

1) Range of sources for GHG emissions (e.g. IEA, EDGAR);

2) What GHGs to include and on what basis (e.g. CO_2, Kyoto Basket, emissions from fossil-fuel burning, emissions from Land Use, Land Use Change and Forestry (LULCF), etc.);
3) Allocation of GHG emissions to Industry Sectors;
4) Aggregation of sectors;
5) Harmonisation of sector classifications between different databases;
6) Financial data for Inter-industry flows;
7) Assigning import and export data;
8) Construction methods;
9) Treatment of ROW region.

Although progress has been made towards improving our understanding of uncertainties, it is clear that each research question requires careful consideration of the data and methodology used to answer it

6.6 Conclusion

In this chapter, we have examined a hierarchy of errors and issues that are associated with the estimating of company supply chain footprints. These include a consideration of the data that underlies the model and as a result adopts from earlier studies an estimate of uncertainty in results of at least 10% to 21%. We have also discussed implementation issues, and identified some of the practices that could be implemented by a modeller using EEIO and hybridisation to reliably estimate footprints. Finally, we have looked beyond the data, and implementation to wider ranging issues about the suitability of this technique for footprint estimation. Some theoretical developments have been presented to address weaknesses in the single region model. The final chapter will draw all the strands together, discuss key issues, and suggest some fruitful areas for further work.

Chapter 7 Conclusions and Discussion

7.1 Introduction

This thesis has discussed the requirement for techniques to measure the footprint of organisations as a method of drawing attention to and reducing carbon emissions. This is seen as important on a number of levels. It seems evident that relying only on governments which are inherently focussed on short term goals and the requirement of being re-elected should not be the only strategy employed to tackle global, long term problems. Whilst businesses can also be accused of being short-term owing to the necessity to perform well for shareholders, there is a considerable movement towards sustainability and an increasing realisation that they must look further forward than the next quarter's results. Some stakeholders require financial performance **and** a sense of corporate responsibility. Customers may be attracted and retained by suppliers that perform well on an environmental front. Furthermore, larger organisations tend to be in a position to influence not only their supply chain but also their competitors and provided that a race to the bottom is not indulged, this can act as a force for improvement. Business can be an important part of the set of solutions to climate change.

However, it has to be acknowledged that at the moment the process based tools and techniques for allowing businesses to estimate their carbon footprint are reasonably restricted in application as they are primarily aimed at goods rather than services. The issue of truncation error means that the results derived are potentially misleading by systematically under-estimating footprints. Finally, they can incur high overheads in terms of the resources required to deploy them. The methods and extensions described in this thesis are intended to provide a methodology that is widely and easily applicable to a range of businesses. This could allow carbon metrics to make the transition from the sustainability manager to the main board and therefore increase the momentum towards reducing carbon emissions. In this chapter we consider four vital questions and provide a response.

7.2 What is the contribution to knowledge?

The literature showed that the application of Environmentally Extended Input-Output (EEIO) modelling to the assessment of organisational supply chain footprints is limited, and has been pursued with data that is considerably out of date. The main achievement of the project is to produce a time-series of UK single region models that are based upon the most up to date data. The models are organised in accordance with the classification structure that is used by the ONS and this should be applicable for some years to come. The models are easily updated each year with the most recent national accounts data.

These models have been used in an extended case study with a large UK telecommunications company. This has offered the opportunity to use the tool in the a demanding business environment and demonstrate its reliability, flexibility and ease of application by comparison with other methods of measuring carbon emissions, such as Process Based Life Cycle Analysis, that can only be applied in the context of well-defined processes with clear system boundaries. The model has been used extensively by the company to inform their decision making on environmental issues.

As a result of the company's varied requirements on reporting, we have developed a wide variety of categorisations of the combined data set of EEIO model and financial information. We have also evolved a range of techniques to modify the model so that PBLCA data for specific products or services can be incorporated and also so that supplier provided information about their scope 1 & 2 emissions can be included. These modifications allow the impact of changes in supply chain on the carbon footprint of the company to be assessed without requiring that change to appear in the national accounts of the UK.

7.3 What are the strengths of hybrid EEIO modelling?

Although the EEIO model comprising the financial and emissions model is complex, the development of a template has facilitated the construction of a time-series of models that can be applied to the analysis of a company. The systematic application of a mapping process between organisational purchase ledger codes and national accounts data reduces the workload required to produce results. With thorough preparation in conjunction with the customer, it has proved possible to receive financial and emissions data at the end of their financial year, and return results on the footprint of the company in a week. The ability to provide information in a timeous manner is crucial to integrating information about GHG emissions into the systems of a company.

The flexibility to customise the model in various ways has allowed ad hoc queries to be tackled as they have arisen, and this has allowed us to answer a range of questions. Some of these have been described in detail in this thesis but others, for example calculating the GHG impact of a promotional hot air balloon, have been omitted[3]. Although this customisation comes at the price of making the model less general, the ability to handle a wide variety of queries builds confidence in the model.

The model is based on good quality data from the UK ONS and that gives confidence that it would be widely applicable for UK businesses. The ONS do a fine job, turn around their data quickly, and

[3] The direct emissions of the balloon we estimated were similar to that of driving a 4x4 vehicle at 90 km/hr, the embodied emissions the equivalent of 4 medium sized cars.

provide comprehensive metadata and methodology updates. As a result, constructing the model is made easier and we can have confidence in the reliability of the data.

The financial model is transparent to the user and is implemented in common business software. This allows clients to see the data underlying the model and understand how changes to the UK economy filter into the estimate of their footprint. As the data is publicly available then the client has the option of reproducing the results themselves, and they have also stood up to external assessment by environmental audit bodies.

There are a number of advantages to using this technique and data in assessing the footprints of organisations. During the course of this project we have demonstrated reliability, speed of response, flexibility, a wide range of applicability and transparency to the end user. It is not all good news, and some of the drawbacks are considered in response to the next question.

