AN ANALYSIS OF INFLUENTIAL METHODOLOGICAL PRACTICES IN CONSUMPTION-BASED ACCOUNTING METHODS

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Declaration

I, Cara Kennelly, declare this work to be entirely my own and not published or submitted anywhere else or for any other merit.

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Contents

Contents 2
Abstract 5
1. Introductory material 6
1.1. Literature and background 6
1.1.1. Historical carbon accounting methods 6
1.1.2. Input-output carbon accounting models 6
1.1.3. Process-based life cycle assessments 8
1.1.4. Hybrid carbon accounting methods 8
1.1.5. Consumption-based accounting and the UK 9
1.1.6. System boundary selection 9
1.2. Aims and objectives 10
1.2.1. Aims 10
1.2.2. Objectives 11
2. Methodology 12
2.1. Input-Output Model Comparisons 12
2.1.1. Input-output Model Mechanics 12
2.1.2. Model Descriptions 12
2.1.3. Consumer Price Index Correction 15
2.1.4. Accuracy Analysis 16
2.1.5. Precision Analysis 16
2.2. Copper Wire Case Study 17
2.2.1. Argonne GREET.net model methodology 17
2.2.2. Process-Based Life Cycle Analysis Methodology 18
2.2.3. Gap Analysis 18
3. Model Comparison Results 20
3.1. Accuracy Analysis 20
3.1.1. Confounded Analysis 21
3.1.2. Unconfounded analysis 22
3.1.3. Multi-regional data comparison 23
3.1.4. Gap analysis 25
3.1.5. Accuracy Analysis Conclusion 27
3.2. Precision Analysis 28

3.2.1. Low Agreement Industry Sector Examples 29
3.2.2. High Agreement Industry Sector Examples 35
3.2.3. Precision analysis conclusions 40
4. System boundary analysis methodology 42
4.1. Process-Based Life Cycle Analysis Methodology 42
4.2. Gap Analysis 42
5. System Boundary Analysis Findings 44
5.1. System boundary identification 44
5.2. Gap Analysis 46
6. Discussion 49
6.1. Limitations of the study 49
6.1.1. Input-output model comparisons 49
6.1.2. Process-based life cycle assessment limitations 49
6.1.3. System-boundary analysis 50
6.2. Significant methodological practices and their implications 51
6.2.1. Location base of the model 51
6.2.2. Inclusion of multi-regional data 51
6.2.3. High-altitude factors 53
6.2.4. Economic differences 53
6.2.5. Outlier findings 54
6.2.6. Other influential issues 54
6.3. System boundary analysis findings 55
7. Conclusions 58
7.1. Recommendations 59
7.2. Future research opportunities 60
8. References 61

Figure 1. Comparative graphs of the input-output analysis results of all models as a percentage of the process-based calculation with respect to a) year b) inclusion of gross fixed capital formation (GFCF) c) inclusion of a high-altitude factor (HA) d) basic or purchasers' prices 22
Figure 2. Unconfounded comparative graphs of the input-output analysis results of all models as a percentage of the process-based calculation with respect to a) year b) inclusion of gross fixed capital formation c) inclusion of a high altitude factor d) basic or purchasers' prices. 23
Figure 3 Comparison of a single and multi-regional model produced by Small World Consulting Ltd. Model 24
Figure 4. The average carbon emissions factor calculated by each of the different input-output models as a percentage of the process-based life cycle assessment with gap analysis. Model acronyms are: Process-based life cycle analysis [PBLCA], PBLCA supplemented with gap analysis [PBLCA + gap analysis], Carnegie Mellon University [CMU SRIO], Department for Farming and Rural Affairs [DEFRA MRIO], Multi-regional Small World Consulting Ltd. model [SWC MRIO] and Small World Consulting Ltd. single region model [SWC SRIO] 25
Figure 6 Comparison of carbon emissions factors for the manufacture of iron and steel 30

Table 1 Metadata of input-output models compares in this study 13
Table 2 Gap analysis results tabulated by supply chain tier 46

Abstract

A key tenet of the work to mitigate anthropogenic climate change is to reduce carbon emissions. An entity; be it individual, company, or nation state, is more able to reduce their carbon dioxide equivalent emissions if they can be monitored and attributed, and their effects measured. The current state of carbon accounting methods does not consistently meet the standards required to tackle this global challenge, therefore this study aimed to identify key methodological practices affecting carbon accounting models and to assess the use of the system boundary.

Models currently available are either input-output based, (using macro-economic analysis), process-based, (using specific carbon emissions attributes through a life-cycle), or a hybrid of the two. A detailed comparison was made and the findings applied to a case study assessing the carbon burden of copper wire. An industry-leading process-based model was analysed using gap analysis and system boundary selection, and identification methods assesed.

Key methodological factors were found to be the inclusion of multi-regional data and sensitivity to the economic situation embodied in the model. Multi-regional data was found to increase carbon accounting model accuracy by reducing the need to make methodological assumptions and increasing the models' ability to represent real-world complexity. Economic sensitivity also enables the models to better represent complexity by describing differences in location, price volatility and market situations. System boundaries were identified as inadequately reported universally, the improvement of which is key to any future consumption-based carbon accounting accuracy, comparability asnd usefulness.

1. Introductory material

1.1. Literature and background

Climate change is arguably the most important environmental issue faced by humanity (IPCC, 2014), and a key part of addressing climate change is reducing the emissions of greenhouse gases associated with specific goods and services; often called a ‘carbon footprint’. The goods and services businesses provide are key sources of carbon dioxide and other greenhouse gases (collectively known as carbon dioxide equivalents: CO_2e). Estimating the magnitude of emissions allows mitigation efforts to be directed more strategically; particularly important following ratification of the Paris Climate Agreement (November 2016) and anticipated zero-carbon policies.

1.1.1. Historical carbon accounting methods

Estimation of carbon footprints has had a varied methodological history. Net energy analysis (NEA), which measures the use of resources for valuable work within the economy, was an important forerunner to life cycle analysis (LCA). The practice of carbon footprinting began as the life cycle analysis of products and their impacts across a range of environmental issues. Life cycle analysis is a holistic tool for evaluating full ‘cradle to grave’ environmental impacts of a product or service, from initial extraction of raw resources (cradle) to the final disposal (grave) (Ayres, 1995; Suh et al., 2004). This method became a key method of making rational judgements on the environmental loads of end-use products (Ayres, 1995) which itself is crucial to making products with environmental awareness. Life cycle analyses have inherent errors due to a number of issues including unreliable measurements, estimates and assumptions; bias in original source data; temporal, geographical and technological miscorrelation; and deficiencies in knowledge of the systems in question (Lenzen, 2000).

1.1.2. Input-output carbon accounting models

Input-output analysis is a ‘top-down’ technique making use of financial transaction data to monitor and account for the complexities of modern economic systems (Lenzen, 2000). By applying known environmental data to this method it can be “environmentally extended”, creating the ‘EEIO’ (environmentally extended input-output) model. Since the initial creation of the input-output economic model by Leontief in the 1930s, it has been successfully extended internationally with national and regional input-output tables being adopted as a United Nations standard (Wiedmann, 2009), however the UK was the first country to report regular consumption-based accounts (Defra, 2014).

Input-output analysis is well described and consistent. It can be applied at various scales to a wide variety of products and services or with other models and analysis tools. It is standardised and, despite limitations at the micro level (Wiedmann, 2009), has economy-wide completeness and an unambiguous consumption-production link. Due to the versatility of the method, input-output analysis can be used to evaluate trade-offs in decision-making scenarios between carbon, financial and social objectives (Weber et al., 2009). It can ensure system completeness and act as a method of establishing the significance of different supply chain paths (Weber et al., 2009). Despite the relative complexity of creating input-output analysis models, once established their operation is simple, and the necessary data input minimal (Wiedmann, 2009). Input-output analysis is particularly useful for capturing upstream emissions which contribute significantly to scope 3 emissions (Wiedmann, 2009).

Recently input-output models, previously describing only a single region of production and trade, have been redesigned to represent multiple regions, thus better representing the globalised nature of modern commodity trade. However, this has substantially increased the data requirement of input-output models (Andrew et al., 2009). Single-region models focus on only the production and trade within the borders of the country in question, whereas multi-regional models take into account the imports of commodities from outside the national boundaries. This has presented methodological challenges, namely the sourcing and integration of trade data, both multi- and uni-directional, into consumption-based carbon accounting methods resulting in greater complexity, however benefits in accuracy outweigh the costs which are not untenable (Andrew et al., 2009) and thus the multi-regional input-output consumption-based accounting model has become the benchmark standard.

However, input-output analysis has inherent limitations and uncertainties:

Firstly, each input-output model sector is assigned an embodied value for outputs which is homogenous across the sector (Bullard et al., 1978), despite the heterogeneous nature of the products and processes within that sector, thus leading to aggregation error (Suh et al., 2004).

Secondly, inflation (as the monetary value changes without necessarily affecting the physical quantities and therefore the associated carbon emissions; Bullard et al., 1978) and the infrequency of expenditure on expensive long-life products, can result in incorrect results for periods of atypical spend (Suh et al., 2004).

Thirdly, the constantly evolving nature of technological and economic systems results in frequent change of input-output economic categories which results in the need for constant monitoring and adjustment (Bullard et al., 1978). For example, the supply and use tables published annually by the Office of National Statistics has comprised of 110, 106 and now 105 industrial sectors.

Fourthly, the underlying tables require periodic updating to reflect the most recent national or regional figures or methodological updates. Without this financial and time expenditure the models would quickly become out of date and obsolete.

Fifthly, the process has remained largely inaccessible to non-academic audiences due in part to a lack of communication (Wiedmann, 2009). To be used widely in the business sphere, input-output analysis must be made comprehensible through language, information sharing, support, training and education (Weber et al., 2009). There is a widely-held belief that input-output analysis is impractical for organisations, and is unreliable or difficult to apply. (Weber et al., 2009), however, with appropriate communication and education these preconceptions could be overcome. Input-output analysis requires a large amount of data (Bullard et al., 1978) and multi-regional input-output analysis more still (Wiedmann et al., 2011), although these data are generally easily accessible from national accounts (Suh et al., 2004).

1.1.3. Process-based life cycle assessments

Process-based analyses are a 'bottom-up' approach to carbon accounting that involves itemised research of the carbon burden of a products life-cycle. They are prone to truncation error as the diminishing contribution of infinite terms results in a point where it is too costly or labour intensive to extend the system boundary beyond that point. However, the energy cost of processes beyond the system boundary can be very substantial (up to 87% in one analysis; Crawford, 2008). Potentially excluded processes have often never been assessed and therefore cannot be guaranteed negligible before being excluded from analysis - which may have impacts on the reliability of future comparative analysis (Suh et al., 2004).

Process-based analysis is high cost, labour-intensive, inflexible, has subjective boundary definition (Joshi, 1999) and the methods largely ignore supply chain aspects of environmental load (Lenzen, 2000). Simple processes require simple process-based carbon accounting - however the more complex the process the more complex the carbon accounting requirement (Weber et al., 2009). Thus, the results of this method are dependent on the effort expended by the analyst so a comparison of methods is somewhat irrelevant and has been deemed outside the scope of this study.

The amount of carbon embodied in a product estimated by process-based analysis is consistently lower than that estimated by input-output analysis (Lenzen and Dey, 2000; Crawford, 2008). However, there are exceptions which may be caused by better quality and/or quantity of process data than is usually available (Crawford, 2008). Despite the different process-based analysis approaches, truncation error is always significant as it contributes to the significant underestimation of final life-cycle inventory values (Suh et al., 2004).

There is a significant disparity between the results of process-based analysis and input-output analysis (Crawford, 2008) and thus significant debate on the method by which to determine the system boundary between the two. The ability to fully understand optimal practice with boundary selection is key to successful hybridisation, and thus creation of a both a specific and systemically-complete carbon accounting method.

The use of cut-off thresholds in process-based analysis, (a system boundary beyond which supply chains are deemed insignificant) is unreliable and creates extremely variable analysis (Weber et al., 2009). Though each supply chain cut-off may be insignificant the sum of all cut-offs could be influential (Suh et al., 2004) and thus cannot be rigorously assessed for accuracy. Understanding the system boundary selection process and isolating the boundary itself is therefore key in the hybridisation of carbon models. System boundary selection decisions based on ISO standards are not typically made using a scientific basis (Suh et al., 2004). One scientific method on which to base system boundary selection decisions is structural decomposition analysis which is relatively easy to implement, requiring only excel processing, thus lending itself to both organisational accessibility and scientific rigour.

1.1.4. Hybrid carbon accounting methods

The hybrid life cycle analysis method is the use of input-output analysis alongside process-based methods. The input-output model is used to identify the significant sources of supply chain carbon emissions which the process-based analysis then calculates accurately. The input-output model is then used to calculate the remainder of the carbon burden as defined by gap analyses (Minx et al., 2008; Bullard et al., 1978; Treloar, 1997; Suh et al., 2004). This ideal is used within this study as an assumed best practice as it is the most accurate method currently available to estimate actual carbon emissions, unmeasurable with current technology.

Within business carbon monitoring, scope one and two emissions (the direct emissions from point of sale and indirect emissions from energy and electricity use respectively) are often assumed to be more significant that scope three (other indirect emissions) (Wiedmann, 2009), however this is not always the case (Weber et al., 2009). In a hybrid approach to carbon footprinting, emission hotspots can be readily identified using the broader input-output approach. By then combining with the process-based approach, the intention is for to gain specificity in key areas, as well as complete economic coverage. A significant benefit of the hybrid model over others is the system-completeness that merging top-down and bottom-up approaches brings (Wiedmann, 2009), as well as the increased cost-effectiveness and specifiable accuracy (Bullard et al., 1978). These improvements led to the results of hybrid models having consistently larger carbon values than those of purely process or input-output models (Crawford, 2008) and thus hybrid approaches have been recommended by multiple scholars (Minx et al., 2008; Lenzen, 2002). At its core a hybrid carbon model is the use of both process- and input-output based databases and the application of a system boundary selection process to describe where to use each model in order to utilise the best of each methodology.

1.1.5. Consumption-based accounting and the UK

Consumption-based accounting has dominated carbon accounting methods more recently due to it's methodological grounding in economics. Where production-based accounting methods can show you only a limited part of the carbon emissions of a product, an input-output model can describe the entire supply chain, an increasingly important dimension of the environmental impact of products in an increasingly complex market and world. Analyses of supply chains through consumption-based accounting can help identify and address risks that are intrinsically tied to procurement, such as resource taxation, price volatility and availability shocks (Owen et al., 2017). It is crucial for a governing body, such as the UK but at any spatial or political scale, to have confidence in and an understanding of the causes, influencers and mitigation strategies for these risks. Accuracy and consistency in these analyses encourages stability in supply chains that can be made unstable by economic, political or environmental factors.

1.1.6. System boundary selection

This study aims to assess the effects of system boundaries in hybrid carbon accounting methods. Gap analysis will be undertaken to attempt to isolate aspects of the method or analysis to identify options to make future system boundary analysis more reliable and scalable.

There are three main methods of system boundary selection, according to the International Organisation for Standardisation report 14040; physical allocation, economic allocation, and system expansion (BSI, 2006). The physical allocation method uses data on the mass of commodities used in the production of a given product or service and assigns carbon burden data to those figures to calculate the carbon footprint of the product. The economic allocation method attaches environmental data to economic data and uses this matrix to assign the proportion of carbon burden of each input to a product to calculate the final carbon footprint. The system expansion method involves accounting for the displacement factor of co-products created during the production of the primary product.

System boundary identification using different methods cannot be compared to each other as they each use incomparable parameters and datasets in the selection process. It is therefore important *not only t*o identify the most accurate system boundary selection method, but also the most *widely adopted* to ensure comparable carbon accounts across platforms. (For example, business reports and academic reports could be used in tandem if the methodologies were comparable and thus knowledge could be shared more easily and effectively). This is key to the future of carbon accounting as it will enable a more holistic approach to carbon emissions reductions.

Gap analysis is particularly important in isolating system boundaries within carbon accounting methods. By providing insight into the way input-output and process-based analyses work in conjunction, it allows a more accurate overall system boundary to be calculated. Whereas input-output analysis achieves completeness it can be prone to overestimation, conversely process-based analysis sacrifices completeness for specificity. Gap analysis allows valuable insight into the trade-offs of locating the system boundary in different places in relation to each method.

