An Application of Hybrid Lifecycle Assessment as a Decision Support Framework for Green Supply Chains

A. Lake[a] , A. Acquaye[b], A. Genovese[a], N. Kumar[a*] and S. C. L. Koh[a]

[a]Logistics and Supply Chain Management Research Centre, Sheffield University Management School

Conduit Road, Sheffield, S10 1FL, UK

[b]Kent Business School, The University of Kent, Canterbury, Kent, CT2 7PE, UK

*Corresponding Author: N.Kumar@sheffield.ac.uk

Abstract

In an effort to achieve sustainable operations, green supply chain management has become an important area for firms to concentrate on due to its inherent involvement with all the processes that provide foundations to successful business. Modelling methodologies of product supply chain environmental assessment are usually guided by the principles of Life Cycle Assessment (LCA). However, a review of the extant literature suggests that LCA techniques suffer from a wide range of limitations that prevent a wider application in real-world contexts; hence, they need to be incorporated within decision support frameworks to aid environmental sustainability strategies.

Thus, this paper contributes in understanding and overcoming the dichotomy between LCA model development and the emerging practical implementation to inform carbon emissions mitigation strategies within supply chains. Therefore, the paper provides both theoretical insights and a practical application to inform the process of adopting a decision support framework based on a LCA methodology in a real-world scenario. The supply chain of a product from the steel industry is considered to evaluate its environmental impact and carbon 'hotspots'. The study helps understanding how operational strategies geared towards environmental sustainability can be informed using knowledge and information generated from supply chain environmental assessments, and for highlighting inherent challenges in this process.

***Keywords*:** Green supply chain, Lifecycle assessment, Decision support framework.

1. Introduction

The conflict between environmental sustainability and economic competitiveness is a false dichotomy based on a narrow view of prosperity sources and a static view of competition (Porter 1991). Therefore, it is unsurprising that environmental sustainability now forms an integral part of the contemporary Supply Chain Management (SCM) practices (Markley and Davis, 2007; Gold *et al*., 2010, Gunasekaran and Irani, 2014, Bai and Sarkis, 2014). Sustainability-related constructs have thus emerged in the broad literature of SCM (Seuring and Müller, 2008, Linton *et al*., 2007).

Sarkis (2003) and Srivastava (2007) describe the framework of Green supply chain management (GSCM) from a product lifecycle and operational perspective. Often, these two perspectives within GSCM are mutually exclusive as there is a lack of integration between product lifecycle and business operations (Srivastava, 2007). Indeed, Porter and Kramer (2006) stated that prevailing approaches towards environmental sustainability-related issues are fragmented and disconnected from business and strategy, thus obscuring opportunities for innovation. Efforts to link these together are therefore crucial in enhancing sustainability within supply chains. To integrate these complex processes, it is imperative for firms to implement an advanced yet flexible management systems to enable planning and coordination of an effective and efficient supply chain (Sengupta et al., 2006; Bhattacharya et al., 2014). Decarbonisation efforts within product supply chains involve a systematic process of measuring and strategically managing carbon emissions which can be facilitated with a decision support framework. In order to prioritize mitigation efforts, the process must be able to provide understanding of emission hotspots (described as highly carbon-intensive processes) and opportunities to model alternative scenarios to inform decision-making.

Such modelling methodologies of product supply chain environmental assessment are usually guided by the principles of Lifecycle Assessment (LCA) (Acquaye *et al*., 2014). However, a review of extant literature suggests that (see, for instance, Wang *et al*., 2013), on its own LCA is somewhat limited; hence it needs to be incorporated within decision support framework to aid environmental sustainability strategies. These frameworks should provide firms with the opportunity to use SC knowledge and information on product lifecycle environmental impacts to inform operational strategies. Despite the potential benefits of decision support frameworks, their use to model product supply chains is often compounded by the complexity of the production system due to the infinite inputs and processes at different tiers of the supply chain (Min and Zhou, 2002). Decision support frameworks for supply chain should therefore address such complexities (Angerhofer and Angelides, 2006) and provide practical information to inform new business models (Cigolini et al., 2004). However, the analysis of the literature shows that, in many cases, proposed frameworks used in supply chain analysis are tested on generic applications, numerical examples and computational experiments, with less emphasis on issues and problems that could emerge in a potential real-world implementation in an industrial context (Genovese et al., 2014).

Considering this evidence, the goal of this paper is to contribute to understand and overcome the above dichotomy by providing theoretical insights and practical applications to inform the process of managing environmental impacts, such as carbon emissions mitigation strategies, within supply chains. This paper therefore argues that by integrating the environmental assessment based on a LCA approach into a decision-making process, businesses can be able to formulate and evaluate effective strategies for green supply chains.

Consequently, the main research questions that will be addressed in this paper are:

- How can general hybridized LCA constructs serve as a basis for a supply chain decision support framework for measuring and reporting environmental impacts?
- What are the main inherent challenges in the adoption of LCA methodologies in a real-world scenario?

To address these research questions, the paper is structured as follows. In Section 2, a literature review is conducted on LCA and its utilisation as a basis for Supply Chain Decision Support. Details of the methodology and theoretical formulations underpinning the proposed Decision Support Framework, together with details of the test case study are provided in Section 3. Section 4 illustrates key findings, by presenting the results of the application of the Decision Support Framework to an environmental assessment process undertaken in a real-world supply chain context. Section 5 discusses the findings in the broader context of the SCM literature, drawing some managerial implications. Concluding remarks are then reported in Section 6.

2. Literature Review

Modelling methodologies of product supply chain environmental assessment have been usually guided by the principles of LCA. The following sub-sections provide some literature background of LCA applications to GSCM, its integration in decision support frameworks and emerging knowledge gaps.

2.1 Lifecycle Assessment (LCA) as a basis for Supply Chain Decision Support

Initiative for Global Environmental Leadership (2012) recently reported that systems capable of collecting, analysing, and reporting data for SCM are now evolving to take into account environmental information from a lifecycle perspective. Sarkis *et al.* (2012) and Acquaye *et al.* (2014) have both therefore suggested that principles of LCA can form the basis for developing decision support framework to inform strategies to decarbonize supply chains.

In this context, Horne (2009) discusses that a systematic process is needed to understand sustainability standards in the supply chain. GSCM (Sarkis, 2003, Srivastava, 2007) and sustainable operations management (Kleindorfer et al., 2005, Gimenez et al., 2012) have emerged from the broad theoretical constructs of environmental sustainability to represent such strategic process. Fundamental to these concepts are the principles of LCA, used as the basis for evaluating the environmental sustainability performance of supply chains. A review of extant literature suggests that traditional process LCA approach has been widely used in an attempt to understand the environmental impacts of product supply chains (Sinden, 2009, Reich-Weiser and Dornfeld, 2009). This particular LCA approach is characterised from a bottom-up approach, seeking to reproduce elementary activities along the supply chain and related environmental impacts. This approach however suffers from several problems, the most notable being the truncation of the system boundary, which results in missing part of the product supply chain (Suh *et al*., 2004). As such, current state-of-the-art in LCA suggests that process-based LCA should be integrated with environmental input-output LCA into a hybridized framework (Wiedmann *et al*., 2011, 2013; Acquaye *et al*., 2012,Lee and Ma, 2013).

Despite the universal acceptance of LCA based approaches in providing a useful way of making sound environmental decisions (De Benedetto and Klemeš, 2009, Seuring, 2013) and ongoing work of the related workgroup of the United Nations Environmental Programme (UNEP) Life Cycle Initiative (UNEP and SETAC, 2011), there is no consensus on a consistent LCA methodology at the operational level (Labuschagne et al., 2005, Loiseau *et al*., 2012)

Literature analysis suggests that hybrid approaches (Cordero, 2013, Grimm *et al*., 2014) provide the most consistent and robust framework to account for supply chain environmental impacts of products, processes, etc. Hybrid LCA integrates two basic LCA approaches (the above-mentioned process LCA and environmental input-output LCA) together in order to overcome the truncated system boundary problems in process LCA and the lack of specificity and accuracy in environmental input-output LCA (Crawford, 2008, Acquaye *et al*., 2011a).