7.4 What are the weaknesses of hybrid EEIO modelling?

Although we have argued that it is rare for a company to analyse its purchases down to individual product level, the generic nature of the UK's account sectors means that it is sometimes difficult to match purchase categories as precisely as we would like. Sector 26 "Computer, electronic and optical products" provides a classic example of this. This sector is widely used in the company that is the subject of the case study, but it covers a range of purchases from modems, to laptops to telephone exchanges. A purchase category that includes copper cable purchases has to be mapped to sector 24.4-5 "Other basic metals and casting" which clearly covers a wide range of processes with potentially very different emissions intensities. This is a clear weakness of the technique.

The model is single region and based on UK data. Whilst we have noted that this provides a number of advantages it has its disadvantages as well. Clearly it is difficult to argue that the model based on UK data could be used for companies based in other countries. It misrepresents the footprint estimates of the case study company with its international supply chains in ways that are difficult to measure. However, for the analysis of UK based SMEs it offers a better fit and at least the limitation is made clear for use with other businesses.

While the UK ONS publish their results quickly, at the point of use the model is using data that is 2 years old. The adjustment to current date that has been implemented is quite crude, and to attempt to use the model to predict the future based only upon price inflation is fraught with potential for error. The ability to make predictions about how the future course of the economy might affect the footprint of the company is regularly requested but is beyond the capabilities of this model. To attempt this would require some form of computable general equilibrium (CGE) model that uses production functions rather than linear coefficients and this makes the solving of the model much more involved. Though widely used in macro-economic contexts, these complex models may be too unwieldy for business use.

Perhaps the greatest concern centres around the uncertainty in the model which is not well quantified but is believed to be substantial. This uncertainty is not communicated well to users and clearly the onus for communicating this uncertainty lies largely with the implementer, and the interpreter of the results. Given the reassuringly large number of significant digits in the SUT and environmental accounts it is easy to be seduced into thinking the models are more precise than they actually are. This has resulted in an undue confidence in the results of the analysis. In the long term this may prove to be the undoing of this analysis at the micro-economic level unless it is tackled both by being open about, and seeking to quantify, the uncertainties in the analysis. That brings us to the final question, whither now?

7.5 What are the implications for Business decision making

The first research question posed in chapter 1, was "How can Environmentally Extended Input-Output models influence business decision making in relation to their supply chain impacts?" The answer to this question is that the model has to be integrated into the company, whilst retaining the status of being an independent assessment of the Upstream Scope 3 components of the company's carbon footprint. In chapters 4 and 5, the ease of use of the model has been demonstrated in a number of ways. Firstly, the model forms part of publicly available reports on sustainability, is included in external audits of the company, and forms part of the company's long term strategy for sustainability. It has been used as the basis for discussion with the supply chain, and has been endorsed by the company to its suppliers. The reports of the footprint are reported at vice-president level. Balanced against that is that the results of the analysis have shown that the supply chain emissions have shown very little decoupling from the spend (see Figure 5). This supports the assertion of Doda, *et al.,* (2015) that businesses have yet to change sufficiently to make an impact on emissions. The reporting has, however, facilitated a discourse between the purchasing department and suppliers by highlighting suppliers who are over or under-performing against their sector.

The second question - "What are the impacts in the use of an EEIO model to estimate the supply chain footprint of a major multinational company over a 4 year timescale?" If assessed objectively then the impacts of the EEIO model are yet to be felt, although the model is receiving some attention amongst suppliers as a result of being endorsed. The full power of the model to incorporate feedback from emissions savings made by suppliers is yet to be utilised. However, there is a greater engagement from the supply chain as evidenced by the response rate to supplier questionnaires from CDP documented in Table 14. The availability of a time-series does allow the company to assess its own performance, and also, that of its supply chain and ultimately this would allow the comparison of company performance with indicators of global climate change, such as global emissions. This offers up the possibility of showing whether the organisation is lagging or leading those emissions. This could prove a spur to action, although again there is not much evidence.

On the third question "How can EEIO models be extended to use "real world" data such as that available from PBLCA or from suppliers?" It has been demonstrated over the course of 4 years that this can be done. The challenge as will be noted from Table 14, is that whilst response rates are encouraging, quality of information is still poor.

There is an argument that businesses have not really changed sufficiently to make an impact on emissions globally (Doda*, et al.*, 2015) and that more radical actions are required, in fact, a new paradigm of business that changes the emphasis from market mechanisms and growth to a more sustainable view of economic development (Wittneben*, et al.*, 2009). Wittneben, *et al.* (2009) pose the question whether business can switch from generating growth to redistributing wealth from the developed world to the developing world, and keep climate change effects minimal, e.g. aiming for maximum 2 degrees with an aim of 1.5 degrees (UNFCCC, 2015).

The models and applications of the models described in this thesis have proved effective in raising awareness of carbon emissions in some areas of the subject company, and are used to demonstrate movement towards a long term strategic goal. They provide the opportunity for the company, not only to understand its own performance, but also to investigate and engage with its supply chain. This is enhanced by the inclusion of supplier provided data which provides feedback in less than one year.

There is an argument that providing technology that integrates carbon emissions management with existing management strategies is not helpful in tackling the root cause (Wittneben*, et al.*, 2009). An organisation using tools like this can show its efforts, and its cleverness and its use of technology. It can talk of changing paradigm, but is such claimed paradigmatic change radical and deep enough to achieve the commitments of the Paris agreement. While the evidence again is limited that radical change has been induced, it is still possible and worthy of further investigation, that change could be induced in the company and its supply chain. These tools might form a part of that, however progress is slow and reflects how difficult it is to shift momentum in large companies.

7.6 What could be done next?

There are two main areas that could be fruitful. The first area would be work to address the weaknesses of the model, and move towards what a physicist might term a theory of everything. In carbon foot printing terms this would mean a generally applicable model that applies at all scales and for all types of business. Like its physics counterpart, this model is likely to be a long time coming, if it can ever be achieved. The second area and arguably the more important is to make the modelling more widely available in a rigorous setting that ensures confidence in the results of the analysis. We consider these two areas in the next few paragraphs.