1.2. Aims and objectives

The intention of this study is to compare the calculated $kgCO_2e$ per pound sterling (£) of spend from different input-output models and subsequently analyse system boundary selection approaches and their impact within current hybrid carbon footprinting methods. Comparative techniques and statistics on both specific and general examples afford insight into recent carbon accounting practice and for this to be understood in terms of both individual techniques and broad use of carbon accounting methodologies. An improved understanding of carbon accounting mechanisms will be key in the future reduction of carbon emissions particularly for end users. Despite recent recognition that carbon accounting methods must be constructed with the end user in mind (Owen et al., 2017), there is much progress to be made, and so this study aims to maintain the interests of specifically commercial end users.

1.2.1. Aims

- Compare the calculated emissions intensities of four input-output carbon accounting models.
- Identify influential methods in input-output carbon accounting models and their impact on calculated emissions intensities.
- Understand the role of the system boundary in a carbon footprint case study of copper wire.

1.2.2. Objectives

- Use confounded and unconfounded (multiple variable and single variable) analysis to identify and assess the strength of influential methodological practices in input-output models.
- Conduct structural path and gap analysis on industry sectors with simple supply chains.
- Identify industry sectors for which the input-output models most agree and most disagree and compare each model within these sectors to assess significant methodologies.
- Conduct a process-based life cycle assessment of copper wire in the UK using gap analysis.

2. Methodology

A detailed breakdown of the methodology used in each stage of this research will be explained and justified in this chapter.

Models were sourced directly from the creator. Where possible the models were publically available, however due to the lack of clarity in the methodology of publically available models and the requirement for meaningful analysis it was deemed appropriate to use a model for which the data was not directly publically available but whose methodology was completely transparent, which was the case for the Small World Consulting Ltd. models, and thus a link to the 2011 model has been provided in table 1 for context. Small World Consulting Ltd. provided their two models with methodological papers and the Defra and Carnegie Mellon University models (and associated methodological papers) were downloaded from the associated webpages. These models and documents were analysed to isolate influential methodological practices using statistical measures such as range and mean. The prevailing model was then compared to the Argonne Laboratory GREET.net model in order to assess system boundary methodology using a case study on the carbon burden of copper wire. All methods were undertaken using 2012 data and models were run both according to the published version of the model and in deconstructed ways, (as far as the methodological transparency would allow), in order to isolate the most influential methodological practices.

2.1. Input-Output Model Comparisons

2.1.1. Input-output Model Mechanics

The model mechanics on which input-output carbon emissions models are based is matrix algebra of national supply and use tables. As the name suggests, databases describing the supply (or input) and demand (or output) of a system are used to map the relationships between different elements of that system. In the case of carbon accounting the system is usually an economy, regional, national or international, and the different elements are industries within that economy. The relationships are mathematically described using the leotief inverse which follows the equation:

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

Where *I* represents the identity matrix and *A* represents the technical coefficient matrix. A detailed description of the theory behind this equation and the steps required to build an input-output model can be found in (Miller and Blair, 2009).

2.1.2. Model Descriptions

There are a number of different carbon accounting models available in the UK and internationally. The main characteristics of the models compared in this research are summarised below:

Table 1 Metadata of input-output models compares in this study

Database	SWC SRIO	SWC MRIO	Defra MRIO	CMU SRIO
Reference year	2012	2012	2012	2002
Year released	2015	TBC	2013	2008
Number of sectors	106	106	106	458
Number of regions	1	4	4	1
Original Currency	GBP	GBP	GBP	USD
Economic data source	Office of National Statistics Supply and Use Tables	Office of National Statistics Supply and Use Tables	Office of National Statistics Supply and Use Tables	Bureau of Economic Analysis
Environmental data source	Office of National Statistics Environmental Accounts	The Eora MRIO Database	UK GHG Inventory; JEC Well-to-Wheels; DECC Quaterly Energy Statistics for Renewables;	US Census Bureau; US Energy Information Administration; US Department of Energy;
Link	2011 SWC SRIO: http://media.ontheplatform.org.uk/sites/default/files/gm_footprint_final_110817.pdf	N/A	https://www.gov.uk/government/statistics/uks-carbon-footprint	http://www.eiolca.net/cgi-bin/dft/use.pl?newmatrix=US428PURCH2002

2.1.2.1. Carnegie Mellon University Environmental Input-Output Life Cycle Assessment

The Carnegie Mellon University Environmental Input-Output Life Cycle Assessment model was developed by the Green Design Institute of Carnegie Mellon University. It uses 458 industrial sectors categorised using the North American Industry Classification System (NAICS). Gross fixed capital formation (GFCF) and high-altitude factors for aircraft emissions of greenhouse gases are not included in the model. Gross fixed capital formation is a measure of the fixed assets used continuously for over a year, such as buildings (Eurostat, 2013) and represents the long-term carbon burden of these fixed assets. This is a single-region model based on the United States that uses old, incomplete data with inherent uncertainty, thus any findings based on this analysis should be treated with caution. Use and end-of-life phases of the product life-cycle, (otherwise known as scope 3 emissions), are not included in the Carnegie Mellon University model. This is therefore not a full life cycle assessment despite the title of the model.

This model represents the United States economy using 458 industry sectors, whereas the UK-based models use 106 industry sectors (table 1). In order to conduct meaningful comparisons the 458 industry sectors in the USA model were aggregated and disaggregated according to the NAICS and SIC codes as they related to the Office of National Statistics supply and use tables, using the detailed classification descriptions and ratios to best relate each of the 458 industry sectors to the corresponding sector in the UK models. These calculations can be found in appendix A.

2.1.2.2. Department for Environment, Food and Rural Affairs (Defra)

Defra is a UK government department that uses data from the Digest of UK Energy Statistics (DUKES). This is a multi-regional model that distinguishes four world regions: the UK, countries within both Europe and the OECD, non-European OECD countries, and non-OECD countries (Minx et al., 2008). This data source and model is updated annually and uses the Standard Industrial Classification (SIC) categorisation for its industrial sectors. There is inclusion of gross fixed capital formation, however no high-altitude factor is included in the Defra calculations and they do not account for scope 3 emissions consistently or precisely across sectors. There is a multiplier used to account for the non-CO_2 effects of air travel, such as the radiative forcing; however this is not as influential as a direct high-altitude factor would be. As a multi-regional model this model, and the Small World Consulting Ltd. multi-region input-output model described below, would require a much larger dataset thus making it more difficult to set up and update, however the trade data would more accurately represent the globalised supply chains (Andrew et al., 2009).

2.1.2.3. Small World Consulting Ltd. Single-Region Input-Output Model

Emissions estimates are calculated predominantly based on supply and use tables from the Office of National Statistics (ONS) using conversion factors from Defra on data relating to travel, fuel and energy consumption and national purchases of products and services from the Office of National Statistics, with additional calculations based on Small World Consulting Ltds' specific methodology. Unlike all other models, this includes *both* gross fixed capital formation *and* a high-altitude factor for aircraft emissions. In this model all supply chain pathways from the air transport sector are multiplied by 1.9 to reflect the increased impact of releasing greenhouse gases at altitude compared to releasing them at ground level. This factor of 1.9 is used in accordance with a Defra reporting guidelines publication where the 1.9 high altitude factor figure was published in footnotes.

2.1.2.4. Small World Consulting Ltd. Multi-Regional Model

This model is very similar to the single-region model described previously with the significant difference that it accounts for the different carbon implications of imported goods compared to domestically produced goods. Specifically, it includes three regions other than the UK: China, the EU, and the rest of the world (RoW), and uses purchase data to map the source of goods and services globally, (which are then allocated location-specific carbon burdens). This is undertaken in order to better represent the global nature of trade in the current economy. Due to the different mathematics involved in a multi-region model, the high-altitude factor included in the single-region model could not be satisfactorily included in the multi-region version. However, the model does include gross fixed capital formation in calculations of final demand.

2.1.2.5. Process-Based Life Cycle Assessments

The process-based life cycle assessments used to compare the input-output models in chapter three are based on the Defra process-based life cycle analysis figures published relating to 2012. Data was extracted from Defra and the Office of National Statistics relevant databases and other individually researched datasets. Simple calculations were undertaken to establish the kilograms of carbon dioxide equivalent greenhouse gases emitted for every £1 of spend in each of the industries. Each industry was disaggregated into relevant product types to reflect the specificity ideally gained through process-based life cycle analysis techniques over input-output methods and thus to create a more accurate and objective comparative database. For example, the electricity production, transmission and distribution industry was broken down into the following product groups: UK Domestic, UK Industry, UK Industry & Domestic, UK Total, UK Average. The same breakdown was conducted on US-produced electricity to reduce the impact of the different geographical sources of models on the comparison of the models and methods.

2.1.2.6. Important Notes

The theoretical basis of the Carnegie Mellon University model is the economy of the United States. Therefore it is not directly comparable to the other models as the theory of the Defra and Small World Consulting Ltd. models is based on UK economics and industry. All carbon factors, as produced by the relevant models, represent the kilograms of carbon incurred during the production of £1 worth of goods in that sector. As such, all models are comparable at the final results stage as presented in this study.

2.1.3. Consumer Price Index Correction

Due to the limited availability of input-output carbon accounting models with sufficient published methodology to conduct this analysis and a requirement for methodological diversity it was decided an inflation-based correction of some older models would be better suited than a smaller sample size. The consumer price index (CPI) was used to correct data relating to time points before 2012 using inflation so that they better aligned with the economic data described in the carbon accounting models that represented the year 2012. In this analysis, the Carnegie Mellon University model was the only model that consumer price index correction was applied to.

The key assumption at this stage of the methodology is that the carbon emissions associated with £1 of spend in each of the industry sectors was the same in 2012 as it was during the year the model was originally designed to represent. Consumer price index correction only adjusts the economic data according to temporal changes and does not adjust the corresponding environmental data, thus potentially leading to discrepancy. This assumption was deemed necessary in order to achieve the best possible comparative databases. As there was no way to correct the environmental data without reconstructing the entirety of each of the models, a task far beyond the scope of this study, better that only the environmental data was an indirect comparison rather than both environmental and economic data. This is a significant assumption as the actual carbon emissions associated with each industry sector are likely to have reduced, and almost certainly have changed in one way or another.

For the calculation of the correction ratio the industry-specific consumer price index for the base year, in this case 2002, was divided by the target year, which would be 2012 for the Carnegie Mellon University model. This method follows basic mathematical principles of ratios. The resulting ratio from that calculation was then multiplied by the conversion factors produced by the Carnegie Mellon University input-output model to calculate the conversion factors corrected to the 2012 economic value.

2.1.4. Accuracy Analysis

Within the accuracy analysis a process-based life cycle assessment was used as a benchmark which all input-output models were compared to. This benchmark represented a theoretical 100% of life cycle carbon emissions comprising a hybrid life cycle assessment (process-based, input-output, and gap analysis assessments) for the mining of coal and lignite, the manufacture of coke and refined petroleum products and the electricity production, transmission and distribution industry sectors against which the input-output models in question and the process-based assessment without the gap analysis were compared. This enabled the calculations to identify methodological practices that were more likely to lead to the assumed 'correct' carbon emissions factor.

These industries were chosen as they were considered simple enough that a process-based analysis method would represent them relatively accurately and their databases contained enough supply chain documentation that any findings would be relatively easy to contextualise. These parameters meant that detailed and in-depth analysis was possible enabling a better understanding of any results.

While this method was not ideal due to the significant issues with the process-based methodology, as discussed in the introductory material, it was deemed the best option available to this study. A benchmark had to be used that was not based in input-output methodology in order to ensure the any findings from input-output model comparisons were independent. As there is no way to directly measure the full life cycle carbon burden of a product, industry, service, etc. process-based analysis was used. A process-based analysis was conducted of the three industry sectors in question and a gap analysis applied to each of these industries individually. This gap analysis resulted in a ratio of truncation error which was applied to the process-based analysis result to increase it to a value that was both specific and systemically complete. This hybrid carbon accounting method used established process-based databases, namely Defra and Office of National Statistics, and gap analysis ratio application which, for the purposes of this study, was considered best practice. It is acknowledged that there are issues with this methodology and that in the real world it would not represent a best-practice case as it is is still subject to many of the methodological issues associated with process-based carbon accounting methods.

2.1.5. Precision Analysis

The degree of precision an input-output model achieved was based on the degree of agreement between multiple input-output models. Each of the original models was manipulated to represent different methodological practices, as far as the publications would allow, leading to multiple versions of each model. For example, the Carnegie Mellon University model was run using purchasers prices to find the final conversion factors, and then run again using producers prices, creating two versions of the same model but with variable methodology. Each of these variants was collated and used to calculate mean values for each industry sector. In total there were 30 variations of the models, sixteen representing the Small World Consulting Ltd. single-region model, ten from the Small World Consulting Ltd. multi-region model , two from Carnegie Mellon University and two from Defra. The potential for the greater amount of Small World Consulting Ltd. models compared to either Carnegie Mellon University or Defra is a result of the lack of transparency of the methodological papers provided by the latter two organisations. The implications of this are discussed in more detail in chapter 6.1.

In this instance for Small World Consulting Ltd. single-region input-output model, although the final results and in-depth methodology was available online the model itself was not publically available. Access to the model for academic purposes was requested and provided readily, and the full model was manipulated using information from the publically available methodology papers. This method of accessing the model allowed a greater level of manipulation and therefore the Small World Consulting Ltd. single region model contained the greatest number of variations in this comparative analysis.

2.2. Copper Wire Case Study

Analysis of the system boundary was undertaken on the case study of 1 kg of copper wire production. Consumption-based accounting analysis was conducted, supplemented with gap analysis and supported by related research. The aim of this was not only to identify and isolate the system boundary within hybrid carbon emissions models but also to attempt to identify the potential to make any part of this process more generic in order to make it more accessible to a wider audience.

2.2.1. Argonne GREET.net model methodology

As the GREET.net model is currently being dismantled by the Argonne National Laboratory the detailed methodology papers do not exist (Dieffenthaler, 2016). An in-depth understanding of the processes is therefore not possible, however the copper wire supply chains data were supplied by personal correspondence from the Argonne National Laboratory and the following system boundary analysis was based on that data.

The Argonne GREET.net model is based on the US economy, but the input-output model it is hybridised with is based in the UK. For the purposes of this study this is not critical as the intent is to study the method rather than the results. However it does mean that this exact method should not be undertaken outside of this study. In all real-world cases the input-output and process-based methods intended for hybridising should represent the same individual or set of regional economy(ies) to ensure the highest levels of accuracy and reliability in the results.

GREET stands for Greenhouse gases, Regulated Emissions and Energy use in Transportation, therefore the analysis is designed specifically to cover the burdens incurred in the production of products for the transport sector only. In the case of copper wire this has minimal, if any, impact on the reliability of the study however this would not be the case for every product covered in the GREET.net model and thus caution should be taken when applying their process-based figures to other hybrid carbon model analyses.

For the commodity copper wire, the results of GREET.net describe specifically the drawing of the copper wire as it uses the following: virgin copper, petroleum as manufactured from crude oil by industrial boiler, coal (average US mix) as manufactured by industrial boilers, and electricity (average US mix). Embodied within the model methodology is the energy requirement at Chilean and American manufacturing locations, though at a significantly aggregated level.

2.2.2. Process-Based Life Cycle Analysis Methodology

The greenhouse gas process-based life cycle analysis used is the system boundary analysed for this study was from the Argonne GREET.net model. The GREET.net results for copper wire produced in 2012 were used to make the process-based model as compatible as possible with the input-output models by aligning the data temporally. The Argonne National Laboratory is based in the US but is a global research institution that produces thorough science in the form of reports, databases and models. As such it is a source of some of the best process-based analyses available in terms of breadth of products covered and detail included per product analysed.

Though there have been many academic publications of process-based life cycle analyses these have often been either so specific as to be irrelevant to most carbon intensity analyses (for example: Pearce et al., 2013; Hu, 2012; Stylos and Koroneos, 2014) and/or funded by businesses and hence may be biased (for example: Kumar et al., (2014) funded by HP and Ayushmaan Technologies; Zhang et al., (2015) funded by the Kunming Engineering Corporation Ltd). Even the methods used in life cycle assessments can be subject to biases, such as Steinmann et al. (2014) funded by ExxonMobil, who have a direct and vested interest in the results of carbon analyses yet proposes to refine and adjust the results of carbon footprints. A standardised approach, as this study works towards creating, is critical to enabling the widespread use and understanding of carbon footprints and life cycle analyses.

2.2.3. Gap Analysis

A gap analysis was undertaken by comparison of the input-output sectors of the Small World Consulting Ltd. single-region model to those included in the Argonne GREET model database and methodology papers. Where input-output sectors were not wholly included or excluded in the process-based analysis an effort was made to understand the extent to which the data that were included in the Argonne GREET.net analysis covered the full sector data of the input-output analysis. This ratio was then substituted into the gap analysis to calculate the amount of the input-output analysis covered by the process-based calculations.