However, even the more accurate versions of LCA techniques suffer from intrinsic limitations of this methodology, being just capable of static assessments and lacking dynamic capabilities (Löfgren and Tillman, 2011). In fact, Wang *et al*. (2013) reiterate that LCA needs to be incorporated within empowered decision support frameworks to aid environmental sustainability strategies.

2.2 Literature Gaps

While hybrid LCA has seen numerous applications, a creative and meaningful deployment of it within decision support analysis to address supply chain issues is generally limited due to a number of factors such as challenges deriving from practical applications (Bani *et al*., 2009, Heijungs *et al*., 2006), methodological challenges (Guinee *et al*., 2010), complexity of SC systems (Deng *et al*., 2011, Suh *et al*., 2004) and usefulness of the results (Nansai *et al*., 2009).

Therefore, despite the large number of studies appeared recently, papers published in the field of LCA are more oriented towards the development of techniques, emphasizing the need of quantitative methods and overlooking the importance of integration with strategic thinking across the supply chain. Indeed, while the number of applications is growing, there is little empirical evidence of their practical usefulness, being very often the proposed models tested on generic applications and experiments. Less emphasis is devoted to problems emerging in the practical implementation of the methodology, on its strengths and weaknesses, and on the perceived usefulness to concerned decision-makers. This highlights that, despite the wide spectrum of techniques and methods available for tackling these problems, there is a lack of thorough empirical tests regarding the usability of such methods in corporate environments. In particular, previous studies reported that the application of LCA is limited, because it is a rather sophisticated method, and the direct usage of the method and employment for decision-making is absolutely non-trivial and needs expert support. In addition, the required effort can be quite high, which poses additional barriers for its application (Rebitzer, 2005; Kaenzig and

Wüstenhagen, 2010; Sandin et al., 2014). The result is a deep dichotomy between theoretical frameworks and business practice. In other words, the literature is rich of approaches but their usability in practical applications is questionable.

Therefore, the main aim of the paper is to contribute to overcome the cited dichotomy between theoretical and practical approaches by verifying the actual usability of a wider decision support framework (integrating hybrid LCA principles) in a real-world corporate context. The paper demonstrates how the hybrid LCA approach is used as a mean of informing changes within supply chains through a) enabling decision-making, deriving environmental performance measures, and identifying possible business improvements, and b) acquiring deeper knowledge about the production system being studied; both key reasons for undertaking LCA as reported by Tillman (2000).

The effective usability and adaptability of the decision support framework (illustrated in Section 3) in firms' practices are investigated through an empirical study that will be described in Section 4 and thoroughly discussed in Section 5.

3. Research Methodology

The following sub-sections illustrate the general Decision Support Framework (underpinned by the principles of hybrid LCA) employed in the paper and its specific stages. Furthermore, the real-world case study utilised to test the approach, and to understand challenges deriving from its implementation, is presented.

3.1 Decision Support Framework

The aim of the DSS presented in this paper is to provide insights and evidence to collaborative supply chains for informed decision-making in greening operations. The methodological framework is composed of the following steps (see also Figure 1):

- *Supply chain mapping*, devoted to the reproduction and the representation of the operational and logistical flows across the SC thanks to information exchange among focal firm, suppliers and researchers.
- *Carbon calculation*, oriented to the identification of the carbon hot-spots (namely, carbon-intensive processes) across the entire supply chain using a hybrid LCA methodology.

- *Scenario Analysis*. Aimed at targeting identified carbon hot-spots and reducing their emissions through appropriate interventions, to be evaluated according to their mitigation potential.

The following sub-sections explain, in detail, the principles adopted in the framework.

<< Insert Figure 1 here >>

3.2 Supply Chain Mapping

The following methods can be adopted to collect data for the reproduction and the representation of the operational and logistical flows across the whole supply chain under investigation:

1) Amassing data from company documents such as process maps, bills of materials, invoices and environmental reports.
2) Observing business activities, company processes and implementation of existing environmental policies through site visits.
3) Conducting semi-structured interviews with relevant focal firm and related suppliers' managers to ensure that appropriate data about processes and existing environmental practices are gained.

To supplement primary data, the Ecoinvent (2010) lifecycle inventory can be utilised to ensure completeness of production and SC processes.

The Multi-Regional Input-Output (MRIO) framework data consisting of the UK and Rest of the world (ROW) Supply and Use input-output tables used to construct the hybridized LCA was sourced from the UK and ROW MRIO table expanded upon by Wiedmann *et al*. (2010). Appendix III provides the detailed breakdown of input-output sectors.

The collected information can be organised in a supply chain map. Supply chain maps visually represent the interaction between different entities within a supply chain and can be presented at different levels of the value chain such as product, process, firm and industry levels. In this paper, a product-level perspective is used highlighting the direct and indirect supply chain interactions. Acquaye et al. (2014) explain that the concept of a supply chain map can be used to provide clear understanding of the exact flow of materials and impacts along the supply chain and hence form the basis for managing and benchmarking the environmental performance of the supply chain.

3.3 Supply Chain Carbon Accounting Calculations Framework

Based on general principles of LCA, the general hybrid LCA framework is transformed into a 2 region UK-ROW MRIO framework. A generalized hybrid LCA (Rowley *et al*., 2009) consist of a process LCA (Sinden, 2009) and input-output based LCA (Su *et al*., 2013) integrated together into one consistent framework.

The hybridized MRIO LCA framework deployed in this paper is adopted because of a number of reasons. Firstly, Sundarakani *et al*. (2010) reported that a visibility is a key requirement when modelling carbon emissions across supply chains. By defining the MRIO structure in the hybridized framework (specifically, as a 2-region model between the UK and ROW) ensures that carbon emissions (both direct and indirect) along the entire UK-ROW supply chain become visible and are captured in the analysis. Secondly, the Supply and Use format based on a two-region (UK and the ROW) MRIO framework is adopted instead of the symmetric structure usually used (Kok *et al*., 2006, Rueda-Cantuche and ten Raa, 2007). As reported by EUROSTAT (2008), the advantages of Supply and Use input-output structure lies in its stronger level of detail which ensures a higher degree of homogeneity of the individual product and therefore better possibilities for determining categories of uses and, consequently, environmental impacts.

3.3.1 Process Framework

Process analysis is adopted as the initial method for computing the SC requirements of the production system. A process-based approach evaluates the amount of SC inputs required to produce a given functional unit of the product under investigation.

Being A_p the matrix representation of the production system characterised using process LCA approach, it can be defined as $A_p = [k_{rc}]$, where k represents elements of the production system matrix, r (rows) represents SC inputs for selected product production and c (columns) processes in the production process.

Hence,

$$A_p = [k_{rc}] = \begin{cases} k_{rc} = 0 & if\ r \neq c \\ k_{(rc)n} = q_n & if\ r = c \\ k_{rc} = k_{r,n+1} = -k_{rr} & \forall\ r\ and\ if\ c = n+1 \\ k_{rc} = k_{n+1,n+1} = 1 & \end{cases}$$

(Equation 1)

For n different types of SC inputs into the process production system, A_p would be of dimension $(n+1)\ x\ (n+1)$; where there are n SC product inputs and 1 main product output. q_n represents the quantity of SC inputs of any of the n inputs.

To ensure system boundary completeness and visibility of the entire SC, the initial process production system A_p presented in Appendix II is integrated into the Input-Output framework specifically characterized below as a 2 region (UK-ROW) MRIO framework using the Supply and Use format.

3.3.2 Input-Output (IO) Framework

An input-output (IO) model which records the flows of resources (products and services) from one industrial sector considered as a producer to other sectors considered as consumers (Miller and Blair, 2009) is adopted as the quantitative economic framework to account for upstream SC inputs and consequently the physical impacts (carbon emissions in this paper) along the UK-ROW supply chain. An IO model can be represented as a matrix of all economic (production and consumption) activities taking place within a country, region or multi-region (in this case, UK and ROW).

The process involved in transforming the economic flows of SC inputs (products and services) in the general IO model into physical flows (such as carbon emissions) using the basic assumptions of input-output analysis is extensively described in literature (Suh, 2009, Acquaye *et al*., 2011b, Kagawa, 2012). However, in order to characterise the framework specifically for the UK-ROW supply chain using the Supply and Use MRIO structure, the process is succinctly described below.