To address the weakness of generic sectors it would be good to increase the resolution of the model. This may involve the disaggregating of the national accounts sectors, and the incorporation of the best available data for those disaggregated sectors. The better fit that an organisation can get between its purchasing data, and the model sectors, the more confidence there will be in the process and the results. The best available data should include process based information, but might also take in imported emissions in sectors where these are important, and supplier information.

A much more difficult objective to fulfil is to make a model that is applicable across organisations in countries other than the UK and/or those organisations that have international supply chains. A supra-regional model might apply to businesses based in a trading bloc, if the model were built around the common trading blocs, e.g. EU, North American Free Trade Association (NAFTA), Association of South East Asian Nations (ASEAN) Free Trade Area. There would be concerns about the applicability of this model in national Small and Medium sized enterprises (SME). A model offering details on range of environmental impacts across a wide range of countries based around the WorldMRIO dataset offers high flexibility but with a cost of complex implementation and a lack of transparency. Currently there is considerable effort in investigating the impacts of international trade, and in due course this may trickle down into EEIO modelling used in an organisational context.

The understanding and communication of uncertainty requires effort in a number of unglamorous areas and by a number of agencies. The uncertainty in data sources needs to be understood by the producers of official statistics and communicated to users of those data sources. At the implementation level, models should move from a deterministic mode to a stochastic one, although this is likely to require increased processing and will involve greater complexity. Finally, the impact of uncertainty on the results needs to form part of the discussion with the organisation whose footprint is being assessed.

For the business community access to the flexibility and ease of use of this model has to be increased. This must be accompanied with appropriate implementations, so a web-based mode of access to encourage smaller organisations to implement carbon foot-printing. Additionally, the model should be integrated into accounting software suites as it fits naturally alongside the financial data that forms one cornerstone of the modelling. The implementation of the model needs to be backed by a national or international standard that is relevant to this format of estimating carbon footprint. With a standard in place, then a system of external verification by audit becomes the next step. These developments require a sustained effort across a wide variety of business, government and non-governmental organisations. However, as we must manage our carbon emissions to slow the pace of global warming, we should encourage and facilitate businesses to account for and report their carbon emissions as carefully as they account for and report their sales and purchases.

Appendix A Mapping of National Accounts sectors to CPI sectors

Mapping of national account sectors to CPI categories

	Standard Industry Code (SIC) Categories	Consumer Price Index (CPI) Category
01	Products of agriculture, hunting and related services	**CPI (overall index)**
02	Products of forestry, logging and related services	**CPI (overall index)**
03	Fish and other fishing products; aquaculture products; support services to fishing	**CPI (overall index)**
05	Coal and lignite	**CPI (overall index)**
06 & 07	Extraction Of Crude Petroleum And Natural Gas & Mining Of Metal Ores	**CPI (overall index)**
08	Other mining and quarrying products	**CPI (overall index)**
09	Mining support services	**CPI (overall index)**
10.1	Preserved meat and meat products	01.1.2 Meat
10.2-3	Processed and preserved fish, crustaceans, molluscs, fruit and vegetables	01.1.3 Fish
10.4	Vegetable and animal oils and fats	01.1.5 Oils and fats
10.5	Dairy products	01.1.4 Milk, cheese and eggs
10.6	Grain mill products, starches and starch products	01.1.1 Bread and cereals
10.7	Bakery and farinaceous products	01.1.1 Bread and cereals
10.8	Other food products	01 Food and non-alcoholic beverages
10.9	Prepared animal feeds	**CPI (overall index)**
11.01-6	Alcoholic beverages	02.1 Alcoholic beverages
11.07	Soft drinks	01.2 Non-alcoholic beverages

12	Tobacco products	02.2 Tobacco
13	Textiles	03.1 Clothing
14	Wearing apparel	03.1.2 Garments
15	Leather and related products	03.1 Clothing
16	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	**CPI (overall index)**
17	Paper and paper products	**CPI (overall index)**
18	Printing and recording services	**CPI (overall index)**
19	Coke and refined petroleum products	**CPI (overall index)**
20.3	Paints, varnishes and similar coatings, printing ink and mastics	**CPI (overall index)**
20.4	Soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	**CPI (overall index)**
20.5	Other chemical products	**CPI (overall index)**
20A	Industrial gases, inorganics and fertilisers (all inorganic chemicals) - 20.11/13/15	**CPI (overall index)**
20B	Petrochemicals - 20.14/16/17/60	**CPI (overall index)**
20C	Dyestuffs, agro-chemicals - 20.12/20	**CPI (overall index)**
21	Basic pharmaceutical products and pharmaceutical preparations	06 Health
22	Rubber and plastic products	**CPI (overall index)**
23.5-6	Manufacture of cement, lime, plaster and articles of concrete, cement and plaster	**CPI (overall index)**
23OTHER	Glass, refractory, clay, other porcelain and ceramic, stone and abrasive products - 23.1-4/7-9	**CPI (overall index)**

24.1-3	Basic iron and steel	**CPI (overall index)**
24.4-5	Other basic metals and casting	**CPI (overall index)**
25.4	Weapons and ammunition	**CPI (overall index)**
25OTHER	Fabricated metal products, excl. machinery and equipment and weapons & ammunition - 25.1-3/25.5-9	**CPI (overall index)**
26	Computer, electronic and optical products	09.1.3 Data processing equipment
27	Electrical equipment	08 Communication
28	Machinery and equipment n.e.c.	**CPI (overall index)**
29	Motor vehicles, trailers and semi-trailers	07 Transport
30.1	Ships and boats	07 Transport
30.3	Air and spacecraft and related machinery	07 Transport
30OTHER	Other transport equipment - 30.2/4/9	07 Transport
31	Furniture	05 Furniture, household equipment and maintenance
32	Other manufactured goods	**CPI (overall index)**
33.15	Repair and maintenance of ships and boats	07 Transport
33.16	Repair and maintenance of aircraft and spacecraft	07 Transport
33OTHER	Rest of repair; Installation - 33.11-14/17/19/20	**CPI (overall index)**
35.1	Electricity, transmission and distribution	04.5.1 Electricity
35.2-3	Gas; distribution of gaseous fuels through mains; steam and air conditioning supply	04.5.2 Gas
36	Natural water; water treatment and supply services	04.4 Water supply and misc. services for the dwelling