The gap analysis was applied to copper wire as a case study because it is a common product frequently found in use across all industry sectors and around the world. It is also a reasonably complex product that thereby does not privilege the process-based analysis whilst not having so intricate a production system that it would privilege the input-output analysis. This makes copper wire an ideal case study for both the quantitative analysis of carbon intensity methods and a useful reference for businesses and academics in future studies. The value of 1 kg of copper wire was used during the analysis calculations as this is a standard value of product on which carbon intensity calculations are based within both input-output and process-based methodologies. As the GREET.net model calculates values of greenhouse gas emissions the results had to be contextualised for the input-output model results by applying price values.

3. Model Comparison Results

This chapter describes the findings of the input-output model comparisons undertaken between the Defra, Carnegie Mellon University, and Small World Consulting Ltd. single- and multi-regional input-output models. Two main methods of analysis are used to assess the ability of the models to replicate real world emissions, as estimated by their closeness to a process-based life cycle analysis conducted within this study (i.e. their accuracy, as defined below) and the ability of models to agree amongst themselves (i.e. their precision, as defined below). In-depth comparisons are derived from the methodology documents provided by each organisation and, where possible, a structural path analysis of the results, the full workings and results of which are available in appendix A. The following documents are used in this methodological comparison:

- 2012 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emissions Factors
- Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, WTT Appendix 1: Description of individual processes and detailed input data (Edwards et al., 2011)
- About The EIO-LCA Method, available at: http://www.eiolca.net/Method/index.html, Green Design Institute, Carnegie Mellon University
- The 2002 US benchmark version of the economic input-output life cycle assessment (eio-lca) model, by C. Weber, D et al., Green Design Institute, Carnegie Mellon University, June 16, 2009

3.1. Accuracy Analysis

Accuracy in the context of this study refers to the proximity of an emissions intensity output to the actual emissions intensity of a given product. Input-output models have been criticised as being too generic in their analysis, as whole industry sectors are used to represent, in some cases, just one product. When a product is atypical of the industry sector it is produced in, this results in low accuracy of the input-output models result. Process-based analysis methods have the highest potential accuracy because they are bespoke and specific, and if enough time and money is invested in the analysis the truncation error can be reduced significantly enough to make it comparable to input-output results in terms of system completeness. Thus, detailed process-based analyses were undertaken of three extractive industries, with the simplest supply chains and the most reliable data sources, and these figures were compared to the results from the input-output databases by finding the percentage of the input-output figure that the process-based values covered. To analyse the impacts of different variables, the mean of all models with a specific variable was compared to the opposite methodological mean to obtain the extent of the influence of each variable.

Interpretation of this analysis was undertaken in two parts: confounded and unconfounded variables analysis. Confounded analysis described data with multiple variables in the analysis, thereby providing evidence of the variables with the strongest impact on the carbon accounting of each industry sector. This is particularly useful as the methodological practices of particular influence in these carbon accounting models is not known and this analysis allows the inference of the strength of one variable over another, allowing the potential influence of each analysed methodological practice to be studied in the appropriate context. Unconfounded analysis describes data with only one variable, and thus describes the impact of only one methodological choice on the industry sector carbon accounting results in isolation from other methodological choices. This analysis provides more clarity of the impact of each methodological choice and therefore its potential methodological importance for the accuracy of results. However, the isolation of the impact of each variable means that the influence of other methodological choices on the variable studied is not considered. As such, the inclusion of both confounded and unconfounded analysis was deemed valuable.

A particularly important variable, not included in all models, is a correction factor for greenhouse gases emitted at high altitude by aircraft. This correction factor is designed to reflect the increased potency of greenhouse gases in the upper atmosphere, and the use of this factor increases the calculated carbon footprint of models that include it compared to those that do not. Within calculations it is applied to all air transport involved in the supply chains of a product or service, thus methodologically applied to the entire economic model, however, the total impact of the high-altitude factor is dependent on the reliance of that products supply chain on air transport. For example, the high-altitude factor is applied to both the manufacture of coke and refined petroleum products and the mining of coal and lignite. In the confounded analysis (figure 2) there was found to be a greater impact of the high-altitude factor on the manufacture of coke and refined petroleum products than on the mining of coal and lignite.

3.1.1. Confounded Analysis

This comparison is designed to identify the most influential methodological aspect of an input-output model as it highlights the factors that affect the results to an extent that is discernible even through the differences caused by other variables. Although useful, this did cause some counter-intuitive results. For example, figure 1c shows that for the analyses of coke and refined petroleum products, the basic mathematical assumption of the addition of a multiplicative factor increasing a resulting value is reversed. For this industry, multiplying the carbon burden data by 1.2, as the Small World Consulting Ltd. methodology requires, appears to reduce the final calculated carbon burden in comparison to not including the high altitude factor multiplication. This anomalous result is caused by the use of calculated means of all model variations, as opposed to single models with only one variable, in the analysis as other biases of the data are included. For example, in the case of figure 1a the darker blue columns correspond to all model variations that use data from the year 2012 regardless of all other methodological variables. This confounds the variables as it privileges the position of the attribute being directly studied, for example the year of data collection, over all others and does not describe the respective influence of each attribute. In this case, the effects of the multi-regional models have the strongest impact, of the methodological processes analysed in this study.

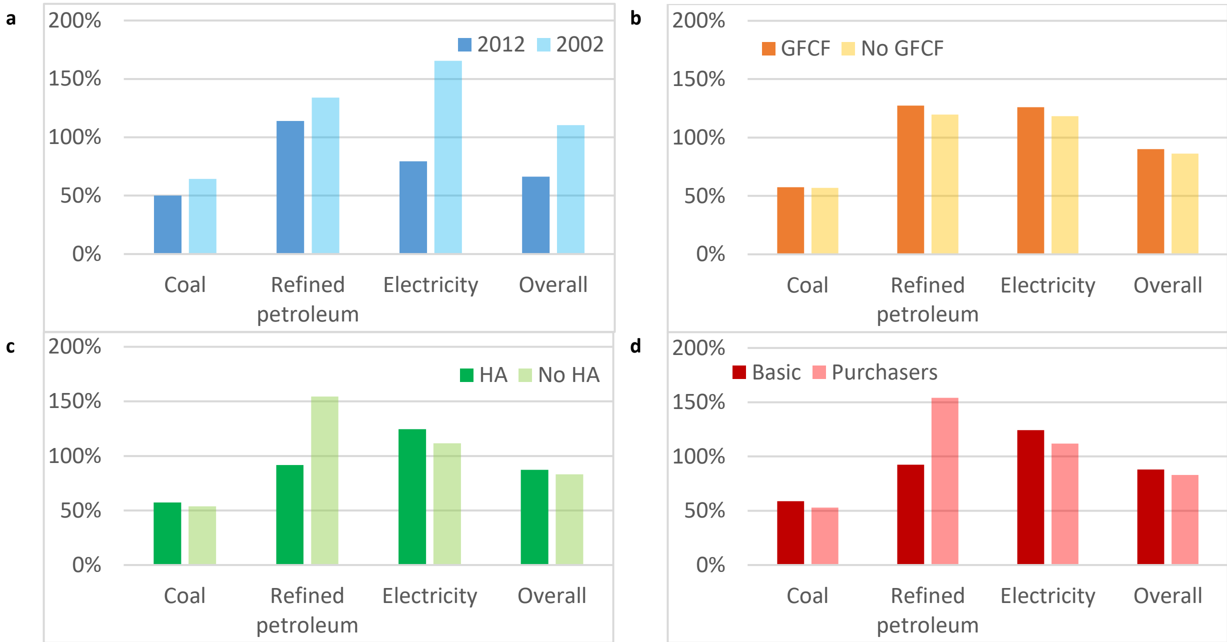

Figure 1. Comparative graphs of the input-output analysis results of all models as a percentage of the process-based calculation with respect to a) year b) inclusion of gross fixed capital formation (GFCF) c) inclusion of a high-altitude factor (HA) d) basic or purchasers' prices

3.1.2. Unconfounded analysis

When the variables presented are not confounded (as in figure 2), based on the manipulation of the Small World Consulting Ltd. single-region model alone (as this was the model with the most accessible methodology), the apparent influence of each factor can be significantly reduced. For example, comparing figure 1c with 2c shows the almost non-existent impact of including or excluding a high-altitude factor on any of the sectors studied here. Figure 2c shows a maximum difference between high-altitude factor inclusive and exclusive models of 1.4%. This confounded and unconfounded results comparison suggests another methodological variable may have a stronger impact on the resulting estimation of the carbon footprint of the coke and refined petroleum products industry.

Other factors also had some impact, varying between methodology and industry sector. The inclusion of gross fixed capital formation is only a directly significant consideration in the case of the manufacture of coke and refined petroleum products (figure 2b), possibly due to the gross fixed capital formation embodied in refineries and the increased carbon burden they place on the commodity production compared to other industries.

There is minimal difference between the confounded and unconfounded analysis of the different years of data. This is likely due to the adjustments for inflation which are standardised and therefore lead to low variation between results. It is apparent that the 2002 values were larger than the 2012 values as the consumer price index adjustment would have increased the carbon emissions attributed to each pound sterling of spend in relation to economic adjustments, rather than assigning larger emissions intensities to the 2002 model than the 2012 models.

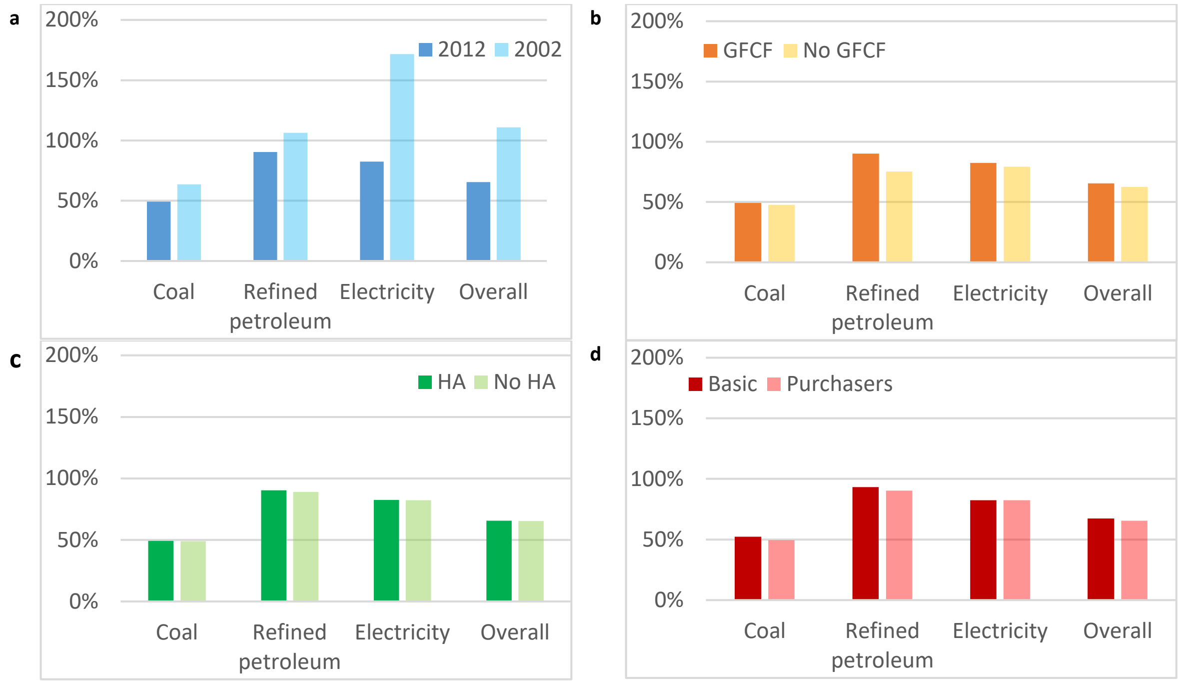

Figure 2. Unconfounded comparative graphs of the input-output analysis results of all models as a percentage of the process-based calculation with respect to a) year b) inclusion of gross fixed capital formation c) inclusion of a high altitude factor d) basic or purchasers' prices.

3.1.2.1. Confounded and unconfounded analysis conclusion

Both confounded and unconfounded variable analyses are useful in this study. The confounding variables analysis has been included as it highlights the relative importance of certain methodological factors over others and allows a comparison of the non-independent variables in which their interdependencies can be analysed. This issue does not seem to influence either the electricity production or the mining of coal and lignite sectors. Their comparative figures, discounting multi-regional models, are only ever a few percentage points different to calculations that include multi-regional figures, compared to up to 30 percentage points difference in the coke and refined petroleum products industry. This suggests a difference in production methods that implies that coke and refined petroleum products manufacture is more heavily dependent on international trade than either of the other comparative sectors.

This analysis also highlights the relative importance of different methodological practices within different industry sectors and the potential impact these practices, and their inclusion or exclusion within carbon intensity calculations, can have on final carbon emissions factor results. For example, consider the minimal impact of high-altitude generally, and the strength of the gross fixed capital formation influence in the refined petroleum industry. Such subtleties are likely be part of comprehensive understanding of carbon accounting in all industries.

3.1.3. Multi-regional data comparison

The influence of including multi-regional data in environmentally extended input-output models is potentially high but would not have been reliably compared in the previous analysis due to the significant changes in methods required when including multi-regional data and the limited sample sizes as available in this study. As such, the Small World Consulting Ltd. single- and multi-region models have been compared directly for the industries of coal mining, refined petroleum products and electricity production, transmission and distribution. Theoretically, the inclusion of multi-regional data into an economic model representing the globalised markets of modern economies should increase the accuracy of results. This analysis found that changing the regions included by an input-output model had a limited impact on the carbon burdens calculated for coal mining and electricity industries, but increased the refined petroleum products industry.

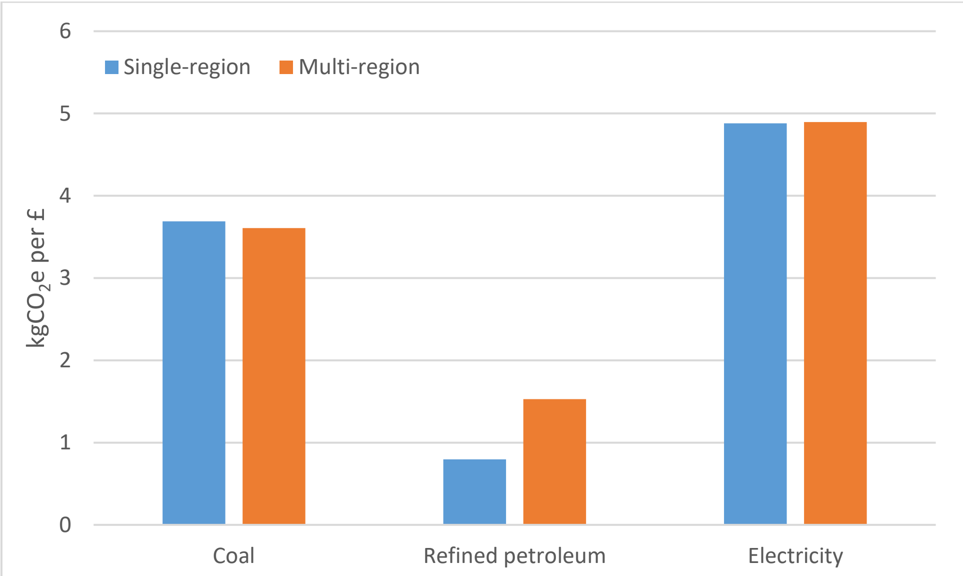

Figure 3 Comparison of a single and multi-regional model produced by Small World Consulting Ltd. Model

Measureable impact of multi-regional data inclusion in these industries seems limited to refined petroleum products, with the methodological practice creating only a marginal difference in both the coal mining and electricity industries. This is likely due to the lack of imports in the electricity industry and the predominant source of coal imports to that of the UK coming from Europe, which has a similar carbon profile for coal to the UK. The refined petroleum products industry is more global in its trade, which could explain the difference.

The influence of the number of regions included in the model calculations has been hinted at but not fully examined. When all other variables are equal, there is no significant effect from using a multi-regional model apart from in the case of the manufacture of coke and refined petroleum products (figure 3). Within that industry sector there is a clear distinction between the single-region model, which calculates the smallest carbon intensity, followed by the multi-regional model and subsequently the process-based analysis.