Following on from IO literature (ten Raa, 2007, Ferng, 2009, Minx *et al*., 2009), it can be shown that: $\underline{x} = A_{io}\underline{x} + \underline{y}$ implying that:

$$\underline{x} = (I - A_{io})^{-1} \cdot \underline{y} \qquad \text{(Equation 2)}$$

Where: $A_{io} = [a_{ij}]$ is a matrix describing all the SC product requirements in monetary values from sector (i) needed by industry (j) to produce a unit monetary output. It is called the technical coefficient or technology matrix because it describes the technology of a given industry which is characterised by the mix of SC inputs (including raw materials, machinery, energy, goods, transport, services) required to produce a unit output. In Input-Output economics, it is assumed that the total production of goods and services in a system is equal to the total consumption (Miller and Blair, 2009). Hence the total output x of any industry j is equal to the sum of the amount consumed by that same industry and other industries in making their own products and that consumed by the final demand y groups consisting of households, governments, exports.

I is the identity matrix which is of the same dimension as A_{io}. $(I - A_{io})^{-1}$, referred to as the Leontief Inverse matrix; $(I - A_{io})^{-1} \cdot \underline{y}$ describes the total (direct and indirect) requirements needed to produce the total output, $\underline{x}$ for a given final demand $\underline{y}$ (Barrett and Scott, 2012). Hence, in terms of SC visibility, the SC of a given product can be set up in such a way that not only direct inputs are captured, but also, irrespective of their origin (domestic or imported), indirect SC input can also be captured in the analysis in addition to the direct inputs already captured by the process production system described in Section 3.3.1. This is as a result of the extended system boundary of the IO framework (Acquaye and Duffy, 2010, Mattila *et al*., 2010, Wiedmann *et al*., 2011). As a result, the whole lifecycle perspective, which is a key principle of GSCM (Carter and Easton, 2011) is upheld based on the generalised principles surrounding IO analysis (Wiedmann, 2009).

3.3.2.1 Multi-Regional Input-Output (MRIO) Framework

In this paper, the generalised IO approach presented in Section 3.3.2 is extended to a MRIO framework to specifically characterize the UK-ROW supply chain in order to evaluate upstream SC inputs not directly captured in the process production system, A_p.The MRIO framework A_{io} used in this paper is presented as a 2-region (UK and ROW) model shown below.

$$A_{io} = \begin{bmatrix} 0 & A_{(UK)U} & 0 & 0 \\ A_{(UK)s} & 0 & A_{(UK)EXP} & 0 \\ 0 & 0 & 0 & A_{(ROW)U} \\ A_{(UK)IMP} & 0 & A_{imp} & 0 \end{bmatrix} \qquad \text{(Equation 3)}$$

Where A_{io} becomes the 2-region MRIO technical coefficient matrix. This includes the respective technical coefficient matrices for UK Domestic Use, $A_{(UK)U}$, UK Domestic Supply, $A_{(UK)s}$, UK Export to ROW, $A_{(UK)EXP}$, ROW Use, $A_{(ROW)U}$, UK Imports from ROW, $A_{(UK)IMP}$ and ROW Supply to ROW, $A_{(ROW)S}$. The UK and ROW economies have been classified into 224 sectors. Hence all the individual A matrices representing product sectors and industries in the UK and ROW are of dimension $224\ x\ 224$; hence, A_{io} is therefore of dimension $896\ x\ 896$. Refer to Appendix III for the detailed breakdown.

The Technical Coefficient Matrix for UK Imports from ROW, $A_{(UK)IMP}$, for example is defined as:

$$A_{(UK)IMP} = \left[\frac{q_{ij}^{(ROW,UK)}}{x_j} \right] \qquad \text{(Equation 4)}$$

Where: $q_{ij}^{(ROW,UK)}$ represents elements of UK imports input-output table from the ROW region indicating the input of product (i) from ROW into the industry (j) of the UK while x_j represents the total output of UK industry, (j).

The MRIO framework A_{io} representing the UK-ROW supply chain is integrated with the process production system A_p within the general hybridized framework (state-of-the-art in LCA).

3.3.3 MRIO Hybrid LCA Framework

From Equation 1, given that $\underline{x} = (I - A_{io})^{-1} \cdot \underline{y}$ defines the total (direct and indirect) requirements needed to produce an output x for a given final demand, y; a pure input-output LCA can therefore be defined in a generalised form as:

$$\underline{E} = E_{io} \cdot \underline{x} = E_{io} \cdot (I - A_{io})^{-1} \cdot \underline{y} \qquad \text{(Equation 5)}$$

However, in a generalised hybrid LCA, the pure input-output LCA is integrated within one consistent framework with the initial process production system A_p by connecting the two

LCA systems at the downstream and upstream with SC flows D and U respectively. See Suh and Huppes (2005), Acquaye *et al.* (2011b) and Wiedmann *et al.* (2011).

$$Total\ CO_{2-eq}\ Emissions\ = \begin{bmatrix} \hat{E}_p & 0 \\ 0 & \hat{E}_{io} \end{bmatrix} \begin{bmatrix} A_p & -D \\ -U & (I - A_{io}) \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix} \qquad \text{(Equation 6)}$$

Where: the total carbon emissions consists of the sum of the direct and indirect SC impacts for $CO_{2\text{-eq}}$.

Carbon emissions were chosen as the main environmental impact because it is the most commonly cited environmental indicator and because of the challenges in accessing data. In this paper, because the MRIO framework is presented in the Supply and Use format, the corresponding environmental extension matrix, $\hat{E}_{io}$ is also presented in the Supply and Use format. $\hat{E}_{io}$ which has unit (kg CO_2-eq/£) is a diagonalised $CO_{2\text{-eq}}$ intensity vector of UK-ROW industries.

$$\hat{E}_{io} = \begin{bmatrix} \hat{E}_{UK} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \hat{E}_{ROW} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad \text{(Equation 7)}$$

$\hat{E}_p$ (kg CO_2-eq/unit) denotes the diagonalised $CO_{2\text{-eq}}$ intensity vector of processes in the initial process production system A_p. $\hat{E}_p$ thus represent the respective environmental values e_n of each input n into of the process LCA system used to produce the functional unit of the product associated with the SC under investigation. e_n is obtained by multiplying the quantity of each product inputs q and the respective emissions intensity e_{int}. Hence, $\boldsymbol{E}_p = [\hat{e}_n]$; where $\forall\, n$ into the process LCA system; $e_n = q_n \times e_{(int)_n}$.

Matrix D and Matrix U are the SC flows linking the process production matrix (that is the foreground system) and the MRIO matrix (that is the background system) at the downstream and upstream of the LCA system respectively. It can be argued that the downstream SC flows D from the process production system into the much larger background system (The MRIO of the UK and ROW supply chain) are often negligible and can be ignored (See for instance Strømman *et al*, 2009). However, U is not set to zero since it represents the upstream SC inputs which have not been captured as a result of truncating the process production system (Acquaye et al., 2011b).

y is the functional unit denoting the output of the initial process system. Within the hybridized framework, the functional unit is linked to the initial process production system A_p already described in Section F has having a dimension of $(n + 1)\ x\ (n + 1)$; hence, the final demand matrix can be defined as: $\underline{y} = [f_{d,1}]$; where $f_{d,1} = 1$ if $d = n + 1$ and $0, \forall$ other d.

Refer to Appendix II for the process production matrix A_p, the $CO_{2\text{-eq}}$ intensity vector of processes in the initial process production system $\widehat{\mathrm{E}}_{\mathrm{p}}$ and y, the final demand matrix for the production of a functional unit of the product.

By interconnecting the domestic (UK) and the imported (ROW) Supply and Use input-output tables into a 2-region MRIO framework, the hybrid LCA can overcome the complexity of product SC as a result of the globalized nature of all the interconnecting and theoretically infinite product, process and service inputs at different tiers of the SC. Indeed, in addition to direct inputs, the framework captures all indirect upstream requirement that are needed to produce all the individual SC inputs either from resources from the UK or from outside the UK (that is ROW).