37	Sewerage services; sewage sludge	04.4.3 Sewerage collection
38	Waste collection, treatment and disposal services; materials recovery services	**CPI (overall index)**
39	Remediation services and other waste management services	**CPI (overall index)**
41	Buildings and building construction works	**CPI (overall index)**
42	Constructions and construction works for civil engineering	**CPI (overall index)**
43	Specialised construction works	**CPI (overall index)**
45	Wholesale and retail trade and repair services of motor vehicles and motorcycles	**CPI (overall index)**
46	Wholesale trade services, except of motor vehicles and motorcycles	**CPI (overall index)**
47	Retail trade services, except of motor vehicles and motorcycles	**CPI (overall index)**
49.1-2	Rail transport services	07.3.1 Passenger transport by railway
49.3-5	Land transport services and transport services via pipelines, excluding rail transport	07 Transport
50	Water transport services	07.3.4 Passenger transport by sea and inland waterway
51	Air transport services	07.3.3 Passenger transport by air
52	Warehousing and support services for transportation	07 Transport
53	Postal and courier services	07 Transport
55	Accommodation services	11 Restaurants and hotels
56	Food and beverage serving services	11.1 Catering services

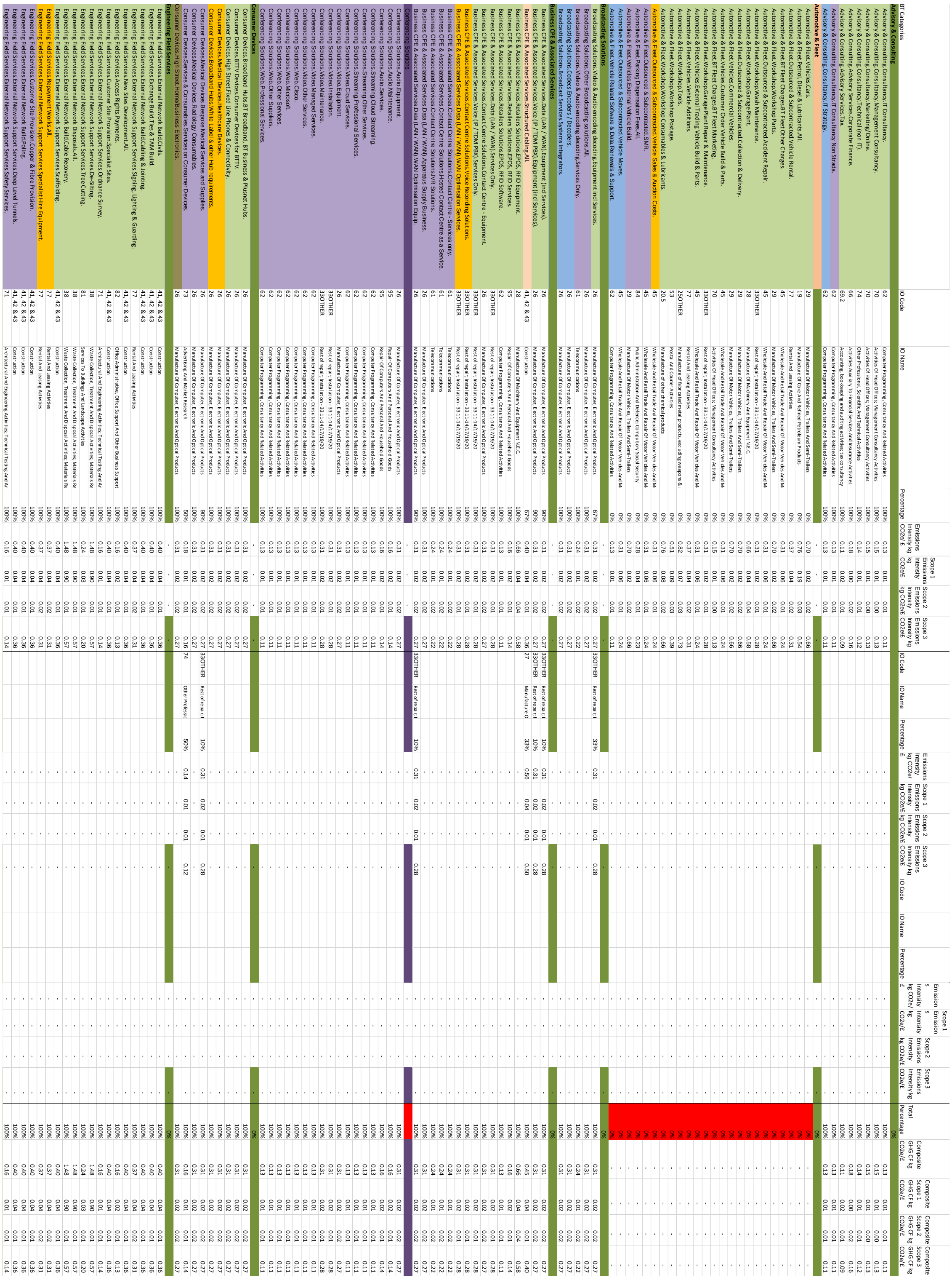
58	Publishing services	08 Communication
59	Motion picture, video and TV programme production services, sound recording & music publishing	08 Communication
60	Programming and broadcasting services	08 Communication
61	Telecommunications services	08 Communication
62	Computer programming, consultancy and related services	**CPI (overall index)**
63	Information services	08 Communication
64	Financial services, except insurance and pension funding	**12.6 Financial services (nec)**
65.1-2 & 65.3	Insurance and reinsurance, except compulsory social security & Pension funding	**12.5 Insurance**
66	Services auxiliary to financial services and insurance services	**12.6 Financial services (nec)**
68.1-2	Real estate services, excluding on a fee or contract basis and imputed rent	**12.6 Financial services (nec)**
68.2IMP	Owner-Occupiers' Housing Services	**12.7 Other services (nec)**
68.3	Real estate activities on a fee or contract basis	**12.7 Other services (nec)**
69.1	Legal services	**12.7 Other services (nec)**
69.2	Accounting, bookkeeping and auditing services; tax consulting services	**12.7 Other services (nec)**
70	Services of head offices; management consulting services	**12.7 Other services (nec)**
71	Architectural and engineering services; technical testing and analysis services	**12.7 Other services (nec)**
72	Scientific research and development services	**12.7 Other services (nec)**
73	Advertising and market research services	**12.7 Other services (nec)**