3.1.4. Gap analysis

Although process-based methods have the potential for high accuracy in some sectors, they are always subject to some amount of truncation error and thus the inclusion of gap analysis gives the greatest likelihood of systemically complete accuracy. The theoretical 'best practice' has here been assumed a hybrid of a detailed process-based life cycle analysis (PBLCA) with a gap analysis conducted on it from a robust input-output model. The resulting truncation error calculated as a percentage was then used to factor up the process-based life cycle analysis (PBLCA + gap analysis) to give a best estimate of actual emissions, as these are currently impossible to know.

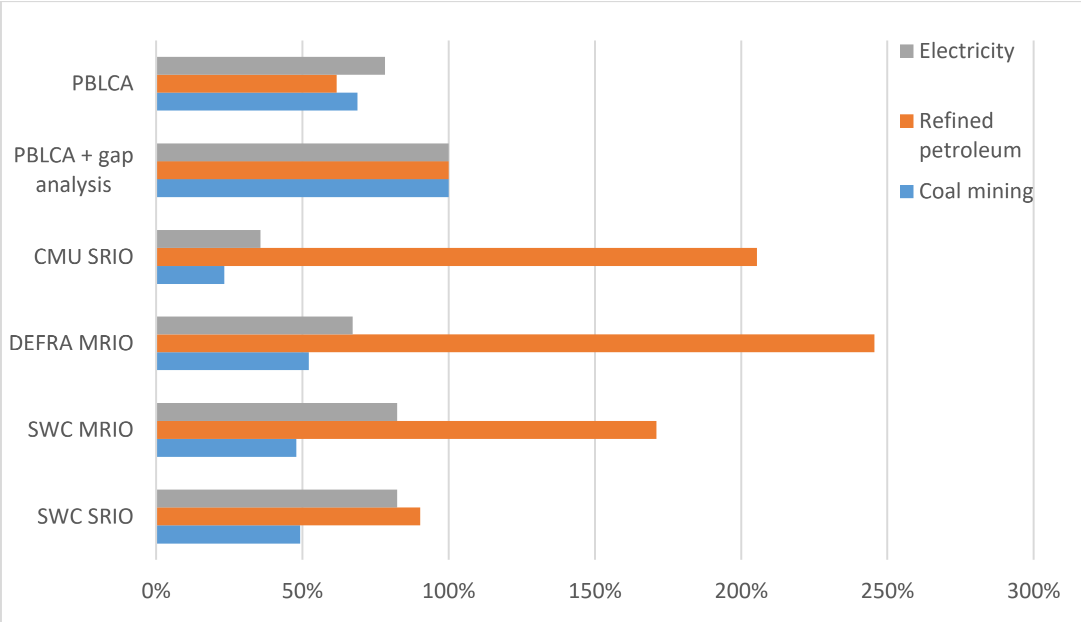

Figure 4. The average carbon emissions factor calculated by each of the different input-output models as a percentage of the process-based life cycle assessment with gap analysis. Model acronyms are: Process-based life cycle analysis [PBLCA], PBLCA supplemented with gap analysis [PBLCA + gap analysis], Carnegie Mellon University [CMU SRIO], Department for Farming and Rural Affairs [DEFRA MRIO], Multi-regional Small World Consulting Ltd. model [SWC MRIO] and Small World Consulting Ltd. single region model [SWC SRIO]

Small World Consulting Ltd. produced the model with the greatest consistency of accuracy and the greatest accuracy with respect to this research (49% to 90%, figure 4). The Carnegie Mellon University model had the widest range of results (53% to 246%, figure 4) suggesting a low degree of accuracy across the full scope of the model. Production of coke and refined petroleum products was found to be the industry sector with the greatest variability across models in this process-based analysis, with calculations covering 62% to 246% of the process-based analysis figure (figure 4). While a manufacturing industry, it is not as simple as the mining of coal and lignite extractive industry sector or as well-regulated and monitored as the electricity industry, possibly causing the differences between model estimations of this industry.

There is significant variation in the accuracy of each model according to comparison to the assumed best practice model, both between and within models. Of particular note in figure 4 is the Carnegie Mellon University estimation of refined petroleum products as 246% of the process-based life cycle assessment and gap analysis, which is likely due to the significantly lower prices of petroleum in the United States. However, not all disagreements in the data can be explained so readily. The implications of truncation error and the related accuracy consequences are explored in further detail below.

3.1.4.1. The mining of coal and lignite

Although the gap analysis shows that for the mining of coal and lignite sector, the process-based analysis excluded 31% of the supply chain from its calculations, the final value is greater than that of the input-output models because the methodology for the process-based analysis included coal sourced globally. The process-based analysis of this industry sector produced a figure around 17% greater than the nearest of the input-output model results (figure 4). This was unexpected due to the different effects of truncation error of input-output and process-based methodologies. UK input-output models broadly agree here at 48-52% of the process-based model, once adjusted for gap analysis results. One of the reasons that the process-based figure was so much larger than the input-output figure was the difference in the source of the coal used in each analysis. Input-output models used coal supplied from the countries they describe, i.e. UK or US coal depending on the model in this particular study, whereas the process-based figure was global. In the process-based model only 52% of the coal is assumed European, and only 18% from the UK (Edwards et al., 2011). The rest is from South Africa (16%), Australia (12%), the US (10%), Columbia (7%) and the Commonwealth of Independent States (3%). The similarities of these percentages is likely not a coincidence as the increased travel distance of this coal will have incurred a significant carbon burden due to the weight of coal and the implications of that weight on the carbon burden of transporting it. In addition, the difference in mining methods and quality of the coal mined likely impacted the carbon emissions calculated. For example, Australian open-cast mining leads to the release of methane as the coal is extracted. This methane emission caused over 3% of Australia's total carbon emissions in 2008 (Day et al., 2010). Thus, the impacts of including global coal are substantial, in this case potentially increasing the carbon intensity by 48-82% based on calculations of propagations of the discrepancy from the extraction of coal to inclusion in the carbon models.

Despite the described issues with the interpretation of this sector some conclusions can be drawn with reasonable reliability. Defra calculated the value closest to the 'best practice', thus performed the best in this comparison in terms of model accuracy. While the other UK models performed similarly, the Carnegie Mellon University model calculated only 23% of 'best practice'. This was most likely due to the fact that it represented an entirely different supply chain.

3.1.4.2. The manufacture of coke and refined petroleum products

Small World Consulting Ltd. provided the most accurate models in the manufacture of coke and refined petroleum products sector by a significant margin, over 250 percentage points closer to the gap analysis adjusted process-based carbon burden of the industry sector than the other input-output models analysed in this study. The single-region model constructed by Small World Consulting Ltd. also performed with the greatest accuracy of any model in any of the three sectors directly compared in this study, at 90% of the 'best practice' calculations for this sector. It was also the only input-output model to underestimate the carbon footprint of this industry, though by the comparatively small margin of 10%. The Carnegie Mellon University model calculated a value of 246% of the ‘best practice’ model and thus performd the worst of all models and all sectors compared. Unlike the other two sectors subjected to accuracy analysis in this study, for the manufacture of coke and refined petroleum products the Defra model overestimated compared to the process-based value. It is unclear precisely why this is the case; however, it may be due to the fact that the petroleum coke figure used in the process-based analysis was based on a calculated liquefied petroleum gas carbon intensity that was scaled using a direct emissions ratio and thuse the input-output models are describing different products to the process-based analysis, leading to uncertainty.

3.1.4.3. Electricity production, transmission and distribution

The process-based analysis of electricity production, transmission and distribution was represented with reasonable accuracy, in methodological terms. The Small World Consulting Ltd. single and multi-regional models were equally accurate when calculating electricity sector carbon intensities. No input-output model covered the full value calculated by the process-based analysis. Fluctuations in price are significant in the electricity industry and this may be a reason for the difference in carbon emissions intensities calculated by input-output and process-based models. However, the input-output models did marginally out-perform the process-based analysis when the gap analysis was excluded from the final process-based figure, supporting the knowledge that input-output models will calculate larger values for carbon intensities than process-based analyses alone. The Carnegie Mellon University model significantly under-estimated the process-based life cycle analysis figure, both with and without gap analysis, thus was the least accurate model for the electricity production, transmission and distribution sector.

3.1.5. Accuracy Analysis Conclusion

As accuracy here represents the closeness of the input-output model results to the process-based results with the addition of gap analysis, the accuracy of each model was assessed by identifying and calculating the input-output model results as a percentage of the process-based plus gap analysis results, the latter of which it has been established is the most likely to be closer to the true carbon burden of the industry. As such, the closer to 100% an input-output models results were, the more accurate that model was deemed to be. The Small World Consulting Ltd. single region model was found to be the most accurate, and most consistently accurate, input-output model over the three industry sectors analysed. Carnegie Mellon University’s model appeared accurate when describing the mining of coal and lignite and electricity production, transmission and distribution. However, it produced an estimate for the production of coke and refined petroleum products that was 246% greater than that produced using process-based analysis. This incongruity between sector findings could be the result of the basing of method on the US industrial economy and not the UK, as other models were based. This finding suggests the need for more detailed assessment of the Carnegie Mellon University model for accuracy and consistency, which has not been possible within the scope of this study in order to fully understand the reasons for the apparent high accuracy in some areas. The Defra model also seemed inconsistent in accuracy across sectors, though not to the extent of the Carnegie Mellon University model. However, the Small World Consulting Ltd. multi-regional model performed with some inconsistency of results, though much less pronounced than either the Carnegie Mellon University or Defra input-output models. Thus, both Small World Consulting Ltd. models showed the greatest accuracy of carbon intensity calculations.

3.2. Precision Analysis

In this context, 'precision' refers to the likelihood that multiple carbon emissions models will calculate the same emissions factor for a given industry sector, i.e. the closeness of each model to the mean of all models for any given industry sector. This type of precision was assessed by analysis of the difference between the mean of all available model variations for each respective industry sector to the individual model results for that industry in both real terms (kgCO_2e/£ difference) and percentage differences. Precision can vary between both models and industry sectors and therefore each industry sector was analysed for precision independently of other industries. Comparison of each sector output from individual models to a calculated mean of all model outputs allowed for a comparison of the precision of calculations for each sector. Where models broadly agreed, such as sector 81, "Services to Building and Landscape", these can be said to have high statistical precision. Where models disagreed, such as sector 92, "Gambling and Betting Services", model precision was low. By comparing methodologies and influential factors of both high and low precision sectors the important methodological factors were isolated that will enable increased precision in future models. However, it should be noted that a high degree of precision does not necessarily imply a high degree of accuracy in model results.

Input-output sectors can be broadly categorised into four groups of similar industry types: extractive, manufacturing, distribution, services. Each of the industry sectors in these four broad categories have not only similar products but also similar supply chain structures, which theoretically should lead to similarities of precision of sectors in the same broad categories. Extractive industries are not only relatively simple in supply chain terms but they are also high regulated and monitored so data is reliable and readily available, leading to largely high precision levels. Conversely, service sectors have incredibly complex supply chain structures that are often more significantly influenced by factors such as gross fixed capital formation which is not always included in input-output analysis models. For this reason, they are potentially more prone to low levels of precision.

3.2.1. Low Agreement Industry Sector Examples

3.2.1.1. 19: Coke and refined petroleum products

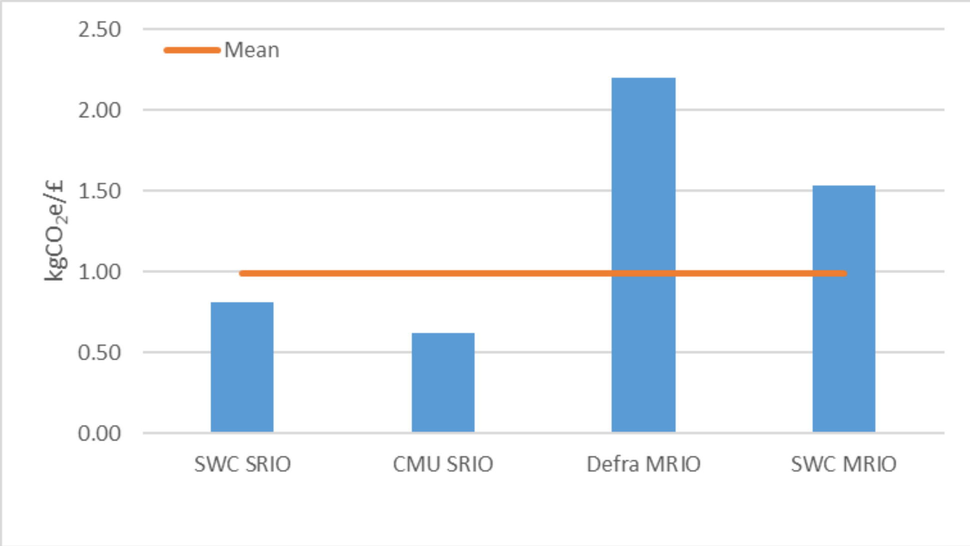

Figure 5 Comparison of carbon emissions factors for the manufacture of coke and refined petroleum products

Estimates ranging from 0.62 to 2.20 $kgCO_2$/£ may not initially seem to be in disagreement, but they represent a deviation of 23% below to 98% above the mean of all models, and therefore can be interpreted as meaningful disagreement between models. The low agreement between models was predominantly between the multi-regional models and single-region models. The multi-regional models calculated carbon burdens 122% (Defra) and 55% (Small World Consulting Ltd.) above the mean, whereas the single region models calculated burdens of 37% (Carnegie Mellon University) and 18% (Small World Consulting Ltd.) below the mean, which implies a significant consequence of the methodological choice to include or exclude global supply chains. This was likely due to the significance of imports and exports to this industry sector. The same cause of the misleading data in the accuracy analysis is likely responsible for the variation of carbon intensity calculated for coke and refined petroleum products in this precision analysis.

3.2.1.2. 24.1-3: Manufacture of iron and steel

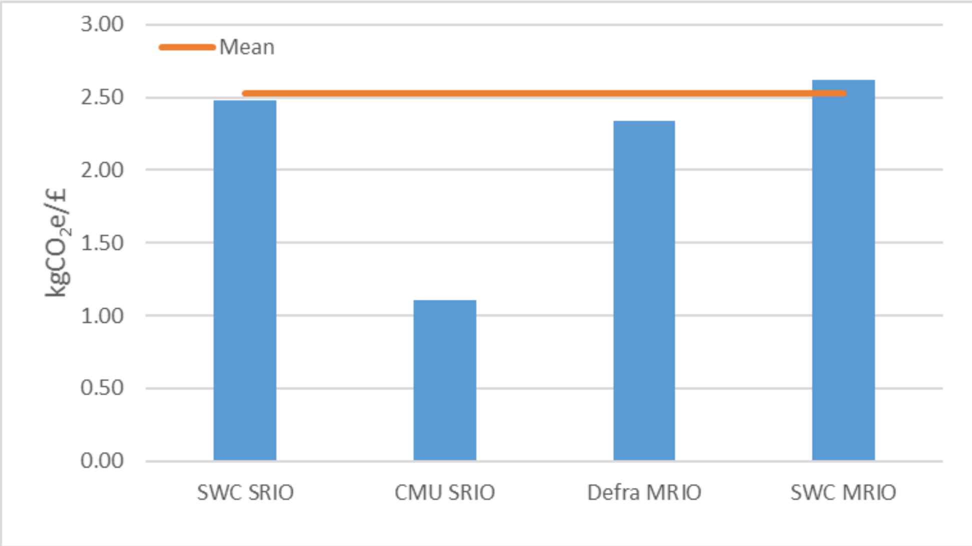

Figure 65 Comparison of carbon emissions factors for the manufacture of iron and steel

Within carbon emissions intensity models for this industry the UK-based models broadly agreed, with a range of less than 0.15 $kgCO_2e/£$. However, the Carnegie Mellon University model underestimated compared to the mean by over 1.5 $kgCO_2e/£$. This factor of ten difference may be related to the difference in location of the base economic model.

In this case, 68% of carbon emissions were found to be a result of the manufacture of iron and steel industry itself, thus it is relatively self-reliant and models are therefore self-determining of in precision and accuracy. The total range of carbon intensity estimations for this industry sector was 1.52 $kgCO_2e/£$.