In this study, the Hybrid LCA has been employed to produce SC maps of carbon emissions with the graphical output generated using the SC Environmental Analysis Tool (Koh *et al.*, 2011).

3.4 Supply Chain Carbon Maps

Results of the assessment are displayed through SC carbon maps, graphically displaying the product SC enriched with information about environmental impacts. SC carbon maps can be derived using the hybrid LCA methodology presented above. The process LCA system impacts are presented on the main grid of the map while the upstream indirect impacts captured by the MRIO system are presented at the bottom row of the map. These indirect impacts which are upstream of the process LCA system and come from the wider economy (UK and the ROW) are traced to the 224 separate industrial sectors presented in Appendix III, and, for ease of presentation, aggregated across 18 economic segments as shown in the Concordance Table presented in Appendix IV.

The SC carbon maps use the following thresholds for the carbon emissions ranking of the hotspots (described as high carbon inputs): Very High (shown in Red, it indicates inputs with emissions greater than 10% of the total lifecycle emissions); High (Orange, 5 to 10%); Medium (Yellow, 1-5%); Low (Green, Less than 1%). The SC carbon maps re-affirms the fact that inputs having significant emissions impacts within a product SC are not limited to just direct inputs or domestic supplies (in this instance from the UK) but may also include upstream and imported SC inputs (in this instance from the ROW). Hence, by using the hybrid LCA framework the paper presents how the SC carbon maps are able to capture and display both direct and indirect inputs under different scenarios and help in decision-making. Additionally, for upstream SC impacts, the focal firm can identify in an intuitive way, partners belonging to a particular economic sector that should be prioritized in terms of de-carbonization efforts.

3.5 Scenario Analysis

Scenario analysis is an important approach for strategic decision-making, particularly in environmental impact assessments, due to its ability to define future developments for cumulative impact assessment and to determine the effects of contextual change on possible interventions (Duinker and Greig, 2007). In the framework, Scenario Analysis will be aimed at targeting identified carbon hotspots and reducing their emissions through appropriate interventions, to be evaluated according to their mitigations potential. In particular, once the SC carbon map of the base-case is obtained, the following steps are undertaken:

- Evaluating interventions targeting hotspots at a wide supply chain level, mainly addressing highly polluting manufacturing and distribution processes for which alternative solutions can be implemented;
- Focusing exclusively on processes located within focal firm facilities, evaluating alternative solutions for relatively high polluting manufacturing and distribution processes;
- Evaluating remaining process and activities throughout the SC for spotting out further opportunities for improvement.

For each scenario, associated SC carbon maps will be developed.

3.6 Implementation

A real world example provides the opportunity to use primary data, gauge the practicality and challenges in implementing the research methodology while providing the context to use theoretical constructs to inform practice (Eisenhardt, 1989, Yin, 2009). In this paper, the SC of a Pre-Stressed Concrete Strand (PSCS) from a UK based world-leading specialist in the manufacturing of high-performance steel wires is discussed to test the practicality of the proposed Decision Support Framework based on a Hybrid LCA paradigm. The identity of the company is concealed to protect its business interests. The company (which has a global presence) manufactures steel ropes for oil and gas exploration, mining and construction sectors. The company is in the process of implementing an integrated environmental management system.

At present, around 80% of the company's customers do not request an environmental audit, however the remaining 20% who do insist on environmental auditing are strategic customers who place large orders and establish long and lucrative relationships. The company utilises millions of kWh of energy per year; therefore as more carbon taxes and enforced reduction targets are introduced by regulations, carbon emissions produced both on a company and individual site level must be assessed so that pathways for carbon reduction can be identified. Due to the nature of the steel manufacturing and its impact on the environment, a number of rules, policies and standards apply to this sector. In fact, the first British Standard was developed for the steel industry (UK Steel, 2012).

Therefore, developing the case example in iron and steel sector is important to understand the implications of carbon emission on business models and in intervention options through the use of decision support frameworks in mapping the carbon emission in the SC. Furthermore, there is growing evidence that in the steel sector, technical limits and cost effective environmentally efficient measures have been reached, leaving little room for further environmental improvement (Cullen and Allwood, 2010). As such, decarbonising efforts (Sundarakani et al., 2010, Sarkis et al., 2011) at the SC level become a critical issue. This is the primary interest of the case company in utilising the proposed Decision Support Framework for assessing its SC and the potential of mitigation interventions. In this study, the SC of 1 tonne of PSCS is analysed to illustrate the proposed methodology.

4. Implementation of the Decision Support Framework

The Decision Support Framework based on the Hybrid LCA methodology presented in Section 3 forms the basis for performing the environmental analysis of the selected SC.

4.1 Supply Chain Environmental Analysis

In this study, the SC of a PSCS, a specialist high performance material manufactured for the construction industry is subjected to environmental analysis by using a Hybrid LCA framework. Reinforcing steel rods (or 'rebar') go through a series of high-intensity processing steps, including batch cleaning, wire-drawing and stranding, to produce the final product made up of six wires wrapped around a 'king' wire. Figure 2 illustrates the process map for producing PSCS.

<< Insert Figure 2 here >>

There are four main forms in which the PSCS final product can take: 'not sheathed/not dyformed', 'sheathed/not dyfomed', 'not sheathed/dyformed', and 'sheathed/ dyformed'. This study will concentrate on the 'not sheathed/not dyformed' product (being the latter the basic version from which more complex products can be obtained through some additional processes). Tables 1 and 2 detail the data used in the process LCA system (collected according to the procedures outlined in section 3.2 and to the specific Data Collection Protocol outlined in Appendix I). This includes, with respect to the production of 1 tonne of PSCS:

- Quantities and unit prices of utilised raw materials;
- Quantities and unit prices of utilised consumables (such as chemicals);
- Quantities and unit prices of utilities (in the form of electricity, gas, diesel, water and air);
- Quantities and unit prices of packaging;
- Quantities of waste generated;
- Location and transportation modes of the different suppliers which provide raw materials and consumables.

With the consultation of the company, necessary raw materials and processes involved in manufacturing 1 tonne of PSCS is estimated. Table 1 presents the amount of inputs used to produce 1 tonne of PSCS at the company. For instance, on average, 1.06 tonnes of steel rod is processed to become 1 tonne of PSCS (before scrap).

The MRIO framework data consisting of the UK and ROW Supply and Use IO tables used to construct the hybridized LCA was sourced from the UK and ROW MRIO table expanded upon by Wiedmann *et al*. (2010). Appendix III reports the detailed breakdown of input-output sectors.

The Ecoinvent (2010) database is used to compile secondary data regarding the carbon dioxide emission equivalent (CO_2-eq/unit) for each unit of inputs and transportation. Table 2 presents this data, illustrating the input, CO_2-eq/unit and Ecoinvent (2012) lifecycle inventory description. Table 3 shows the information regarding the tkm CO_2-eq/unit of ship and lorry transportation used to assess the carbon emissions of raw material and consumable distribution.

<< *Insert Table 1 here* >>

<< *Insert Table 2 here* >>

<< *Insert Table 3 here* >>

Although Ecoinvent (2010) database has amassed an extensive set of lifecycle inventories, exact data for certain inputs intrinsic to the PSCS process was sometimes unavailable. In these cases, a closely related input was substituted to provide emission data as it was decided that slight variations in CO_2-eq/unit could be tolerated as long as substituted values were highlighted. Ensuring that these inputs are included in the environmental assessment enables a more complete picture of the carbon emissions produced by 1 tonne of PSCS and adheres to accepted carbon accounting guidelines (namely the Greenhouse Gas Protocol, 2011). These include $CO_{2\text{-eq}}$ emissions intensity for zinc oxide in place of zinc phosphate; quicklime for lime and reinforcing steel for strap-banding and seal (see Table 2).

Figure 3 presents the SC map for PSCS built using the information provided.

<< *Insert Figure 3 here* >>

An important part of the lifecycle environmental analysis of a product is the evidence that can be gathered by the focal firm and communicated to partners. Carbon emission attributed to 1 tonne of PSCS, broken down into the process LCA and the upstream SC contributions are detailed in Figure 4. Based on the Hybrid LCA calculations, total lifecycle greenhouse gas emissions are estimated to be 2562.62 kg CO_2-eq per tonne of PSCS (not sheathed/not dyformed) produced.