74	Other professional, scientific and technical services	**12.7 Other services (nec)**
75	Veterinary services	**12.7 Other services (nec)**
77	Rental and leasing services	**12.7 Other services (nec)**
78	Employment services	**12.7 Other services (nec)**
79	Travel agency, tour operator and other reservation services and related services	**09.6 Package holidays**
80	Security and investigation services	**12.7 Other services (nec)**
81	Services to buildings and landscape	**12.7 Other services (nec)**
82	Office administrative, office support and other business support services	**12.7 Other services (nec)**
84	Public administration and defence services; compulsory social security services	**12.7 Other services (nec)**
85	Education services	10.0 Education
86	Human health services	06 Health
87	Residential care services	06 Health
88	Social work services without accommodation	**CPI (overall index)**
90	Creative, arts and entertainment services	09.4 Recreational and cultural services
91	Libraries, archives, museums and other cultural services	09.4.2 Cultural services
92	Gambling and betting services	09.4.1 Recreational and sporting services
93	Sports services and amusement and recreation services	09.4.1 Recreational and sporting services
94	Services furnished by membership organisations	09 Recreation and culture
95	Repair services of computers and personal	**05.3.3 Repair of household**

	and household goods	**appliances**
96	Other personal services	**12.1 Personal care**
97	Services of households as employers of domestic personnel	**CPI (overall index)**

Appendix B Company Accounts to National Accounts Mapping

The screen shot below is an operationalisation of the mapping process outlined in Chapter 3.11, and shows how industry sectors from the national accounts are mapped to purchase categories of the company.



Appendix C Using supplier reported emissions information to enhance an EEIO model to estimate the GHG emissions of businesses

Submitted to IIOA conference, Lisbon 2014

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1 Abstract

Many businesses recognise the contribution of scope 3 emissions to their Greenhouse Gas (GHG) emissions footprint (Wiedmann and Minx, 2007) and are often in a powerful position to positively influence the GHG policies of their supply chain partners. Estimates of their supply chain GHG footprint obtained by the application of environmentally extended input output (EEIO) models can form an important part of strategic decision making. In collaboration with LEC and SWC and using an EEIO model of the UK, an international telecommunications company estimated its supply chain GHG footprint for the past three financial years (April 2010-March 2013).

The existing EEIO model was found to be limited by the aggregated data it contains which typically reflects the emissions and technology of an industry sector within one economy. It had no capability to capture the emissions performance of individual suppliers. However since 2011, the company has also been actively encouraging supply chain partners to participate in the Carbon Disclosure Project's (CDP) climate change reporting programme. As a consequence, supplier reported information on recent supply chain emissions was available and the model was enhanced by incorporating scope 1 & 2 emissions intensity data.

This paper reports on: 1) how supplier reported emissions intensities were integrated into an adapted EEIO model; and 2) the preliminary results arising.

While at the aggregate level only a small and non-significant difference in the estimates of the supply chain GHG footprint was found, interesting supplier level differences between high and low performing suppliers were identified. As more businesses engage in emissions reporting and methodologies for estimating footprints become standardised, it is argued that such supplier level insights could support more environmentally responsible purchasing; allow businesses to predict the impact of supplier's emission reduction targets on future emissions; and support the monitoring of supplier progress towards such targets over time.

2 Introduction

As the UK continues its transition to being a services based economy, the country has become increasingly dependent on imported materials and goods. This move has meant that the UK's production emissions have declined since 1990. However consumption based metrics have indicated the footprint of consumption in the UK is going up (Minx*, et al.*, 2009). Not all consumption is by households, in 2010 for example the national accounts of the UK report intermediate consumption by industry as £1,360,227 million, compared with final consumption expenditure of £1,276,577 million (ONS, 2012a). The goods and services that businesses consumed clearly constitute a potentially high source of embodied emissions. Furthermore large companies can have a substantial impact upon embodied emissions by controlling their expenditure to influence their trading partners (Matthews*, et al.*, 2008). These companies can gain a competitive advantage on at least two levels, one by controlling emissions they potentially reduce cost. Secondly by demonstrating leadership on climate change the attractiveness of their goods and services is enhanced and revenue increased.

This paper considers an international telecommunications company that has reported its scope 1, 2 and 3 emissions for the last 3 years. The estimates of supply chain scope 3 emissions are derived from an Environmentally Extended Input-Output (EIO) model. Whilst allowing estimates to be made quickly and with relatively little resource, this method of estimating emissions has a number of drawbacks:

1) The estimate is based upon UK national accounts and Greenhouse gas (GHG) inventories and hence is not representative of global supply chains;
2) The industry sectors covered by the national accounts are highly aggregated and hence emissions intensities are averaged over a wide range of products.

In parallel with the reporting of its emissions footprint, the company has encouraged its major suppliers to engage with the Carbon Disclosure Project and report on their carbon mitigation policies, targets and achievements. The 2012-13 emissions data for the company were combined with surveys of scope 1 and 2 emissions arising from tier one suppliers for the same reporting year to make an estimate of supply chain emissions.