3.2.1.3. 05: Mining of coal and lignite

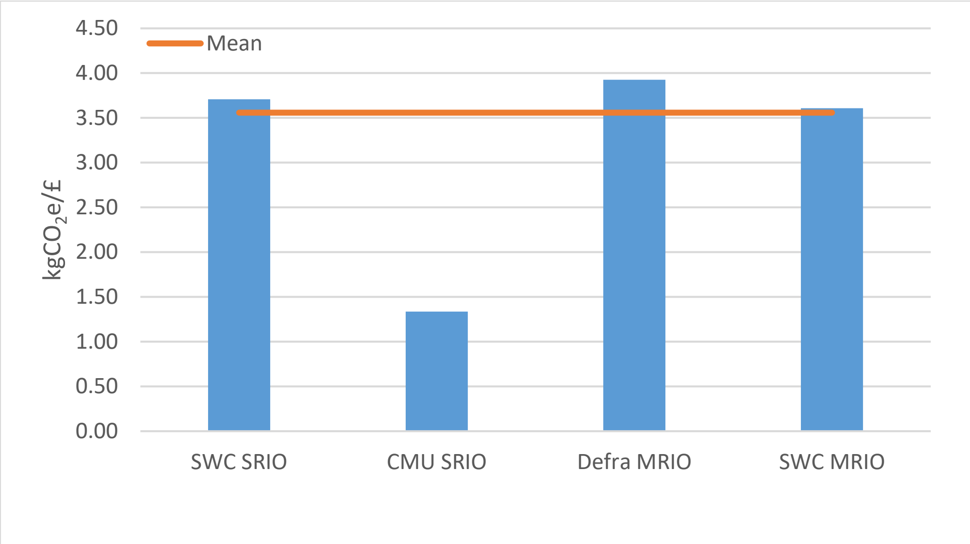

Figure 7 Comparison of carbon emissions factors for the mining of coal and lignite

There was significant disagreement between these models with a total range of 2.59 $kgCO_2e/£$. As with the manufacture of iron and steel industry, the UK-based models broadly agreed for the mining of coal and lignite. Carnegie Mellon University calculated a much lower carbon emissions intensity that was more that 2 $kgCO_2e/£$ less than the next lowest result. Defra calculated the greatest carbon factor for this industry at 3.93 $kgCO_2e/£$.

The issues raised in the accuracy analysis of this industry sector regarding the impacts of multi-regional data may be partly responsible for this disagreement in precision analysis. The supply chain of mining of coal and lignite is quite simple, with 74% of the carbon emissions coming from the mining of coal and lignite sector, as this is an extractive industry. 11% of the carbon emissions for this sector come from the electricity production, transmission and distribution sector, which also has low agreement between models. This may have had some influence on the mining of coal and lignite industry model calculations.

3.2.1.4. 35.2-3: Gas; distribution of gaseous fuels through mains; steam and air conditioning supply

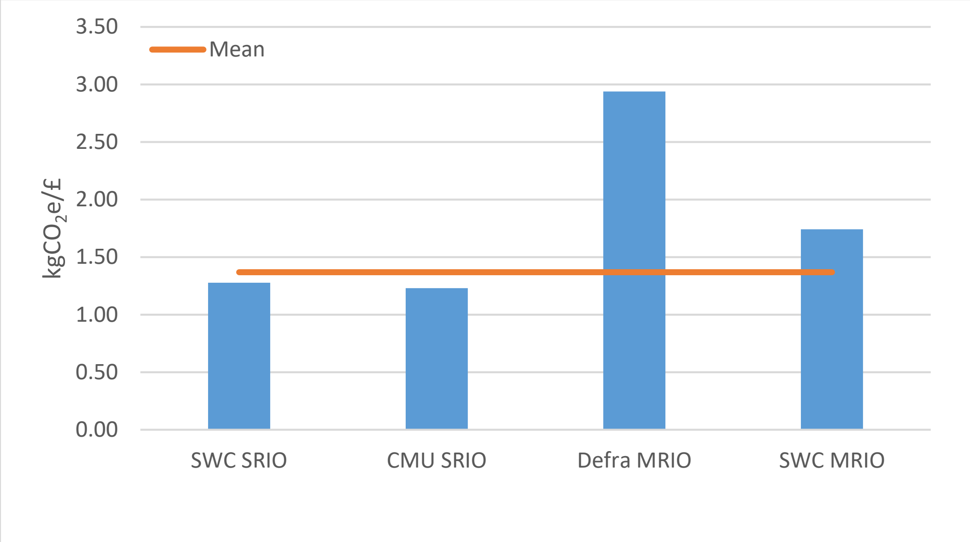

Figure 8 Comparison of the carbon emissions factors for gas

Both of the multi-regional models calculated carbon emissions intensities above the mean of all models compared to the single-region models, both calculating values below the mean. The Defra value was the largest by a margin of 1.2 $kgCO_2e/£$, with a total industry range between models of 1.7 $kgCO_2e/£$. The single-region models agreed quite closely, only 0.05 $kgCO_2e/£$ between them, however the specific reason was unclear. The Small World Consulting Ltd. single-region model was the most precise in this industry, calculating a value less than 7% from the mean of all models.

3.2.1.5. 01: Agriculture

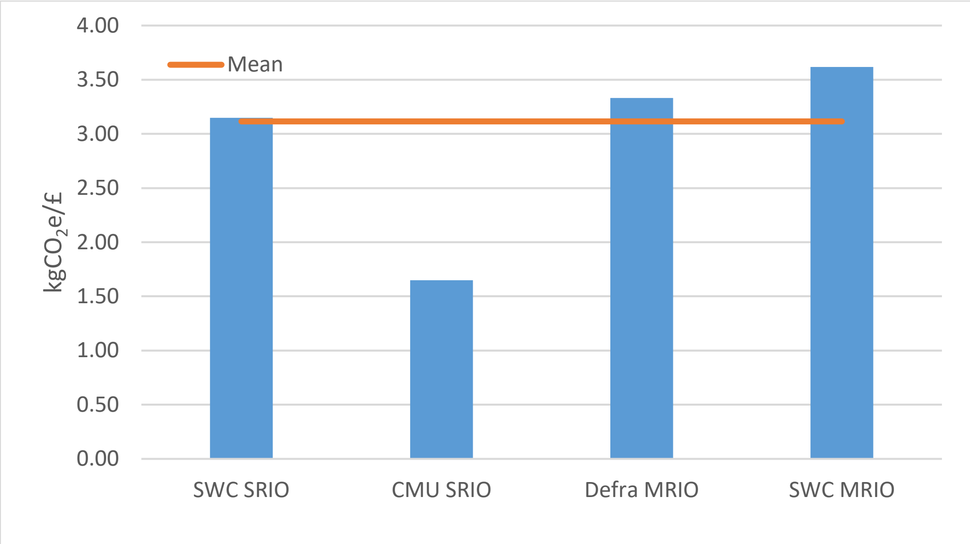

Figure 9 Comparison of carbon emissions factors for agriculture

The Small World Consulting Ltd. single-region model calculated, for agriculture, the most precise carbon emissions intensity with 0.03 $kgCO_2e/£$ difference from the mean. The Carnegie Mellon University model again underestimated the mean significantly, whereas both multi-region models calculated estimates over the mean of models.

3.2.1.6. 51: Air transport

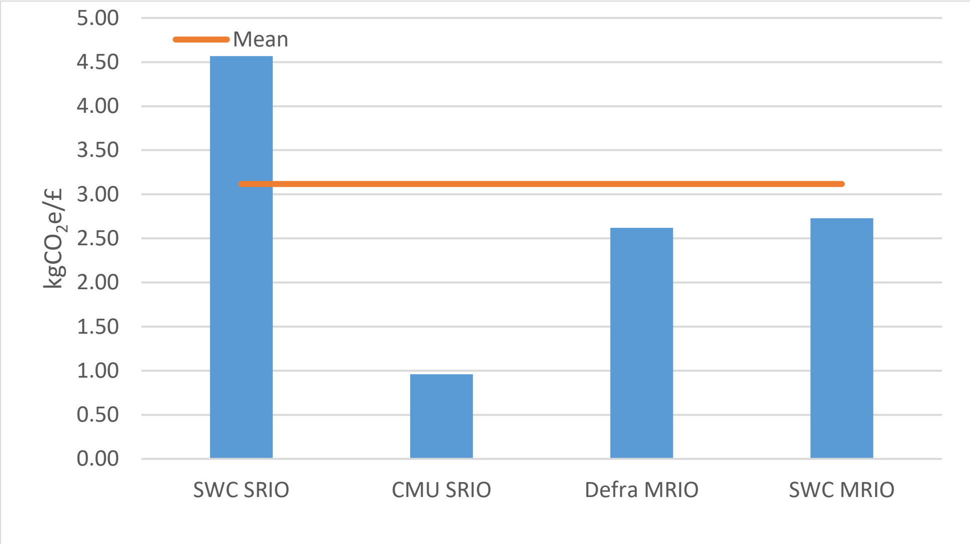

Figure 10 Comparison of carbon emissions factors for air transport

For the air transport sector, the low agreement between models was most likely due to different assumptions within the calculations and methodology. The Small World Consulting Ltd. single-region model was an outlier in this industry sector. Their calculations simulated the highest value for the carbon intensity of the air transport industry; more than 1 kgCO_2e/£ greater than the next nearest model. The lowest carbon intensity value was calculated by Carnegie Mellon University. This is likely at least partially due to the exclusion of a high-altitude factor from its methodology; however it is unclear if this accounts wholly for the disparity.

Within this industry the multi-regional models were the most precise with a range of 0.44 kgCO_2e/£ between them, and the Defra model with a difference of only 0.03 kgCO_2e/£ from the mean of all model estimates for the air transport sector. In this case, the Small World Consulting Ltd. single-region model calculated the largest estimate of 4.51 kgCO_2e/£, 1.4 kgCO_2e/£ larger than the Defra estimate and 2.87 kgCO_2e/£ larger than the Carnegie Mellon University calculations.

3.2.2. High Agreement Industry Sector Examples

The six industry sectors with the highest agreement were all service sectors. For this reason, only the three most precise service industry sectors were analysed. In addition to this, the three sectors from other industry types with the closest agreement were analysed for comparison. It should be kept in mind that high levels of agreement between models do not necessarily equate to accuracy of results.

3.2.2.1. 08: Other mining and quarrying products

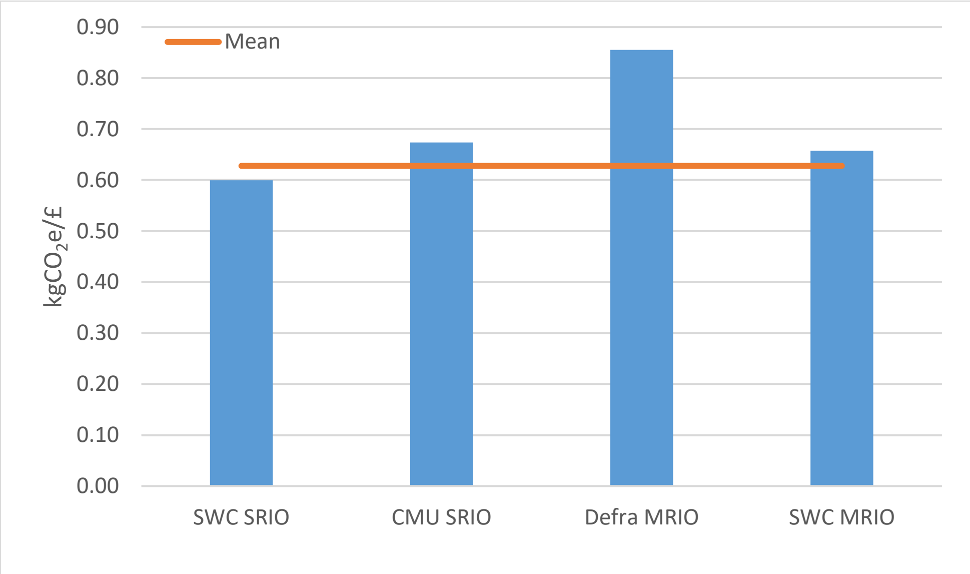

Figure 11 Comparison of carbon emissions factors for other mining and quarrying products

Both of the Small World Consulting Ltd. models were the most precise in this industry as the single region-model calculated an emissions factor 0.03 kg $CO_2e/£$ less than the mean of all models, and the multi-regional model calculated the same value greater than the mean. The Small World Consulting Ltd. single-region model was the only model to underestimate the carbon burden of this industry against the mean, whereas Defra overestimated compared to the mean most significantly. This suggests an influential role for multi-regional data inclusion.

3.2.2.1. 41-43: Construction

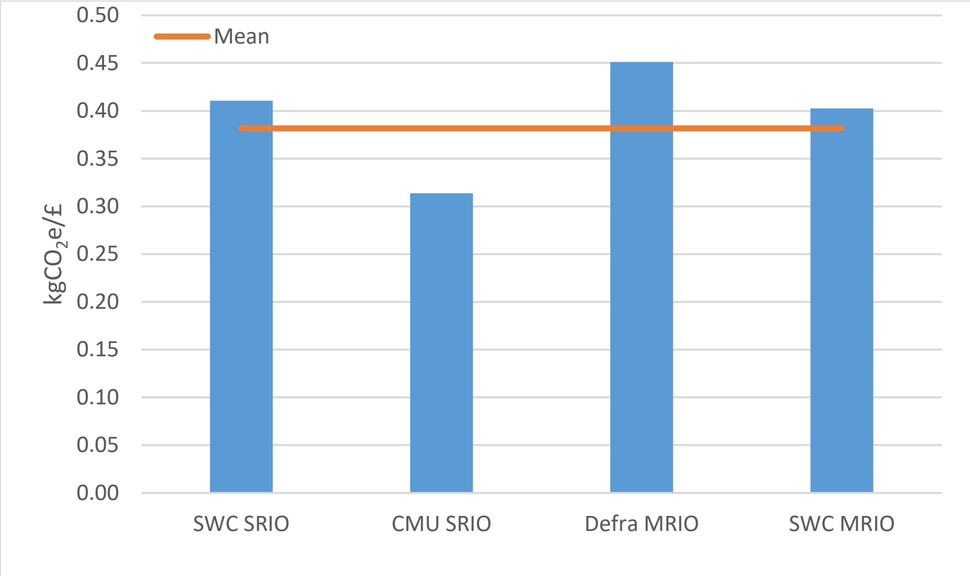

Figure 12 Comparison of carbon emissions factors for construction

All UK-based models overestimated the mean of the construction industry, whereas the Carnegie Mellon University underestimated the mean. The Defra and Carnegie Mellon University models both disagreed with the mean by the same amount, though in different directions, potentially due to the difference in geographical background of the models or model structure, as the Carnegie Mellon University model disaggregates the construction industry into seven distinct industry sectors. The Small World Consulting Ltd. multi-regional model caluated the most precise carbon emissions factor.

Although the supply chain is reasonably diffuse among extractive and production industries for construction there is some reliance on the cement, lime, plaster and articles of concrete industry (11.7%) and the electricity production, transmission and distribution industry (21%). This may have some bearing on the findings in figure 12.

3.2.2.2. 68.2IMP: Owner-occupiers' housing services

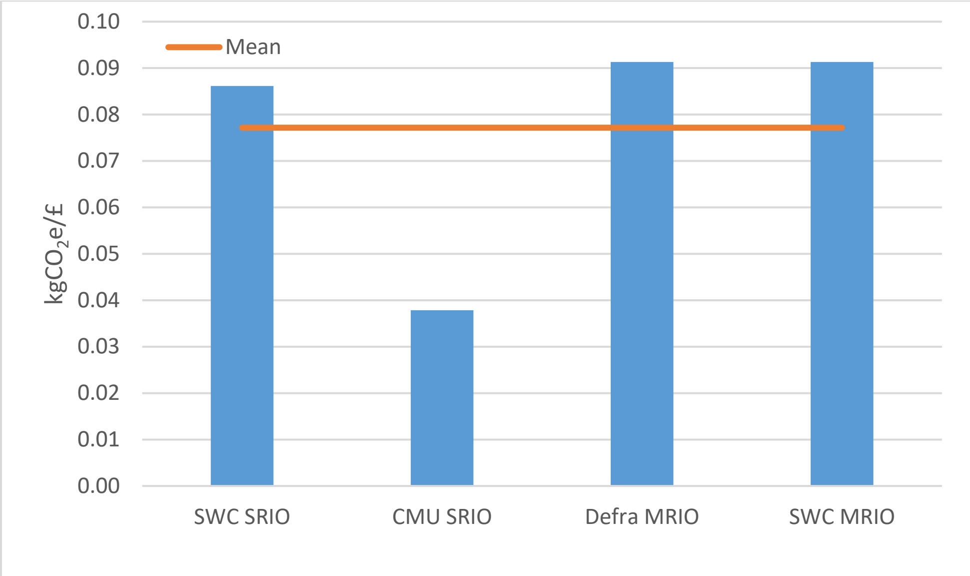

Figure 13 Comparison of carbon emissions factors for owner-occupiers' housing services

With only 0.05 kgCO_2e/£ between the largest and smallest carbon intensity results for this industry sector it had the highest agreement of all industry sectors for the input-output models compared in this study. The multi-regional models both predicted the greatest values, and agreed extremely closely, down to the fifth decimal point, with Small World Consulting Ltd. providing the most precise calculation by a small margin. The Small World Consulting Ltd. single-region model also calculated a value very close to the mean of all models. The Carnegie Mellon University model disagreed most strongly as it underestimated the mean of all models by almost 0.04 kgCO_2e/£, compared to the next largest disagreement with the mean at 0.01 kgCO_2e/£.