<< *Insert Figure 4 here* >>

The greenhouse gas emissions of the PSCS supply chain (namely steel processing and transportation activities) are represented on the related SC carbon map in Figure 5, using the subjective ranking scale presented in Section 3.4. SC carbon maps highlight the relative carbon emissions for each entities used in the direct and indirect SC of the product.

<< *Insert Figure 5 here* >>

In the PSCS supply chain, direct inputs are calculated to provide 95.5% of the emissions, and indirect emissions were calculated to provide 4.5% of total emissions. It must be noted however that the manufacture of steel rod and road transportation for raw materials and consumables have been included in the carbon map and therefore it could be argued that the emissions produced by these inputs fall outside of the company's direct scope.

From the SC carbon map (and from the numerical values reported in Figure 4), it can be understood that the most significant greenhouse gas emitting 'hotspots' include electricity consumption (11.00%), total transportation (20.20%) and steel rod manufacture (61.00% in total). Others include hydrochloric acid (0.76%), and pressurized air use (0.58%).

It is evident that the top five contributions to the total lifecycle emissions includes not just inputs used directly in the productions system such as steel sourced from Czech Republic and UK suppliers and their associated transportation activities but also upstream SC inputs. The focal firm has a level of control on the main raw materials (such as steel, acid, electricity, transportation, etc) used in the production system; as such, it can use this insight to develop decarbonisation strategies for reducing the overall impact. Further analysis of the transportation activities indicates that the 20.20% contribution to the total lifecycle activities emanates from transport-related activities connected to the movement of steel, namely: Road Transport for Steel Rods from Czech Republic (14.7% of the total emissions), Road Transport for Domestic Steel Rods (3.7%) and Ship Transport related to Overseas Steel Rods (1.8%) (see Figure 6).

<< *Insert Figure 6 here* >>

Regarding the upstream impacts presented in Figure 7, the total contributions were 121.2 kg $CO_{2\text{-eq}}$ per tonne of PSCS or 4.7% of the total emissions. The applicable sectors are as follows: transportation and communication (producing 1.5% of total lifecycle emissions), utilities (producing 1.2% of total lifecycle emissions), mining (producing 0.7% of total lifecycle emissions), fuels and metals (both producing 0.3% of total lifecycle emissions, and equipment, minerals, chemicals, agriculture and business services (each producing 0.1% of total lifecycle emissions).

Although this may seem relatively small compared to process emissions, given the very large production output of the focal firm, the upstream SC emissions cannot be ignored, as GSCM is based on a principle of visibility of the whole SC including upstream inputs and associated impacts.

<< Insert Figure 7 here >>

SC carbon maps presented in this study provide a visualisation technique supporting decision-making. They consists of inputs in the process LCA system directly linked to the production of the final product (these are presented on the main grid of the maps) and the upstream inputs and associated carbon emissions impacts from the wider economy, aggregated in 18 economic segments presented at the bottom of the SC carbon map.

4.2 Scenario Analysis

As the greenhouse gas emitting 'hotspots' of the PSCS supply chain have now been identified, different scenarios are now modelled, which could be implemented to reduce the environmental impacts of the SC. Logical steps outlined in sub-section 3.5 will be followed, focusing first on SC hotspots, then on focal firm specific processes and then identifying opportunities for further improvement.

4.2.1 Increasing domestic sourcing

The main contributors to total lifecycle greenhouse gas emissions as illustrated in the original SC map are inputs related to the production and distribution of steel rod. At present, the case company sources steel rod form two separate suppliers: 30% of supply comes from UK based supplier (which is just under 30 miles away from the company's site) and 70% of supply from a supplier in Czech Republic. In addition to this, the company also source 40% of their wire drawing soap from a supplier in Germany.

Due to the distance and multi-modal transportation, it can be expected that overseas procurement would have a significant effect on the total lifecycle emissions. This scenario will estimate the reduction in total lifecycle emissions that could be achieved through selecting the soap supplier from UK. A 50/50 strategy can also be considered for steel rod procurement where steel rod supplies could be equally distributed between UK and Overseas suppliers. Figure 8 presents this scenario. Hence, Figure 8 is differentiated from Figure 5 (the SC carbon map of the base case) as a result of implementing the decision to reduce overseas sourcing of steel and sourcing soap from the UK. As a result, two differences can be noticed in the SC carbon map in Figure 8. Firstly, as a result of changing the steel procurement from 70/30 percent between overseas and domestic suppliers to 50/50 percent, carbon emissions for domestic road transport for UK steel in Figure 8 increase (hence changes from yellow in Figure 5 to orange in Figure 8). The contribution of sea transport for steel from overseas reduces because percentage importation reduces by 20%; however, the relative hotspot still remains medium (between 1-5% of total emissions). Secondly, because soap is now sourced only from the UK, there is no contribution from road and sea transportation in Figure 8 as originally in the base case carbon map in Figure 5.

<< Insert Figure 8 here >>

In scenario 1, a total lifecycle greenhouse gas emission is estimated to be 2498.69 kg $CO_{2\text{-eq}}$ per tonne of PSCS. This means a saving of 63.93 kg in emissions when compared with the current SC (which has a $CO_{2\text{-eq}}$ of 2562.62kg). Regarding the carbon maps identification of greenhouse gas emitting 'hotspots', it can be clearly seen that, although total lifecycle emissions have been reduced, overseas transportation from the Czech Republic is still one of the most significant producers of emissions contributing 12.1% of total lifecycle emissions.

By re-assigning all steel rod supply to the domestic manufacturer, the case company will be able to collaborate more closely with the group which may be beneficial for both environmental and financial reasons. However, although moving the full supply to UK based supplier would reduce the total emissions produced by transportation even further (as overseas transportation would be abolished from the direct scope of the SC), there are a number of risks presented by adopting a single-supplier strategy. First of all, the single supplier may face capacity shortages. Moreover, a single-sourcing strategy may increase supplier's bargaining power. The focal company, indeed, may become too dependent on the selected supplier, being very exposed to price increases and other measures.

Figure 9 presents the SC carbon map with all overseas input activities removed. This includes the removal of overseas suppliers of steel rod, soap and associated road and sea transportation inputs. In this analysis, it is assumed that all the raw materials are sourced from domestic market. Hence Figure 9 is differentiated from Figure 5 (base case SC carbon map) in that road transportation for UK steel becomes a hotspot (indicated as Red in Figure 9 from it being Medium in Figure 5). However, sourcing exclusively from the UK reduces the total lifecycle emissions.

This is because removing all overseas procurement activities has had a highly tangible effect on the $CO_{2\text{-eq}}$ calculations. This scenario estimates that total lifecycle greenhouse gas emissions are 2339.33 kg $CO_{2\text{-eq}}$ for 1 tonne of PSCS produced. This means a saving of 223.29 kg of emissions from the current SC map (Figure 4). If this scenario is implemented, it means that further efforts should be targeted at decarbonizing domestic road transportation since that has now become a hotspot hence a priority.

For direct impacts, emission 'hotspots' identified by the framework are still related to electricity and steel rod production, while also the domestic transport activities related to steel rod delivery (now accounting for 13.6% of the emissions) are highlighted now.

<< Insert Figure 9 here >>

4.2.2 Alternative processes on site

Most of the carbon hotspots that have been identified and targeted through above-mentioned interventions are outside the direct control of the company, happening at suppliers' plants or being related to logistics activities. For this reason, it may be interesting focusing on processes within the boundaries of the company main site.

This particular scenario involves eliminating inputs related to batch cleaning (namely the removal of consumable data for borax, zinc phosphate, hydrochloric acid and associated data concerning transportation and waste processes). Although this scenario is unlikely to have a high impact on overall emission hotspots (mainly due to the fact that inputs are grouped according to their type rather than the specific process they correspond to), it is particularly important for scenario analysis as the case company have already initialised a £3 million project to close their batch cleaning facility and introduce a mechanical de-scaling system. By implementing this change, the company hopes to reduce gas consumption at main site by around 18-19%, reduce the amount of chemicals used in processing, decrease the output of contaminated water and waste sludge and ultimately close the steam generating plant which is used to maintain high temperatures needed for batch cleaning. The updated SC carbon map illustrating eventualities of removing batch cleaning can be seen in Figure 10. Inputs related to the batch cleaning process were therefore removed; the mechanical descaling process was included in the map, by considering its primary inputs according to Gillström amd Jarl (2006), who found that the descaling of 1 tonne of steel rods requires 7 kWh of electricity.