3 Method

3.1 Data

The Carbon Disclosure Project is an independent, not for profit organisation that facilitates the sharing of environmental information amongst organisations including companies. Companies who have signed up for the project complete an extensive on-line questionnaire that covers climate change considering governance, strategy, climate change targets, emissions methodology, and emissions made in the reporting year. There are two variants of the questionnaire one which is intended for large organisations and another which is for small medium enterprises (SME). Boundaries for estimating scope 1 emissions (directly from operations) and scope 2 (emissions arising from purchased or acquired electricity, steam, heating or cooling) are quite consistent and uncontentious (Fransen*, et al.*, 2007). As scope 1 and 2 emissions from suppliers constitute part of an organisation's scope 3 emissions this raised the possibility of using the data from CDP reports in place of estimates of scope 1 and 2 emissions obtained using EIO modelling. The relevant data to be included in the hybrid model were the supplier's reported scope 1 and 2 emissions intensity – the amount of emissions per unit of currency revenue and the total scope 1 emissions and total scope 2 emissions. For those suppliers who agree to public disclosure of the data, an Excel™ spreadsheet can be downloaded that presents the responses in a consistent manner and this data could be incorporated in the model with a high degree of automation. For those suppliers who do not agree to public disclosure, data can be obtained from their questionnaire responses which are available from the CDP website and this data were inputted manually to the model.

The EIO model that was used was derived from the UK national accounts as published by the Office of National Statistics (ONS), combined with emissions data also published by the ONS which in turn is derived from the National Atmospheric Emissions Inventory (NAEI). Using a method first proposed by Leontief (1986) and subsequently adapted by others particularly Lenzen (2001b), and Berners Lee (2011) a model of the impact of purchases of goods and services on the greenhouse gas emissions of an organisation was constructed. This model was combined with data on company expenditure to produce an estimate of the supply chain Scope 3 emissions.

Some publicly reported financial data were used to verify or modify the scope 1 and 2 emissions intensity factor as reported in the CDP data. This data were taken from the relevant company websites and consisted of a download of the audited publicly available accounts that many organisations are obliged to report by the jurisdictions in which they operate. Finally some currency conversion data were required to convert reported emissions per unit currency to emissions per GB Pound (GBP). The currency data were obtained from the website www.oanda.com.

3.2 Methods

The EIO model is adapted to make an estimate of the scope 1 and 2 emissions for tier 1 suppliers (suppliers who supply directly to the company), and this estimate is replaced by an estimate based upon CDP reported emissions intensity and expenditure with the company. This estimate can be compared with the scope 1&2 emissions reported by tier 1 suppliers via the CDP. Where the estimate from CDP data was self-consistent according to criteria outlined later, this information was used to form an estimate of the scope 1 & 2 emissions which replaced the estimate arising from EIO modelling.

The data from CDP were not suitable to be inserted directly into the EIO Model and a process of alignment and verification had to be carried out in order to integrate the two approaches. The process that was followed is described below.

1. The name that was reported by the supplier in the CDP data and the reference used by the purchasing company were aligned in order to correctly assign emissions.
2. The Scope 1&2 emissions intensity figure $\epsilon_{scope1\&2}^{(CDP)}$ for each supplier was extracted from CDP data. This figure is measured in tonnes CO_2e per unit currency total revenue. A common sense approach was taken that the combustion of 1 unit currency's worth of material should not result in 1 tonne of GHG emissions and accordingly emissions intensity figures that exceeded 1 tonne CO_2e per unit currency revenue were noted for checking.
3. A GB pound to supplier currency conversion figure C_S was calculated from the average historical exchange rate reported on http://www.oanda.com/currency/historical-rates/ over the 12 months 1/1/12 to 31/12/12.
4. The total scope 1 and 2 emissions arising $T_{12}^{(CDP)}$ from the company's spend S with the supplier was calculated using the formula:

$$T_{12}^{(CDP)} = \epsilon_{scope1\&2}^{(CDP)} \times S \times C_S$$

5. This figure was then compared with the supplier CDP reported total scope 1 and total scope 2 emissions (T_{1S} and T_{2S} respectively). For those suppliers where the calculated scope 1 and 2 emissions arising from the company's spend with the supplier exceeded the total of their reported scope 1 and 2 emissions i.e. :

$$T_{12}^{(CDP)} > T_{1S} + T_{2S}$$

Then the emissions intensity $\epsilon_{scope1\&2}^{(CDP)}$ was checked.

6. For data that passed both sense checks then the scope 1 and 2 emissions estimate arising from the EIO model was replaced by that estimate arising from CDP data.

7. For those suppliers where the emissions intensity figure $\epsilon_{scope1\&2}^{(CDP)}$ failed the sense checks in steps 2 and 5, further research was carried out to verify the reported revenue upon which the figure was based taking into account the organisational boundaries that applied to CDP figures. Many suppliers were calculating their emissions intensity based upon a common multiplier of unit currency e.g. thousands, millions or Lakh rupees. For those suppliers where it was possible to establish a unit currency revenue figure (R_S) then a revised emissions intensity $\epsilon_{scope1\&2rev}^{(CDP)}$ was calculated was calculated using the formula:

$$\epsilon_{scope1\&2rev}^{(CDP)} = \frac{T_{1S} + T_{2S}}{R_S}$$

8. This revised emissions intensity was then used in steps 2 to 6 above.
9. In order to compare emissions intensity amongst suppliers, the emissions intensity per unit currency $\epsilon_{scope1\&2}^{(CDP)}$ was converted to emissions intensity per pound sterling $\epsilon_{scope1\&2£}^{(CDP)}$ calculated using the formula:

$$\epsilon_{scope1\&2£}^{(CDP)} = \epsilon_{scope1\&2}^{(CDP)} \times C_s$$

4 Results

4.1 CDP Data Quality

An assessment of the data quality from CDP respondents was carried out and the emissions intensity factors classified in one of five categories summarised at Table

Description of Category	Proportion of respondents in category (%)
1._Suppliers who have supplied information that passes a sense check of scope 1&2 emissions arising from the company spend < supplier total scope 1&2 emissions based on CDP figures	17.1
2. Suppliers who have miscalculated emissions intensity exponent based on comparison of CDP reported revenue with emissions intensity calculation	19.0
3. Suppliers for whom an emissions intensity was derived based on their total scope 1&2 emissions as reported to CDP and financial figures available online e.g. from annual reports, Form 10-K etc.	4.2
4. Suppliers who have supplied partial information about emissions but not sufficient to calculate or estimate an emissions intensity.	6.0
5. Non-respondents	53.7

Table 4-1 Assessment of Data Quality from CDP respondents

The suppliers who had responded to the CDP questionnaires were in the top 200 suppliers by spend to the company, and those who provided sufficient information to make an estimate of their emissions covered 39% of the total spend. If all suppliers in the survey responded then 56% of the spend would be covered.