42% of the supply chain for this industry is represented by the electricity production, transmission and distribution industry sector and 14% represented by the air transport industry sector, both of which are low agreement industries. The high agreement nature of this industry is therefore likely due to something unrelated to those two industries.

3.2.2.3. 49.1-2: Rail transport services

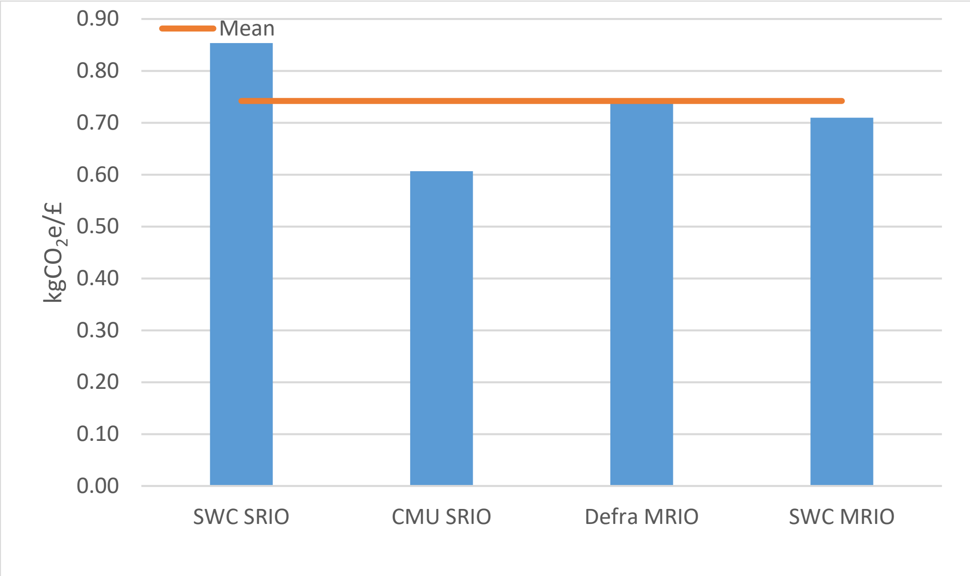

Figure 14 Comparison of carbon emissions factors for legal services

The total range of estimates for the carbon burden of the rail transport services industry was 0.25 kgCO_2e/£. Defra's carbon accounting model overestimated compared to the mean of all models by less than 0.003 kgCO_2e/£ thus was extremely precise in representing this industry, followed in precision by the Small World Consulting Ltd. multi-regional model, suggesting a strong methodological influence of multi-regional data inclusion. Both single region models were less precise, but in opposite kinds. This was possibly due to the methodological grounding. While 43% of the supply chain carbon burden for this industry is embodied in the rail transport sector itself, the other 57% is relatively diffuse thus the potential reasons for these findings are complex.

3.2.2.4. 69.2: Accounting and bookkeeping services

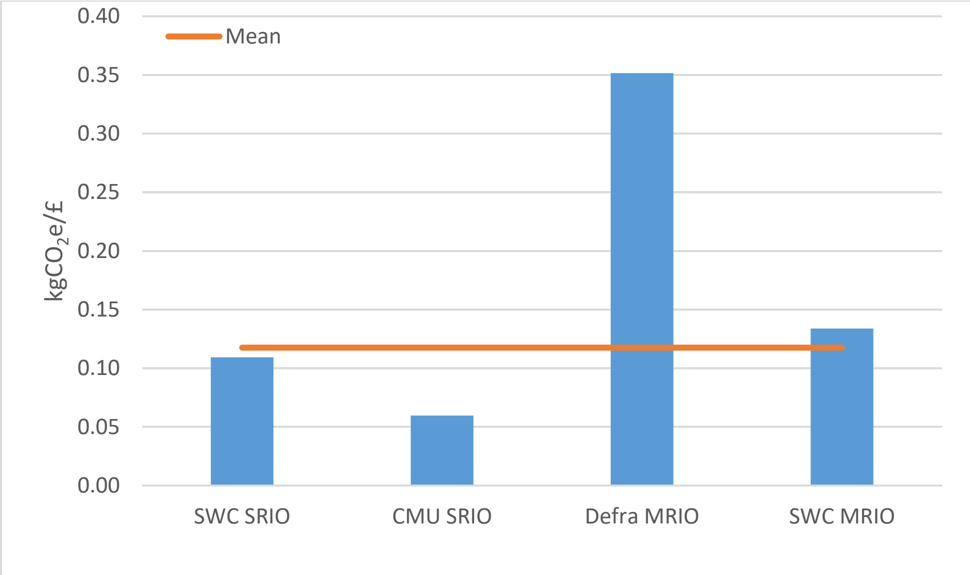

Figure 15 Comparison of carbon emissions factors for accounting and bookkeeping services

Both multi-regional models calculated estimates above the mean, with the Defra model calculating the greatest value at 0.35 kgCO_2e/£, followed by the Small World Consulting Ltd. multi-regional model at 0.134 kgCO_2e/£. The Small World Consulting Ltd. single-region model calculated the most precise estimate with a value only 0.009 kgCO_2e/£ less than the mean.

Almost 20% of the first supply chain tier for the accounting and bookkeeping services is a result of the air transport and electricity production, transmission and distribution industries, both of which were notably low agreement industries, and yet this industry sector had high agreement. This industry sector has a very diffuse and thus complex supply chain, so the high agreement between models goes against the conventional wisdom of input-output models that suggests that models would disagree as complex supply chains are difficult to replicate accurately.

The subtle differences between the models apparent in figure 15 were also logically and simply explained: the multi-regional models calculated the greatest carbon emissions intensity values because they included non-UK supply chain paths which are often more carbon-intensive than domestic equivalents, such as extractive and manufacturing industries in China. The model that included the high altitude factor, the Small World Consulting Ltd. single region model, calculated the next highest carbon intensity value as the high altitude factor would have a noticeable impact on the final carbon intensity value due to the significant portion of the supply chain carbon burden attributed to air transport.

3.2.2.5. *79: Travel agency, tour operator and other reservation services and related services*

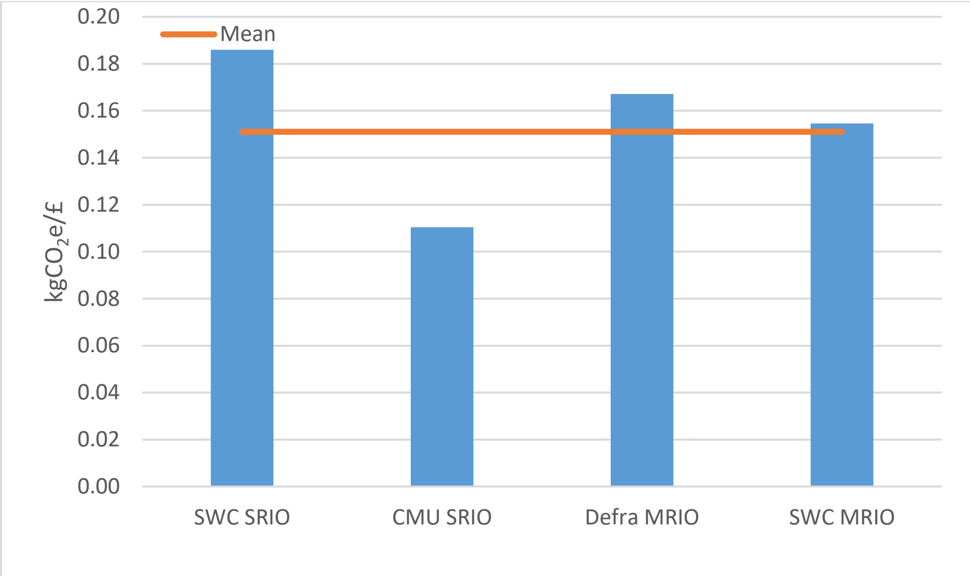

Figure 16 Comparison of carbon emissions factors for travel agency

The Small World Consulting Ltd. multi-region model calculated the most precise carbon intensity in this industry at 0.004 kg CO_2e/£ more than the mean. Unusually, the Small World Consulting Ltd. single-region model calculated the largest emissions intensity, as multi-regional data theoretically would result in an increase in carbon emissions intensity due to the greater emissions intensity of international production processes compared to UK production processes. The Carnegie Mellon University calculated both the lowest and least precise carbon burden for this industry.

The largest carbon intensity estimations were calculated by models that incorporated multipliers for high altitude greenhouse gas emissions. Air transport accounts for 27% of the supply chain burden of this industry, which is likely the reason for this finding.

3.2.3. Precision analysis conclusions

As the five industry sectors with the highest agreement were all services sectors with complex supply chains, it is implied that the complexity of the supply chain does not always lead to disagreement between models, as conventional wisdom would suggest. Perhaps, instead of increased supply chain complexity leading to different methodological practices, the increased complexity leads to similar assumptions made in all model methodologies so as to allow the economic theory of input-output models to apply with relative ease to the industry sector. Hence models may be in close agreement (have high precision) but may still not correctly represent real-world emissions (have low accuracy).

It is clear that across the 106 input-output industry sectors the influencing factors for precision vary depending on the industry in question. In some cases, the regions covered by the model seemed to be the most influential aspect, in others it seemed to be the models methodological roots, and in others the methodological intricacies. In all cases the explanations for agreement, disagreement, and the extent thereof, between models were based in knowledge of the methods for each model, the detail for which varied between models depending on the quality of available documentation. For example, the inclusion or exclusion of gross fixed capital formation seemed to have an imperceptible effect at the 106 industry sector level, whereas the regional extent of a model frequently had a significant and direct impact on carbon intensity calculations. However, gross fixed capital formation was not always explicitly included or excluded in the methodological documents, whereas the regional coverage was more reliably documented. Thus these understandings were interpretations based on research and not necessarily the exclusive reason for any precision findings.

4. System boundary analysis methodology

Analysis of the system boundary was based primarily on gap analysis supported by related research. The aim of this was not only to identify and isolate the system boundary analysis within hybrid carbon emissions models but also to attempt to identify the potential to make any part of this process more generic in order to make it more accessible to a wider audience.

4.1. Process-Based Life Cycle Analysis Methodology

The greenhouse gas process-based life cycle analysis used for this study was from the Argonne GREET model, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. GREET.net results for copper wire produced in 2012 were used to make the process-based model as compatible as possible with the input-output models. The Argonne National Laboratory is based in the US but is a global research institution that produces thorough science in the form of reports, databases and models. As such it is a source of some of the best process-based analyses available in terms of breadth of products covered and detail included.

Though there have been many academic publications of process-based life cycle analyses these have often been either so specific as to be irrelevant to most carbon intensity analyses (for example: Pearce et al., 2013; Hu, 2012; Stylos and Koroneos, 2014) and/or funded by businesses and hence may be biased (for example: Kumar et al., (2014) funded by HP and Ayushmaan Technologies; Zhang et al., (2015) funded by the Kunming Engineering Corporation Ltd). Even the methods used in life cycle assessments can be subject to biases, such as Steinmann et al. (2014) funded by ExxonMobil, who have a direct vested interest in the results of carbon analyses yet propose to refine and adjust the results of carbon footprints. A standardised approach, as this study works towards creating, is critical to enabling the widespread use and understanding of carbon footprints and life cycle analyses.

4.2. Gap Analysis

Gap analysis was undertaken by comparison of the input-output sectors of the Small World Consulting Ltd. single-region model to those included in the Argonne GREET model database and methodology papers. Where input-output sectors were not wholly included or excluded in the process-based analysis, an effort was made to understand the extent to which the data that were included in the Argonne GREET analysis covered the full sector data of the input-output analysis. This ratio was then substituted into the gap analysis to calculate the amount of the input-output analysis covered by the process-based calculations.

The gap analysis was applied to copper wire as a case study because it is a common product frequently found in use across industry sectors. It is also a reasonably complex product that thereby does not privilege the process-based analysis whilst not having so intricate a production system that it would privilege the input-output analysis. This makes copper wire an ideal case study for both the quantitative analysis of carbon intensity methods and a useful reference for businesses and academics in future studies. The value of 1 kg of copper wire was used during the analysis calculations as this is a standard value of product on which carbon intensity calculations are based within both input-output and process-based methodologies. As the GREET.net model calculates values of greenhouse gas emissions, the results had to be contextualised for the input-output model results by applying price values.

5. System Boundary Analysis Findings

5.1. System boundary identification

An in-depth analysis of all available methodology documents for the Argonne Laboratory GREET.net model, and others used in its construction, was undertaken to ascertain the system boundary of the process-based analysis of copper wire in this model. As no methodological documents directly relating to the model construction were available, the understanding of the system boundary of this process-based model was based on the articles from which the Argonne Laboratory collected data for the process-based carbon accounting of carbon wire. As such, the system boundary identification within this report required estimations based on what was and was not mentioned in the published documentation and personal correspondence with the Argonne Laboratory. Justification for the treatment of each point of the supply chain of copper wire production is outlined in appendix B, however as there was limited literature available, assumptions have been made based on available information and what can be reasonably assumed to be included. For example the electricity production, transmission and distribution can be assumed included up to supply chain tier three with reasonable confidence, despite lack of supporting literature or documentation.

The GREET.net model is currently being deconstructed which has led to the lack of available methodological detail. This limitation was brought about by the age of the model, as the Argonne Laboratory has more recent versions of the GREET.net model than was used in this study. The lack of detailed methodology in the case of the production of copper wire in the GREET.net analysis is not representative of the entire GREET.net model and is partly due to the deconstruction that the model is currently undergoing (Kelly, 2016). However, this has not limited the understanding of the inclusions and exclusions of supply chain paths in this model, as detailed investigation of the data sources was still possible and undertaken to the level at which it would have been were the direct methodology available.

The 2012 GREET.net model was used in this system boundary analysis because it allowed continuity between the input-output and process-based models during the comparison. Using models estimating carbon burdens of the same year means the most similar commodity prices, trade patterns and production types across both models. By keeping these variables similar the impact of other areas of the copper wire life cycle that are less accessible or controllable, in terms of carbon accounting, on system boundary analysis, could be limited.

The energy used in the production of copper wire is separated into electricity and separate fuel types. It is broken down into this level of detail for the first three supply chain tiers. Data from the Chilean use of fuels was aggregated and nonspecific and therefore cannot be said to accurately reflect 100% of that aspect of the supply chain.

All of the copper in the GREET.net methodology is assumed to be primary copper. This means that it is assumed to be produced from the mined ore directly and the source assumed only Chilean and American in the GREET.net model, as the bulk of the copper used in the United States is sourced from those two locations (Kelly, 2016; Kelly et al., 2015). However, this assumption does not include copper recycling, known as secondary copper, which is significant globally and has been for over two decades. For example, between 2000 and 2010, the end-of-life recycling rate for copper globally has been estimated at 45% (Glöser et al., 2013). Although the recycling of copper is significantly less energy intensive than primary production and emits no direct sulphur emissions (though there may be varying amounts in the recycling process) it can still cause up to 42 million Btu/ton in energy requirements (Kusik and Kenahan, 1978) in the process. While the exclusion of secondary copper does not exclude an entire supply chain tier, it does exclude economically and environmentally significant pathways that directly relate to a substantial portion of the copper included in the GREET.net analysis.

In terms of production of copper wire itself, the following processes are included in the GREET.net process-based analysis: mining, beneficiation (in the form of concentrating and smelting), refining, and drawing. While this is five technical processes it does not equate to five tiers of the supply chain. The beneficiation process contains two physical steps, but is considered only one supply chain tier as it is only one process in the steps to creating copper wire. This distinction highlights the complexities and potential controversies of applying supply chain concepts to carbon accounting practices.

Data from the production of copper wire as produced in the United States only explicitly includes energy sources for the first three supply chain tiers: ore mining, copper production, and wire drawing (Miller et al., 2012). This energy includes liquid fuels, coal and electricity. Energy use beyond these supply chain tiers has been assumed not included in the GREET.net process-based life cycle analysis.