<< Insert Figure 10 here >>

It can therefore be observed that in Figure 10 consumables such as borax, zinc phosphate, hydrochloric acid used in the batch cleaning are removed compared to Figure 5 (the base case SC carbon map); a new electricity-input used in the descaling process is added. This however was classified as a Low-impact activity, leading to a reduction in total emissions.

Accordingly, total lifecycle greenhouse gas emissions were estimated to be 2535.60 $CO_{2\text{-eq}}$ equivalent for every 1 tonne of PSCS produced. This means an average saving of 27.02 kg $CO_{2\text{-eq}}$ (1.05%) when compared to the current SC carbon map reported in Figure 5 (accounting for 2562.62kg $CO_{2\text{-eq}}$). Although at first glance this value seems relatively insignificant in comparison with overall lifecycle emissions, it must be reinforced that the calculation is estimated for just 1 tonne of product therefore actual emission reductions emanating from this scenario would be significantly higher for overall company activities.

The main benefits of this scenario (apart from decreasing emissions, costs and the threat of legislative action associated with energy consumption) are related to the wider lifecycle and impacts of PSCS. By withdrawing the batch cleaning process, gas emissions from other processing and waste treatment activities will be reduced as the hazardous by-products of acid pickling will be eliminated; less contaminated water will be produced decreasing the quantity of lime and flocculent needed for effluent treatment; further energy reductions will be made from the removal of marginal activities such as the extraction of acid fumes; and costs can be recovered as mechanical descaling produces 'dry' waste' which can be returned to the steel suppliers for recycling. Abolishing the use of chemicals in processing also enhances the safety and general atmosphere of the working environment for employees and adheres to REACH regulations (Health and Safety Executive, 2012) regarding the 'phasing out' of borax use in manufacturing.

The following Table 4 synthesizes emission savings that can be obtained with the above-mentioned scenarios.

<< Insert Table 4 here >>

4.2.3 Discovering further carbon hotspots

In this case, the transportation, electricity and steel rod inputs will be omitted to discover further carbon hotspots that do not fall within the boundary of the case company. The scenario will also assume that batch-cleaning functions have been removed. The resulting SC carbon map in Figure 11 is therefore differentiated from that of the base case in Figure 5 as a result of these omissions and the resulting changes in the relative hotspots of the inputs remaining in the boundary considered. In this scenario, the total lifecycle carbon emissions have been calculated for remaining consumables, namely wiredrawing soap, flocculate and lime (both used for treating waste water); utilities excluding electricity and air (as emissions originate from electricity used to pressurise and transmit the air); packaging, namely newly supplied wooden pallets, steel seals and strap banding; and waste treatment and disposal, including general waste at landfill and the incineration of spent soap. These emissions have been estimated to be 30.8 kg $CO_{2\text{-eq}}$ for 1 tonne of PSCS. Emission hotspots, as shown by both the carbon map and Figure 11, identify that the largest contribution to total lifecycle gas emissions (after excluding transportation, steel production and electricity consumption) originates from water extracted from the company-owned borehole (24%), incineration of soap (30%), and soap supply (21%). Other important inputs that need to be considered include strap banding (6%), gas consumption (6%) and the supply of wooden pallets (5%). Each of these inputs will be now considered, and methods of reducing their associated emissions will be suggested.

<< Insert Figure 11 here >>

- *Reducing water and gas consumption:* The large proportion of total lifecycle gas emissions produced by the company-owned borehole could be considered a surprising result as it is generally assumed that abstracting water direct from underground sources produces a small amount of carbon emissions. Ecoinvent data used, although substituted for the more intensive processing of tap-water, has a very low 0.00031855 kg $CO_{2\text{-eq}}$ per kilogram of water; therefore, it can be understood that emissions emanate from the quantity of water required by to produce 1 tonne of PSCS rather than the gas-emitting intensity of the process itself. This result further cements the need for the water-intensive batch cleaning facility to be phased out as this process requires a large quantity of water for rinsing and producing steam.
- *Soap supply and disposal, wooden pallets and strap banding:* Disposing wire drawing soap is becoming increasingly difficult due to landfilling restrictions. Therefore, the case company could audit potential suppliers' environmental credentials, soap formulation and any services they offer on waste recovery. By doing this, the company could achieve a reduction on their carbon footprint and minimise expenditure on waste treatment. This type of intelligent sourcing, commonly referred

to as green procurement (Emmett and Sood, 2010, McKinnon *et al*., 2012), could also reduce greenhouse emissions and total costs of ownership (taking into account prices for possible rework or returns, delivery costs, lead times, packing, warehousing, inventory holding and obsolescence and administration) for the purchasing of new wooden pallets and packaging systems. This strategy could also be applied to other suppliers to reassess whether there are new products or services being offered which could benefit the company.

5. Discussion

Although a wide range of LCA models are discussed in the literature to assess the carbon-emission across the product life cycle, limited attempt has been made to integrate these models into decision support frameworks to support companies willing to implement cleaner operations. Nevertheless, it is crucial to understand the reasons of this dichotomy between theory and practice, explaining why theoretical models fail to be implemented in the real-world.

In this study, the implementation of a decision support framework in a real-world scenario has allowed the identification of some key issues that may explain this gap. These are discussed in the following.

- *Emission data issues at SC level*: As highlighted by the results of the case study, most of the emission hotspots fall outside the boundaries of the focal company, being related to suppliers' activities. In the process to estimate carbon emission at the SC level, both primary and secondary emissions need to be identified to provide a holistic view of the environmental impact. Therefore, any exercise to evaluate environmental performance of the SC cannot be successful without involving suppliers. Green objectives of the SC should be decided in consultation with the suppliers to effectively operationalize assessment models.
- *Organisational issues*: The structure of the organisation should support the implementation of green practices. Environmental assessment processes would potentially identify emission hot spots in the organisation. However the effective implementation of green practices would depend upon how quickly the organisation can change or improve the carbon intensive processes. The organisation as a whole should take the shared responsibility to implement the sustainability programme that

should be embedded in the culture of the organisation. A shared common ground must be created; when everyone in the organisation understands environmental performance concepts and drivers, they can also assist in improving the performance on sustainability.

- *Green innovation issues*: Even though a number of environmental assessment techniques are available to identify the carbon hot spots, in most cases organisations have limited alternatives to replace carbon intensive processes. Therefore, organisations need to invest in developing green technologies across the product life cycle. In terms of SC, multiples parties can share knowledge and R&D capability to develop green practice from product design to disposal stage. Developing a collaborative approach for green innovation would be helpful to support smaller suppliers in the SC, who may not have enough capital to invest. Focal firm can foster effective development of collaborative green technologies to minimise environmental impact and improve the green performance.

Effective communication, collaboration and commitment are the key factors to improve the SC environmental performance. Also, it becomes apparent that, given the width and breadth of SC and of their environmental footprints, supplier selection is a crucial phase to develop sustainable SC. Often, these decisions are based on multiple selection criteria (Håkansson and Wootz, 1975, Chan and Kumar, 2007, Bruno *et al*., 2012). Along with the traditional criteria, environmental factors should be taken into account (Genovese *et al*., 2013). Implementing the principles of green procurement at the early stage of supplier selection can significantly help to minimise environmental impacts in SC. Also, capability and willingness of each supplier to participate in the environmental performance improvement process should be evaluated.

6. Conclusion and future research

In business practice, environmental issues have historically been tackled in a disconnected way at strategic and operational level thus obscuring opportunities for innovation. GSCM has therefore become an important area for firms to concentrate on reducing environmental impact. In order to integrate these complex and dynamic processes, it is imperative for firms to implement an advanced yet flexible system of management to enable planning and coordination of effective and efficient SC. Modelling methodologies of SC environmental assessment are usually guided by the principles of Life Cycle Assessment (LCA). However, a review of the extant literature suggests that, in its own, LCA techniques suffer from a wide range of limitations; hence, they need to be incorporated within decision support frameworks to aid environmental sustainability strategies.