4.2 Impact on Supply Chain Scope 3 Emissions in 2012-13

	Total (Tonnes CO_2e)	Proportion (%)
Total of Scope 3 Emissions arising from Purchased Goods and Services	2,760,392	100
Tier 1 Supplier Scope 1 and 2 emissions estimate from EIO model	324,506	11.8
EIO model Scope 1 and 2 emissions estimate from suppliers included in CDP survey	135,015	4.9
Estimate of scope 1 and 2 emissions arising from CDP data from suppliers included in CDP survey	162,349	5.9

Table 4.2 Impact of substitution of CDP data on total footprint

The difference between the estimate arising from the EIO model and from the CDP data was 27,334 tonnes which was not regarded as significant.

4.3 Sectoral Differences

The companies reporting to the CDP are self-classified using the Global Industry Classification Standard (GICS) and the emissions intensities from IO model and CDP data at GICS Sub-Industry level are compared at Fig 4.1

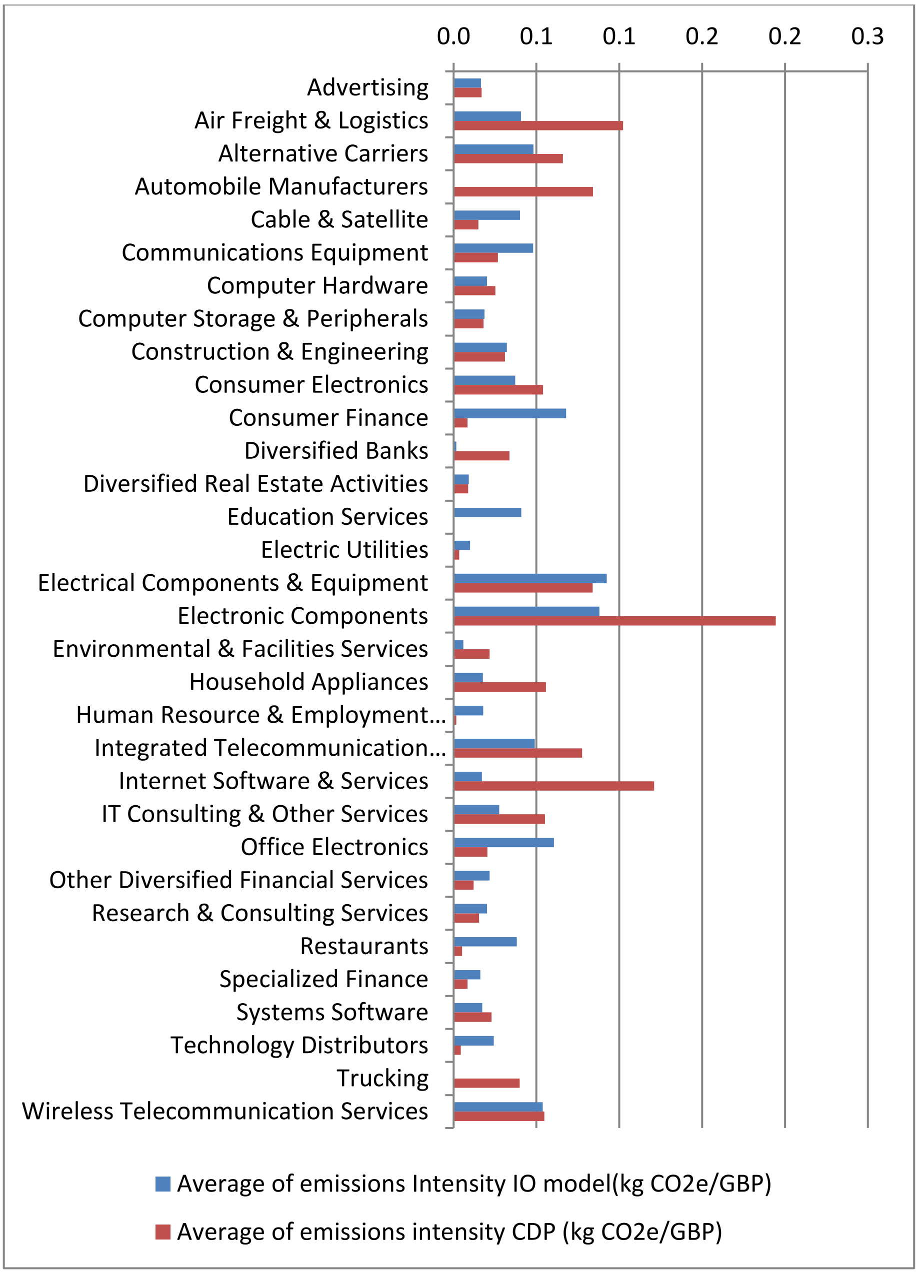
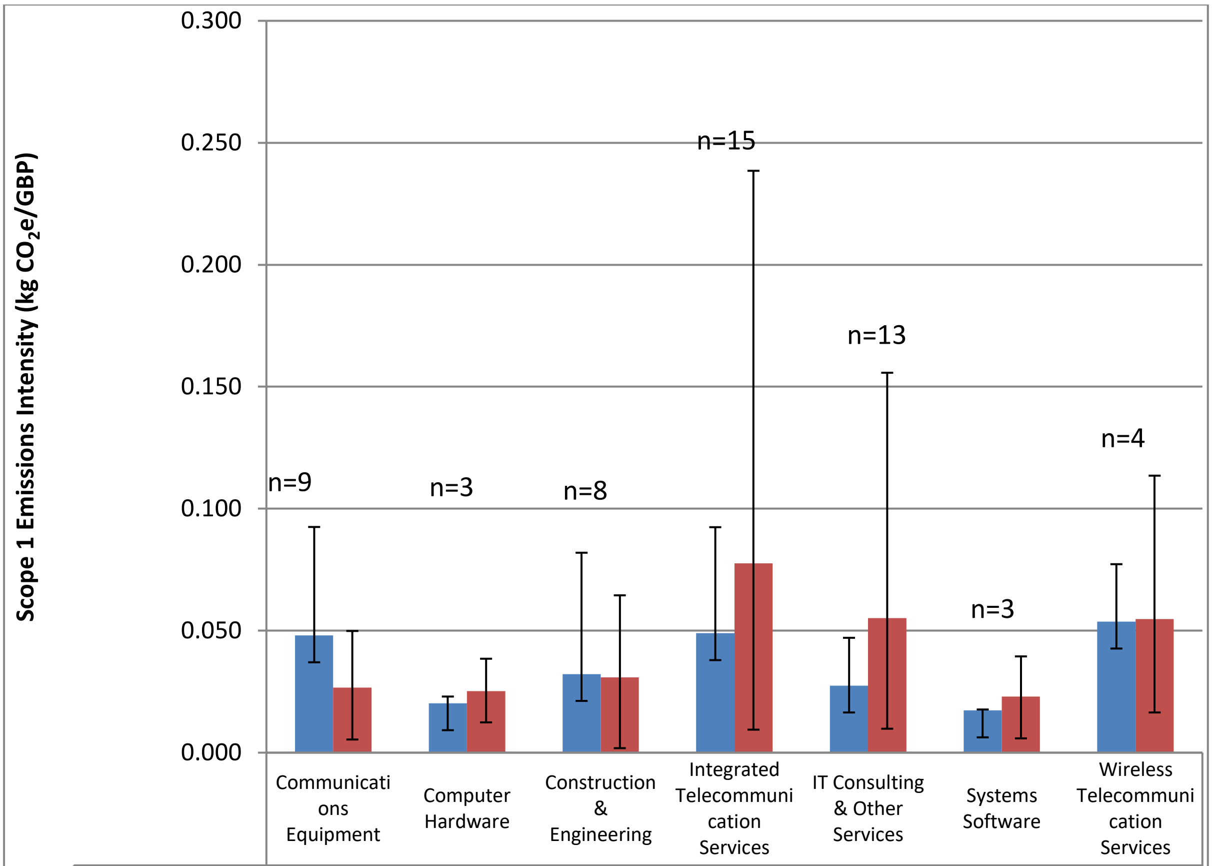