There was no emissions allocation for by-products sold out of the industry in which they were produced (Miller et al., 2012). As the waste produced is a key part of the life cycle of a product it is a significant omission from a life cycle analysis. These by-products have likely gone on to accrue further carbon emissions beyond this industry and supply chain point which, under input-output theory, are attributable to the initial copper wire production to some degree. The degree of relatedness depends on the system boundary applied to the analysis, however in this process-based analysis case there was no inclusion at all of by-products. Thus the system boundary was immediately limited beyond that of an input-output methodology. This highlights the importance of identification and study of system boundaries. The input-output models' complete system, in terms of supply chain pathways, covers such burdens as by-products that are often left out of process-based models.

Inclusion or exclusion of any such supply chain path is often not explicitly stated in the methodology, further confusing the system boundary identification for any stakeholder attempting to understand or use the analysis provided by these carbon accounting methods and reports. For example, there is no mention in any of the material assessed within this report of the inclusion of overhead processes in the Argonne Laboratory carbon accounting of copper wire production in America. Overheads here includes, but is not limited to, any administrative processes, services, and gross fixed capital formation such as buildings. Although it is not explicitly stated that these processes are excluded from the GREET.net model construction it is highly unlikely that they were included as they are beyond the scope of almost all process-based analyses due to the complexity of supply chain pathways of these industries and the subsequent cost incurred mapping, understanding and using the data relating to them. The absence of service sector industries from any of the associated literature supports this interpretation that service sectors were not included in the GREET.net analysis of copper wire.

5.2. Gap Analysis

Gap analysis was used to analyse the extent to which the process-based life cycle analysis for the carbon burden of copper wire by the Argonne Laboratory may not have been systemically complete. Structural path analysis undertaken in this study showed the likely supply chain paths involved in the production of copper wire. The results of this analysis were cross referenced with the data informing the GREET.net model, and the gap between the two was identified and quantified into both percentages of the full carbon footprint of the product and kilograms of carbon dioxide equivalent per kilogram of copper wire produced.

The potential impact of truncation error, in the case of copper wire, is significant. It could result in the exclusion of up to 95% of the supply chain for the product, if only direct emissions are included, and a subsequent near doubling of the carbon footprint figure calculated by process-based analysis (table 2). When production processes up to and including the second supply chain tier are included in process-based analysis of copper wire, the truncation error reduces to 55% (table 2), but this still leaves over half of the true carbon burden unaccounted for. Table 2 describes the carbon burden associated with each supply chain tier of copper wire production as a percentage of the total 'real' carbon burden of production (table 2, column 2), the subsequent truncation error if the GREET.net model cumulatively covered each supply chain tier (table 2, column 3) and a final estimation of the 'real' carbon burden of copper wire production as a ratio, based on the previous two columns applied to the published GREET.net model carbon burden result (table 2, column 4). The initial GREET.net model allocated a carbon burden of 3.08 kg CO_2e /kg to the production of 1 kg of copper wire, the only figure from table 1 which was supplied by the GREET.net model.

Table 2 Gap analysis results tabulated by supply chain tier

Supply chain tier	Supply chain carbon embodied along supply chain tiers	Truncation error of GREET.net model	Estimation of carbon footprint of 1kg copper wire based on gap analysis findings (kgCO_2e/kg)
Direct	5%	95%	57.49
1	24%	76%	12.70
2	45%	55%	6.80
3	62%	38%	4.99
4	73%	27%	4.19
Remainder	100%	0%	3.08
Full gap analysis	40%	60%	7.64

The case study-specific results demonstrate the potentially substantial influence of truncation error on the carbon emissions analysis of copper wire production. A gap analysis of the Small World Consulting Ltd. single-region input-output model and the GREET.net model process-based analysis of the manufacture of copper wire shows a calculated truncation error of 60%, meaning that the detailed process-based assessment by the Argonne laboratory completely failed to account for up to 60% of the carbon footprint embedded in copper wire production. This analysis would imply a true carbon burden of 7.64 kg CO_2e /kg with the application of detailed gap analysis.

The largest contributor to the gap between the actual carbon footprint of copper wire and the GREET.net model estimated figure was found to be the exclusion of electricity production, transmission and distribution beyond the third supply chain from the process-based model supply chain considerations. In total, the electricity production, transmission and distribution sector exclusion translates into a loss of 11% of the total carbon footprint for copper wire. The most significant supply chain tier for this issue was the remainder, supply chain tier 5 and beyond, which included 8% of the total carbon footprint from service sectors alone. A further 23% is lost through the exclusion of the sectors basic iron and steel, basic metals and casting, industrial gases, and petrochemicals in approximately equal parts. In system boundary terms this could be a serious oversight causing significant underestimation of carbon burdens.

Within the available documentation of methodology for the GREET.net system boundary there was very limited explicit statement of supply chain inclusion and none for exclusion. While the methodology for this process-based model was not fully available, this problem can be encountered in almost all process-based life cycle assessments of carbon emissions. Thus, this issue was symptomatic rather of the state of carbon accounting protocol than the dismantling of the GREET.net 2012 model and its methodology.

The gap analysis showed that overall the supply chain is quite diffuse and complex; more so than might be expected of this comparatively simple product. For example, 26.5% of the supply chain emissions are a result of processes beyond the fourth supply chain tier. This is a substantial burden, significantly far removed from the final product and therefore unlikely to be included in a process-based life cycle analysis. This presents significant difficulties with system boundary identification. Complex supply chains make it harder to pinpoint precisely the system boundary location, without which reliable hybrid carbon accounting methods cannot be achieved. This difficulty is mirrored across all industry sectors and all nations and economic areas.

The use of structural path analysis to assess environmental impacts is widely used within academic analysis, from assessments of the powering of China's construction industry (Shen et al., 2016) to analysis of the ecological burden of the Finnish economy (Mattila, 2011). The application of this technique to carbon accounting is relatively new, first appearing in the late 2000's, however it has proved useful. Thus far the energy sector has seen the greatest use of structural path analysis, predominantly in assessing the life-time carbon burden of fuels (e.g. Acquaye et al., 2011; Yang et al., 2015). It has also been shown to have potential applications assessing downstream environmental impacts (Lenzen and Murray, 2010), i.e. environmental impacts after the point of sale of the product or service, so the potential for this method to improve carbon accounting methods could be greater than is currently realised.

It is unlikely that any process-based life cycle analysis of UK copper wire production done to current carbon footprinting standards would include service sector data. Thus, methodologically speaking, this is a relevant criticism despite the different countries involved in each of the individual models assessed in this gap analysis. While in the case of copper wire the service sectors account for only 0.8% of the total carbon footprint, their almost guaranteed exclusion from process-based analyses leaves other products vulnerable to far worse errors in the estimation of their carbon footprints.

Comparing a UK input-output model with an American process-based model was not ideal but was deemed the best option of the publicly available data used in this study. As the GREET.net model is one of the most comprehensive life cycle assessment models publicly available, it is one of the most likely models to have a low truncation error. Although the differences in the supply chains may be of concern to some, this has not been deemed a significant source of concern within this study, as the primary purpose is system boundary identification rather than conducting a process-based life cycle analysis.

The US and UK are both industrialised nations with strongly developed economies that rely on the emission of greenhouse gases to a significant degree to maintain their economic strength. In 2012 the UK imported 38% of its copper wire imports, by cost, from Belgium, a further 26% from the Russian Federation and 14% from Sweden, which covers almost 80% of imported copper wire to the UK in the year in question (UN Comtrade, DESA/UNSD). This covers similar physical distances as the US receiving its copper from Chile and within its borders.

6. Discussion

6.1. Limitations of the study

As there is no way to know the real-world carbon emissions created in production system, particularly such complicated systems as global supply chains, all inaccuracies and imprecisions can only be estimated. This is a limitation in the sense that all comparisons between models must subsequently be compared without the use of most specific and comprehensive carbon emissions measurements. This inherent limitation is compounded by others across each section of research study, depending on the carbon accounting method in use.

6.1.1. Input-output model comparisons

While the analysis presented in the first section of this study was intended to examine input-output methods, the use of process-based analyses was required to contextualise some of the input-output analysis. This means that all conclusions in this study regarding input-output best practice are based on a process-based benchmark, thus are not as specific to input-output methodology as would be ideal. The figures used to calculate the process-based carbon intensities were sourced, where possible, from UK government data, particularly the Defra carbon emissions factors for 2012. While largely accurate, there are some specific issues with these data that are particularly relevant within this analysis. Of most particular concern is that the process-based analysis result for the mining of coal and lignite industry from the Defra model is based on a percentage calculation of the direct emissions from the burning of coal and lignite, with a ratio calculated from the automotive industry applied to calculate the mining figure (Defra, 2012). Not only is this figure calculated from data of an unrelated industry, automotive rather than mining, it is also based on a European mix source of coal which is defined as the average composition of a resource, in this case coal, as used across Europe (Edwards et al., 2011). Input-output methods use data that represents the supply chain of the industry in the region they describe, so the data describing the UK economy would assume UK supply chains and thus UK average composition of coal used. The same would be true of the US model. This disparity of methods is the main reason that the process-based carbon intensity figure is larger than the input-output analysis figure, which is unusual in carbon footprinting history.

6.1.2. Process-based life cycle assessment limitations

The Defra process-based carbon emissions intensities for petroleum coke, a significant portion of the coke and refined petroleum products industry sector, were calculated indirectly using liquefied petroleum gas emissions and adjusting them artificially to represent petroleum coke emissions. This methodological approach is likely to produce inaccuracy as it is not a direct reflection of the supply chain process involved in creating the product it is attempting to represent, thus can only ever approximate the emissions factor based on non-industry-specific base data. This methodological inaccuracy calls the resulting accuracy analysis into question and, similarly to the issues with data sources that impact the accuracy analysis of coal, this process-based analysis should be considered with caution.

6.1.3. System-boundary analysis

The process-based analysis model used here had limited transparency of method, which has knock-on effects on the ability of a consultant to understand the system boundaries involved, and thus the implications of subsequent comparisons of system boundaries.

Within the available methodological documents there were sources of concern with regards to comprehensive understanding of both Defra and the European Commission's methodological processes. For example, the source paper for the coal origin, type and mining method used in the Defra process-based figures was published in 1999, thus it was 11 years out of date when applied to the Defra carbon emissions factors calculations. In addition, different mining methods have diverse economic burdens and carbon implications, and the differences between the mining methods used were not considered in either the Defra or source analysis. The differences between the mining method assumptions in each input-output model analysis calculation could lead to significant differences in results of each model through either economic or environmental pathways. Although the inclusion of international coal sources in the process-based figures more accurately reflects the real world nature of supply chains, and thus could be considered more accurate than the single-region models or simplified region representations of the multi-region models, the data is still over a decade out of date. Thus, the accuracy analysis within this study must be considered with caution as, although potentially more accurate, the process-based life cycle assessment method is far from an exact reflection of real world emissions.

Detailed documentation is key to reliable and accurate system boundary analysis, but this has not been found to be the norm in current carbon accounting. Due to the lack of methodological documentation, particularly on the Carnegie Mellon University model but affecting all carbon accounting methods used here, it is not currently possible to understand fully the system boundaries of the models. This has significant implications for the reliability of this study, however was unavoidable in the study-specific circumstances and scope of this study. Where possible the source of data was traced and analysed to identify the system boundary of that particular carbon burden. This was not ideal as it required significant qualitative interpretation of inclusion and exclusion of data as most of the articles which the studies drew on for data were not written with explicit system boundary definitions. Thus, the gap analysis, while as accurate as possible within the scope of this study, is not wholly comprehensive.

The assumption of the supply chain tiers covered in the specific models was made as a response to the economic theory background of the input-output carbon models. Without detailed methodological papers for each of the models compared here however, it is difficult to say precisely what is responsible for each of the precision analysis findings. The implications of this assumption will require more research to be fully understood.

6.2. Significant methodological practices and their implications

6.2.1. Location base of the model

The Carnegie Mellon University model was found to be the least precise model across all sectors, as measured by closeness to the mean result from all five models studied. As this is a model of the US economy it is likely that the extensive range of precision results was due to the difference in supply chains in the US compared to the UK. These different supply chains would impact the resulting carbon intensities as there are often more or less expensive and more or less carbon intensive methods of production and the methods used will differ regionally and globally depending on politics, geography and economics, among other considerations. For example, within the coke and refined petroleum products industry sector there was significant disagreement between models due to the difference between UK and US economic conditions. In particular, the Carnegie Mellon University model was an outlier, overestimating the carbon intensity by 364% compared to the process-based analysis. The fact that the Carnegie Mellon University model is based on US supply chains, and therefore has different production methods and prices of refined petroleum products internally compared to UK models is likely key in this industry.

The US uses a different categorisation system in its national accounts than most of the rest of the countries that produce input-output models. As previously mentioned, the US uses the North American Industry Classification System (NAICS) and the UK uses the Standard Industrial Classification (SIC). These systems aggregate and disaggregate industries, products, and processes using different methods of assigning relationships between industries processes included in each industry sector. For example, in the case of the construction industry sector, the UK models represented with one industry sector what the Carnegie Mellon University model represented with seven. This initial disaggregation could be the cause of the difference observed in coke and refined petroleum products industry, represented by one SIC industry classification and three NAICS industry classifications, as the NAICS sectors would have been able to achieve greater specificity than the single SIC sector models, thus theoretically return a more accurate figure than the SIC models. The reasonable agreement between the Carnegie Mellon University carbon factor value and that calculated by the Small World Consulting Ltd. multi-regional model suggests that there is some credence to this idea of greater industrial disaggregation resulting in greater accuracy of results as multi-region models tend to more accurately reflect the complexities of the supply chains.

The two multi-regional models agree closely when estimating the carbon burden of the remediation industry, putting more weight behind the interpretation of low agreement in this sector as a reflection of the differences between supply chains in different locations. This may be the case across other industry sectors, the study of which was beyond the scope of this analysis.

6.2.2. Inclusion of multi-regional data

Although input-output tables often describe only one region, for example, the UK, Europe, or the US, the trade in almost all commodities occurs in a global market, and the effects of spatial aggregation in input-output carbon modelling has been found to be notable (Su and Ang, 2010).

One of the most prominent issues this can cause with single region carbon models is incorrect substitution of carbon emissions from domestically produced goods to imported goods. For example, in 2012 the UK imported £25,415 million into industry sector 19: coke and refined petroleum products from all over the world (ONS, 2015) which, in a single-region model, would have been assumed to have the same carbon intensity as UK-produced coke and refined petroleum products. However the carbon intensity of production of all commodities varies globally. China has a manufacturing sector that is significantly more carbon intensive than the UK, yet the single region models give the same carbon intensity to goods produced in China as those produced in the UK, or anywhere else.

The multi-regional models consider the carbon incurred when products, such as iron and steel, are manufactured in carbon-intensive industry locations such as China, for the case of iron and steel, which would increase the emissions intensity per unit currency and thus explain why these models calculate larger values than the single region models. The US may also have a more carbon-intensive iron and steel industry than the UK, which would explain the difference between the single-region models. Within this industry sector there is both high agreement, based in significant and reliable data collection on and within the sector, and also high understanding of what differences there are between models, based in contextual research. Thus, this is an industry that is reliably represented in input-output carbon emissions models.

The Defra and Small World Consulting Ltd. multi-region models both use the supply and use tables published annually by the Office of National Statistics for their input-output models, so the underlying models were similar enough not to be the reason for the discrepancy seen in the electricity production, transmission and distribution sector. The difference in the division of global inputs to the UK system may be a source of some of the difference between the two UK-based multi-regional models. For example, in the industry sectors electricity production, transmission and distribution, and the manufacture of petrochemicals. While both use the UK as one region of the world, the other three regions differ between the models. The Defra model distinguished between Organisation for Economic Co-operation and Development (OECD) regions, which are based on economic development indicators, whereas Small World Consulting Ltd. distinguished between geographical regions (UK, EU, China, and the rest of the world). As this will change the details and aggregations of the methods, this could have a significant effect on the carbon intensity calculations. The impacts of spatial aggregation of multiple regions in input-output models is not as defined as those of of aggregation by economic data, such as exports (Su and Ang, 2010). Comprehensive understanding of the full extent of these implications would require further study.

Including the international trade and carbon emissions data is not necessarily the most influential methodological practice. In the case of the travel agency industry, it is possible that whatever is changed by the inclusion of multi-regional data is compensated for in the single region model by the inclusion of another methodological practice. The disagreement between the multi-regional models in this sector compared to the agreement between two single-region models of different countries suggests a high degree of complexity within this industry sector that would benefit from further study to improve precision.