Thus, this study has provided both theoretical insights and a practical application to inform the process of adopting a decision support framework based on a LCA methodology in real-world scenario. A Hybrid MRIO LCA methodology (capable of ensuring a more comprehensive system boundary in the assessment process) has been integrated within a decision support framework. Through a real-world case study, this paper has shown how a company can evaluate the environmental performance of its SC and identify and assess different interventions to mitigate its impact. Also, the study has tried to shed light on the dichotomy between theory and practice concerning the lack of application of LCA methodologies in decision support methodologies that can be employed by companies in real life, identifying relevant barriers.

Future researches can be oriented at further developing the integration of LCA-based methodologies into decision support frameworks (potentially considering its embedment into operations research, simulation and modelling techniques) and to better understand the cited dichotomy between theory and practice. Specifically, analyses could be focused on investigating barriers, pitfalls and risks related to the use of LCA-based methodologies by non-experts in industrial contexts and on the effect of behavioural and contextual factors on their adoption.

Table 1: Quantity and unit cost of inputs used to produce 1 tonne of PSCS

TYPE	NAME	UNIT*	QUANTITY	UNIT COST
Raw Material	Steel Rod	Kilogram	1057.0000	
	CZ (70% of supply)		739.9000	£0.62
	UK (30% of supply)		317.1000	£0.60
Consumable	Acid	Kilogram	22.9522	£0.08
	Zinc Phosphate	Kilogram	0.0072	£1.27
	Borax	Kilogram	0.6300	£0.59
	Ti Salt	Kilogram	0.3528	£0.27
	Soap	Kilogram	3.7002	
	DE		1.4775	£2.38
	UK		2.2226	£1.43
	Lime	Kilogram	1.5084	£0.17
	Flocculant	Kilogram	0.0014	£4.38
Utility	Water	Kilogram	26391.1140	
	Source: Town's Water		4141.1700	0.001
	Source: Borehole		22249.9440	0.000001**
	Air (detracted from Electricity)	kWh	25.2435	£0.09
	Electricity	kWh	474.6916	£0.09
	Gas	kWh	822.1624	£0.03
	Diesel	Litre	0.1620	£1.39
Packaging	Strapbanding	Kilogram	1.1466	£1.01
	Seals	Kilogram	0.107838	£1.36
	Wooden Pallets (New)	Unit	0.25398	£4.12
Waste Treatment/Disposal	Landfill	Kilogram	41.544	
	General Waste		2.7	£0.03
	Spent Acid		31.032	£0.00
	Ferric Phosphate Sludge		2.214	£0.17
	Borax Sludge		5.598	£0.01
	Incineration	Kilogram		
	Spent Soap		3.114	£0.65

* Unit is determined by the unit denoted by the ecoinvent database
** Unit derived by dividing abstraction license (£1434.97) by total water used in 2011

Table 2: Ecoinvent data providing the CO_2-eq/unit for each input

TYPE	INPUT	UNIT	CO_2-eq/unit	DESCRIPTION (ecoinvent)
Raw Material	Steel Rod			
	CZ (70% of supply)	Kilogram	1.482	Reinforcing steel
	UK (30% of supply)		1.482	Reinforcing steel
Consumable	Acid	Kilogram	0.85292	Hydrochloric acid, 30% in H2O, at plant
	Zinc Phosphate	Kilogram	2.8886	Zinc oxide, at plant
	Borax	Kilogram	1.6475	Borax, anhydrous, powder, at plant
	Ti Salt	Kilogram	4.1315	Titanium dioxide, chloride process, at plant
	Soap			
	DE	Kilogram	1.7105	Soap, at plant
	UK		1.7105	Soap, at plant
	Lime	Kilogram	0.98382	Quicklime, in pieces, loose, at plant
	Flocculant	Kilogram	5.8898	Sodium tripolyphosphate, at plant
Utility	Water			
	Source: Town's Water	Kilogram	0.00031855	Tap water, at user
	Source: Borehole		0.00031855	Tap water, at user
	Air (detracted from Electricity)	kWh	0.59293	Electricity, at grid, high voltage, (GB)
	Electricity	kWh	0.59293	Electricity, at grid, high voltage, (GB)
	Gas	kWh	0.0019927	Natural gas, high pressure, at consumer (GB)
	Diesel	Litre	0.48624	Diesel, at refinery
Packaging	Strapbanding	Kilogram	1.482	Reinforcing steel
	Seals	Kilogram	1.482	Reinforcing steel
	Wooden Pallets (New)	Unit	6.1595	EUR-flat pallet
Waste Treatment/ Disposal	Landfill			
	General Waste		0.0071333	Disposal, inert waste
	Spent Acid	Kilogram	0.1851	Disposal, hazardous waste
	Ferric Phosphate Sludge		0.60391	Disposal, sludge from FeCl3 production
	Borax Sludge		0.32915	Disposal, sludge, NaCl electrolysis
	Incineration			
	Spent Soap	Kilogram	2.8526	Disposal, used mineral oil, 10% water, to hazardous waste incineration

Table 3: Ecoinvent data providing the tkm CO_2-eq/unit for the mode of distribution

TYPE	NAME	TRANSPORTATION	CO2-eq/unit	DESCRIPTION (ecoinvent)
Raw Material	Steel Rod			
	CZ (70% of supply)	Lorry (>32t)	0.1057	Transport, lorry, >32t, EURO4
		Ship	0.046416	Transport, barge
	UK (30% of supply)	Lorry (>32t)	0.1057	Transport, lorry, >32t, EURO4
Consumable	Acid	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Zinc Phosphate	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Borax	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Ti Salt	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Soap			
	DE	Lorry	0.13364	Transport, lorry, >16t, fleet average
		Ship	0.046416	Transport, barge
	UK	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Lime	Lorry	0.13364	Transport, lorry, >16t, fleet average
	Flocculant	Lorry	0.13364	Transport, lorry, >16t, fleet average

Table 4: Scenario Analysis Summary

Intervention	Type	Mitigation Potential	Δ%
Reducing Overseas Procurement	Green Procurement	63.93 $kgCO_{2-eq}$ /tonne	-2.49%
Eliminating Overseas Procurement	Green Procurement	223.29 $kgCO_{2-eq}$ /tonne	-8.71%
Removing Batch Cleaning Facility	Process Innovation	27.02 $kgCO_{2-eq}$ /tonne	-1.05%