Figure 4.1 Comparison of scope 1&2 Emissions intensity IO Model and CDP data

Restricting the comparison to those sectors where there are 3 or more suppliers represented resulted in the analysis presented at figure 4-2.



	Communications Equipment	Computer Hardware	Construction & Engineering	Integrated Telecommunication Services	IT Consulting & Other Services	Systems Software	Wireless Telecommunication Services
IO Model Estimate	0.048	0.020	0.032	0.049	0.027	0.017	0.054
CDP data	0.027	0.025	0.031	0.078	0.055	0.023	0.055

Figure 4.2 Comparison of emissions intensity (kgCO_2e /GBP) between EIO model and CDP data, where number of suppliers in GCIS Sub-Industry sector, n, is greater than 2, bars indicate high and low emissions intensity in sector.

5 Discussion

The method showed some potential although there are some issues to overcome. The use of supplier-specific data to replace broad-based industrial sector data should result in a more representative estimate of supply chain emissions. The increasing awareness amongst leading companies of the importance of the emissions embedded in supply chains and their ability to do something about it should enhance the spreading of best practice. It can be seen from figure 4.2 that within GCIS sectors there was a considerable variance amongst the emissions intensities reported. If the company were able to use these variances to drive purchasing performance then their supply chain footprint could be reduced.

There are issues with the data for example alignment with companies reporting schedules and particularly with complex multinational entities the attribution of emissions within organisational boundaries. Whilst in principle the scope 1 and 2 emissions estimates made by suppliers should be more reliable than those arising from EIO model estimates, there is the possibility that the data had been calculated according to different methodologies and thereby is not suitable for substitution. Although the sources of scope 1 and 2 emissions are well defined, their calculation may be carried out using several methods. For large emitters it is possible that calculations of these emissions are based upon physical measurements of processes, but as the complexity of processing increases methods of calculation may depend upon estimates and generic factors.

There is also a limit to the impact that scope 1 and 2 emissions of suppliers have upon an estimate of upstream scope 3 emissions – in this case it is estimated that 11.8% of the total are due to supplier scope 1 and 2 emissions. If the analysis could be extended to tier 2 and further than more coverage can be obtained but the impact of a company on tier 2 suppliers is weaker, and the effects are more diffuse.

The currency conversion rate that is used in this estimate is quite crudely derived and it may be possible to use an organisation's own data to make a better estimate of the spend in currency. However these data may not be available or the supplier may quote its results in one currency but trade with its customers in several currencies thereby assuming the currency risk themselves. There is an argument for using purchasing parity currency exchange rates rather than a direct estimate of the exchange rate.

If a supplier is targeted on its scope 1 and 2 emissions then there would be a temptation to move those emissions out of that company and into another one. This could result in carbon leakage. The obvious extension would be to attempt to calculate scope 3 emissions intensity for the supplier and substitute this into the EIO model. However whilst definitions of scope 1 and 2 emissions are well understand and the processes of estimating them are understood and can be investigated, calculations on scope 3 emissions are subject to a wide variety of potential exclusions, considerable differences in calculation methods, and sizeable uncertainties. This methodology therefore may reach its maximum efficacy at companies whose tier 1 suppliers are the largest users of energy for example steel or cement manufacturers, and so as a result their scope 1 and 2 emissions form a significant part of the scope 3 emissions.

The technique has been shown to be effective in making alternative estimates of a subset of supply chain emissions and incorporating supplier specific data into hybrid models. This increased awareness of where emissions occur in a supply chain allows targets to be set for companies. As more years of data are reported, then trends and improvements in performance can be tracked. It is suggested therefore that this method with further refinement could be another tool for tracking the greenhouse gas footprints of organisations.

6 Acknowledgments

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Appendix D OECD Members

Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel , Italy, Japan , South Korea , Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia , Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

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