6.2.3. High-altitude factors

Although the inclusion of high altitude emission correction factors is an exception in input-output models rather than a rule, they can have a significant impact on industries for which air transport is a prominent part of the supply chains. The air transport industry was found to have low agreement between models. When the calculations were analysed more deeply it became apparent that the high-altitude factor applied in Small World Consulting Ltd.'s model was the source of the difference accounting for almost 2 $kgCO_2e$/£ of the final carbon emissions intensity. Removing the high altitude factor from the Small World Consulting Ltd. calculations would leave it the second lowest calculation for this industry sector at a similar level to the Small World Consulting Ltd. multi-regional model, which does not include a high altitude factor. This makes further sense when it is considered that the Defra model, which calculated the second largest carbon intensity for air transport, included a multiplier for the non-CO_2 effects of air transport which, while it does not cover the full extent of a high-altitude factor, does increase the carbon intensity of the industry sector.

The influence of the high-altitude factor was not limited to the air transport industry. The fact that both largest carbon emissions intensity factors for the travel agency industry were calculated by single region models rather than the multi-regional models is likely due to the inclusion of the high-altitude factor in the Small World Consulting Ltd. model and high-altitude multiplier in the Defra model. In services sectors an influential air transport pathway is likely due to the movement of people in provision of the service. Otherwise, the high-altitude factor seems to have a limited impact on carbon model calculations when the lack of impact in this sector is contextualised within the earlier accuracy analysis.

6.2.4. Economic differences

This set of limitations is different from the location-based limitations, despite them both centring on economics, because these limitations are not tied to specific countries or regions of the world. As the input-output model is theoretically based on an economic model, any differences in the economic theory applied to an input-output model can have a significant effect on the results. For example, the low agreement of models within the coke and refined petroleum products industry was influenced not only by the various carbon burdens of the different regions included in the data, but also by the various influential economic factors. There is significant price volatility in the refined petroleum sector, and carbon emissions associated with the products in this industry vary significantly around the world, as does the import-export balance of the commodities with time. This leads to a wide range of methodologically acceptable values on which to base the calculations for a carbon accounting model. Thus, a variety of economic variables could influence the carbon accounting of industry sectors, and therefore carbon accounting should be undertaken and reviewed with sensitivity to economic conditions.

The Carnegie Mellon University model can use multiple NAICS sectors to represent what the other models treat as one industry sector using SIC. Theoretically the Carnegie Mellon University model could be the most accurate carbon accounting model for industries such as agriculture, construction and the manufacture of iron and steel, as it describes in more detail the burden of each industry. However, as it represents the US economy whereas the other three models represent the UK economy, and its supply chains, its accuracy has limited application in this study. It is worth noting this point for future comparisons where models are geographically uniform.

The differences in economic theory applications can also impact the precision and accuracy of input-output models. The use of different sources for the electricity price, different rounding or averaging methods or using single months to represent the electricity price over a year can all cause significant variation in the input-output analysis and final carbon emissions intensity. Should any data point fluctuate in an unanticipated way, significant errors could be incurred and risk the accuracy, precision and consistency of a carbon accounting model.

While gross fixed capital formation can have an impact on the carbon emissions factor calculated by a model, such as was found by this study in the refined petroleum sector, and was found for particle board (Garcia and Friere, 2014), in cases where there was no significant infrastructure involved in the supply chain its inclusion made little impact on the final estimate of emissions. This is another scenario in which sensitivity to the economic situation is key in interpreting carbon accounts.

6.2.5. Outlier findings

With regards to the mining of coal and lignite industry sector, the Small World Consulting Ltd. models agree closely with each other, as do the Defra and Carnegie Mellon University models. There is no clear reason for these models to agree more closely to each other more than either of the other models; it is just as likely caused by minor methodological fluctuations, as occur in all models across all disciplines, as to something that significantly affects the precision of a given model due to the slight extent of the disagreement between pairs of models. Theoretically, the global differences in the mining of coal should result in significant differences between the single- and multi-regional models. However, it seems, in the case of this industry sector, the inclusion of multi-regional data has a minimal effect on the final carbon intensity. More in-depth research is needed to discern the true reason for these findings.

6.2.6. Other influential issues

The supply chain for some industries, such as agriculture, are unlike the supply chains of other low agreement industries, in that they are simple. The supply chain of the agricultural industry is 73% described by the agricultural industry itself, and 76% of the supply chain for the sector 35.2-3: gas; distribution of gaseous fuels through mains; steam and air conditioning supply industry is described by three industries (38% electricity productions, transmission and distribution; 23% extraction of crude petroleum and natural gas and mining of metal ores; 13% gas; distribution of gaseous fuels through mains; steam and air conditioning supply. Nevertheless, this can lead to issues of precision as the model results rely more heavily on the precision and accuracy of other industry calculations. For example, electricity is also a low agreement industry, thus reliance on the calculations for the electricity sector within the manufacture of petrochemicals industry carbon factor calculations can lead to a high potential for low precision in the later calculations.

The mining of coal and lignite and manufacture of iron and steel industries are highly regulated and well researched, as well as having comparatively simple production methods. This wealth of knowledge and relative simplicity of supply chain tiers allows carbon model researchers to create detailed supply chains with reliable, up-to-date data with minimal effort and, therefore, enables them to create models that are consistently representative of this industry sector.

However, it is not a steadfast rule in carbon accounting that simple supply chains make for precise emissions calculations, as defined within the context of this study, or that the opposite is true for complex supply chains. For example, the relative complexity of the accounting and bookkeeping or legal services industries should theoretically have resulted in low agreement between models, however they were found to have high precision between models. This implies that other methodological factors are sometimes more important to the precision of a carbon emissions model than supply chain complexity, such as data quality.

A similar effect was found by Owen et al. (2017) in industrial energy use. In this case it was found that economic data was likely to agree between models and the source of model disagreement was likely the disagreement between environmental data. This conclusion could explain some of the discrepancies described in this analysis, including the counter-intuitive precision analysis finding that complex service sectors had higher agreement than simple extractive industries.

However, the apparent high precision could also be the result of oversimplification of complex industry sectors. As there are no process-based life cycle analyses of legal or accounting services, because the industries are too complex to produce reliable results using that method, there is no way to comprehensively assess the models' accuracy when estimating carbon emissions. As carbon accounting becomes more widely used and theoretical understanding of carbon models improves, this question should become answerable.

6.3. System boundary analysis findings

The fact that the input-output model on which this gap analysis was undertaken is based on the United Kingdom's economy when the process-based analysis is of the American economy is a potential source of inaccuracy. As the economies do not have the same structure, the structural path analysis based on the input-output model would not accurately reflect the supply chain pathways of American copper wire production. This is a result of the location of the model base as discussed within the limitations of the study. It was deemed more important to have an industry-leading process-based life cycle analysis than to have a process-based assessment of the same location due to similarities between US and UK copper wire production and substantial superiority of the GREET.net model compared to other process-based models.

In most cases, it can be assumed without controversy that any and all process-based life cycle assessments would not cover any of the supply chain pathways of commodity production at or beyond the fifth supply chain. Based on methodological analysis of the GREET.net model this was found to be the case for copper wire production. According to structural path analysis, 26.5% of the supply chain of copper wire is at or beyond the fifth tier of the supply chain, thus is far removed from the product itself. While overtly useful in the life cycle assessment of copper wire, this presents a potential mechanism for utilising the system boundary to improve model performance across all products and services. Structural path analyses can be undertaken on environmentally-extended input-output models with relative ease, therefore the percentage of embodied carbon beyond the fifth supply chain tier of any given product can be found out and applied to hybrid methods also with relative ease. This, with further research into specific application techniques, could contribute towards greater consistency and standardisation of hybrid methods across carbon accounting stakeholders.

The ambiguity of system boundary identification in most carbon accounting cases is of serious concern. It is currently impossible with almost all process-based analyses to know, with precision and confidence, where the system ends. For example, the carbon burden of services is not mentioned in any of the sources cited by the Argonne Laboratory in the building of the GREET.net model. Although they might have been included to some degree, as there was no mention of them they were assumed excluded due to lack of evidence. While this study has identified some of the difficulties with isolating system boundaries in carbon accounting, it is no less imperative for the future of reliable and comparable carbon accounting methods that system boundary identification becomes as explicit as possible in reporting at all levels. This could be relatively easily achieved with the publication of calculations along with the associated reports, which may not have been feasible when academic article publication occurred only on paper, but with the growing use of online platforms for academic journals this option is becoming increasingly easy to achieve. Issues regarding confidentiality may still be present in this scenario, and so may limit the dissemination of this option. However, this study has dealt with only publicly available data from academic, industrial and governmental institutions. This shows the potential breadth of data this could allow access to, enabling expanded analysis and integration into a wider understanding and contribute to potential regulation of the carbon footprinting process.

One issue with the reliability of carbon accounting has been the trade-off between system completeness and precision in terms of system boundary selection. Within this study it has been shown that systemically complete carbon accounting methods, such as input-output analysis, result in more consistently reliable, and therefore comparable, results. The significantly large gap between the complete system and the process-based results suggests that the purported precision gained from process-based methods does not translate into precision and accuracy of results in real or comparative terms. The implications of this are far reaching in that thorough process-based life cycle analyses such as the Argonne Laboratories GREET.net model are widely considered to have high accuracy, but this analysis suggests otherwise. In the case of copper wire, with a truncation error of 60%, the process-based model under-reports the carbon burden of the product far below the minimum reporting margin of 95%, as encouraged by the PAS2050 standardisation document. More broad analysis of the accuracy of the GREET.net and equivalent process-based life cycle analysis models should be undertaken to investigate the extent of this issue.

Carbon accounting is often used as a measure of sustainability for businesses and organisations: the carbon accounting reports discussed in this study have real world impacts. The relevant carbon accounts for a product, service, or organisation can be compared throughout time and with other organisations to measure the progress of carbon emissions reduction attempts. This is key not only to measure the progress of the sustainability measures of a business, but to assess the climate risk faced by the business, which is key to the business itself and potential investors

(Paddison, 2013). As comparison is a key use of this data in industries outside carbon accounting it is key that the results be reliably comparable in these ways. This is currently not always the case, due to the incomplete and undocumented nature of the system boundaries of most carbon accounting reports and the significant differences caused by different methodological practices in input-output methods. In both system boundary and input-output cases these issues are not necessarily easily identified, let alone understood or addressed. This makes any comparisons based on this data equally unreliable.

7. Conclusions

- The four input-output models tested calculated different carbon footprint estimates for the same activities.
- The precision of the models, as measured by closeness to the mean, is poor for some sectors, better for others, depending on the supply chain pathways and the appropriateness of methodological practices to reflect them.
- One cannot fully assess the accuracy of the models, as measured by closeness to the true result, since this is unknown.
- The high-altitude emission factor makes little or no difference for most activities as air transport is not a significant part of the supply chain for most industries.
- The inclusion of multi-regional data was found to be the most constructive and most widely influential methodological practice.
- Economic sensitivity is critical to robust interpretation of carbon accounts.
- System boundary reporting is incomplete where present and largely not useful for hybrid carbon accounts interpretation.

A number of factors key to the reliability of carbon emissions models have been identified in this study by the use of quantitative comparative analysis. The inclusion of multiregional data has been found to increase the accuracy of the carbon emissions estimates by reducing the need for assumptions of supply chain carbon burdens as singular, and can allow the expression of the complexity of the global supply chains and resulting carbon burdens. Variation in the economic situation globally, nationally and locally can impact the results of consumption-based carbon accounting methods and thus this situation should be considered when interpreting carbon reports. High-altitude factors can also increase the accuracy of carbon emissions estimates for industries that rely in some substantial part on air travel, either for goods or personnel, although for many sectors the inclusion of these factors makes little difference to estimated carbon footprints. All these factors have varying influence depending on the industry being analysed, however the quality and depth of the data used during analysis is universally critical to ensuring consistent and reliable accuracy and precision of results.

Despite the use of process-based life cycle analysis figures to assess the accuracy of the input-output figures, these cases were known outliers in the methodology; usually the potential specificity benefit of process-based methods is lost in the complexity of product and service supply chains. The gap between the complete system of the input-output model and the industry-leading GREET.net process-based model from the Argonne Laboratory made clear the methodological superiority of the input-output method. Though it may involve aggregation and approximation, the risks of the process-based method not accounting for such a substantial amount of the supply chain embedded carbon is irreconcilable with the ideals of consistency and reliability in carbon accounts and reporting. This issue would be of particular worry to the business community as carbon emissions become more heavily regulated and reported, both to governing bodies and through the media.

However, the specificity of process-based analyses and the systemic completeness of input-output models of carbon footprints are of little consequence in hybrid carbon models in the face of the lack of any, if not all, of the system boundary identification data in publicly and academically available publications of the carbon accounting of products and services. As such, in the current state of carbon emissions reporting, input-output models are the most reliable model types in terms of both system completeness and accuracy.

7.1. Recommendations

Greater theoretical understanding of supply chains within process-based life cycle assessors and assessment users would enable increased system boundary knowledge and subsequently an increase in system boundary identification. It would achieve this by allowing process-based life cycle assessors to more easily establish a generic, but appropriate relevant, system boundary in the form of supply chain tiers. An assessment of supply chain coverage could be included in future carbon accounting reports with relative ease and with very little extra effort required from the reporters were they to understand the intersection of supply chain theory with their process-based work as they would combine their in-depth understanding of the products and processes they model with the more broadly applicable supply chain theory as it applies to their products. Although this would still leave room for error, as the assessors may assume 100% of the supply chain tier is covered when it is lower, or exclude small amounts of more distant supply chains, it would give significantly more detail on the system boundaries than is currently available. It would also make hybrid approaches more tenable. Input-output models use supply chain tiers in their base method, so incorporating this into process-based models would enable the two different methods to fit together with more methodological precision.

The gap analysis of one of the most comprehensive process-based models of carbon accounting highlighted the often dispersed nature of supply chains for products and the potential extent of truncation error that process-based models are therefore vulnerable to. This demonstrates a potential for a completely generic method of increasing the accuracy of process-based analyses; assuming the supply chain tier five and those beyond were excluded and applying the percentage gap incurred by that exclusion as a ratio to alter the process-based result. In the case of copper wire this accounts for over a quarter of the carbon footprint of the product. The potential impact of addressing this omission in process-based studies is significant. As this assumption can likely be made across all industry sectors, with almost no additional effort expended, the truncation error can be somewhat reduced with a partial gap analysis that immediately assumes the truncation of all supply chain pathways including and beyond the fifth supply chain tier. This figure can be calculated with relatively little difficulty using structural decomposition analysis of the economic input-output model used in any given analysis.

Transparency across all carbon accounting reports would be very valuable to the future of the practice and the increased understanding and accuracy of its results. This transparency could be gained by utilising the internet. Only publically available data was used in this analysis, and while there was ample data for this study, any increase on the scope of this research would have encountered difficulties with data access. By making emissions factors, models and the associated methodology and assumptions more readily available the entire industry would benefit as this data sharing would increase the calibre of all future carbon accounting reports, and therefore the actions taken based on those reports would be more appropriate. Part of the problem with publishing as much data as would be required in the past has been the limited space available in academic and other journals. Utilising the low cost and high storage capacity of internet databases could prove invaluable. Publishing this data online in publically accessible databases or forums would achieve this.

In order to increase future system boundary understanding there is a great need to include more explicit system boundary definitions in carbon accounting reports and academic articles. This could be achieved by having a classification system similar to the SIC and NAICS applied to the input-output methods. If process-based analyses could have their data sources organised into a table with specific words or codes translating to the same product, process or industry across all process-based reports, this table could be translated into system boundary analysis calculations enabling a simpler translation of process-based methods into system boundary understanding.

7.2. Future research opportunities

Research into refining the process of identifying system boundaries in hybrid carbon emissions models without losing accuracy is evidently key to the improvement of hybrid carbon accounting techniques. Though it may seem an impossible task, progress can be made by developing the techniques currently available and expanding their applications. Of particular note from this study is structural path analysis. As this technique has only been easily applied in the carbon accounting field for the last decade there is likely to be significant progress to be made into new and innovative uses.

Creation of a system boundary identification method that is broadly applicable over a given industry sector, would greatly simplify the system boundary reporting process. Manufacturing may be the best sector to start with as it contains the theoretically simplest supply chains. These macro industry identification methods could then be refined for mining, etc. It would be crucial that this identification method would be openly and freely available thus enabling the consistent understanding of carbon accounting reports.

Although there are papers published frequently on carbon accounts of various products and services, there is a significant lack of clarity in academic publications of carbon accounting methods. This has the potential to lead to a significant knowledge gap in the future. With the current lack of detailed reporting in the carbon accounting industry and increasing use of them throughout the world it is imperative that the methods of carbon accounting are rigorously examined and improved to keep up with the need.

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