List of Figures

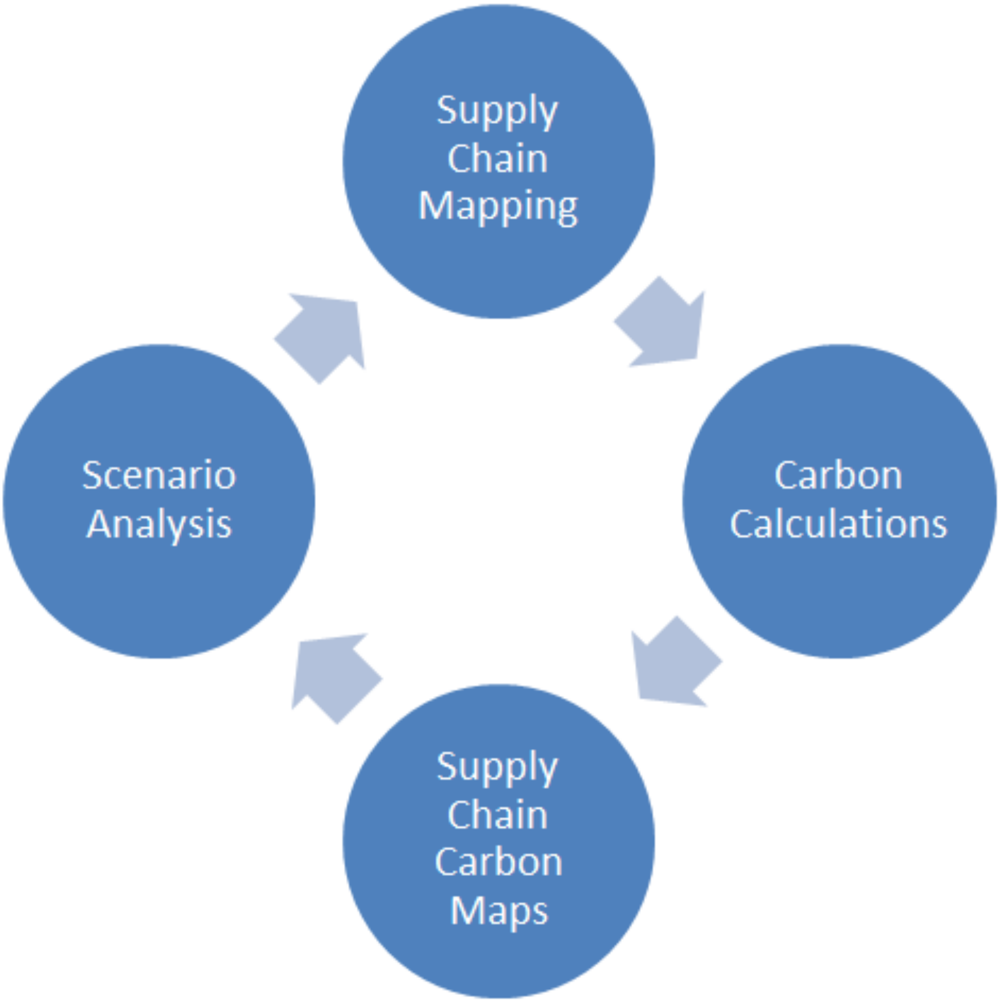

Figure 1: Methodological Framework

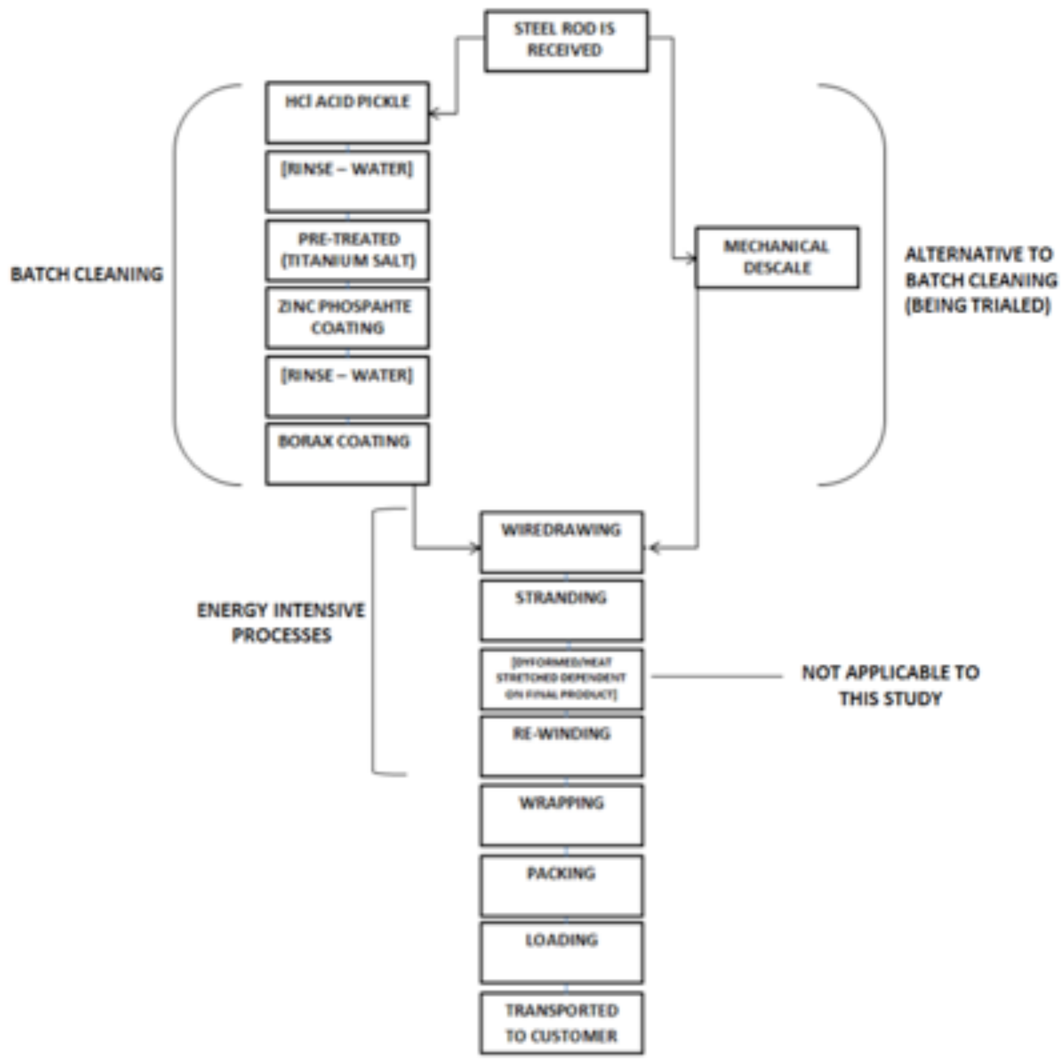

Figure 2: Process map for Pre-Stressed Concrete Strand production

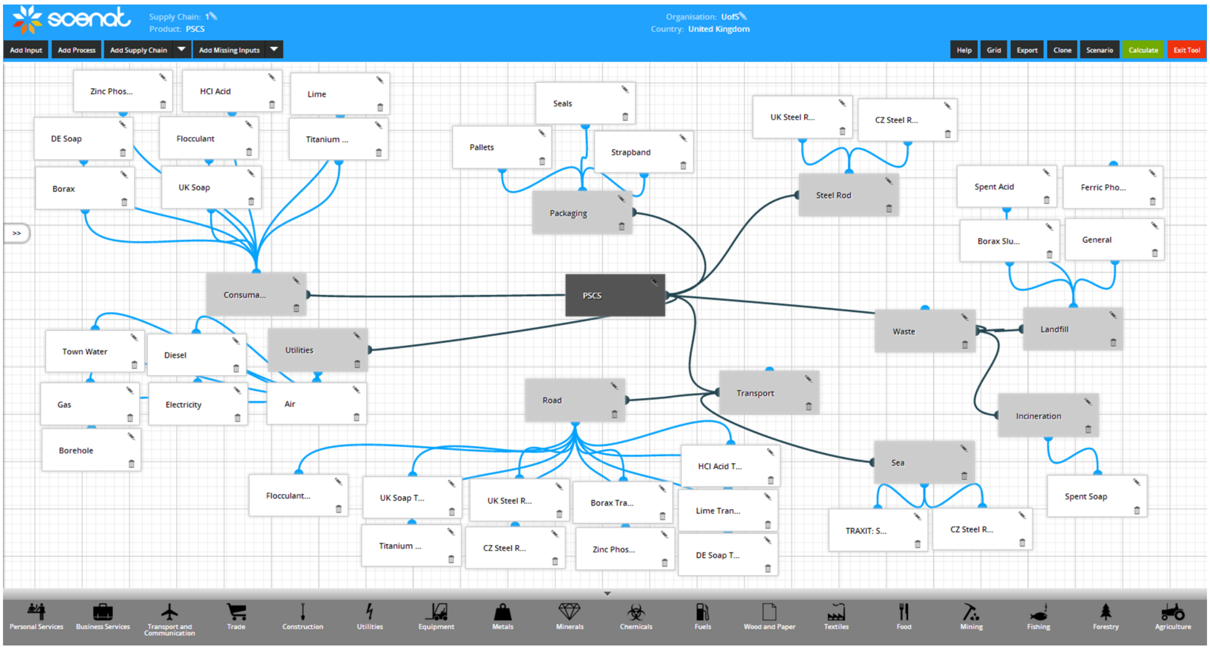

Figure 3: The Pre-Stressed Concrete Strand supply chain map

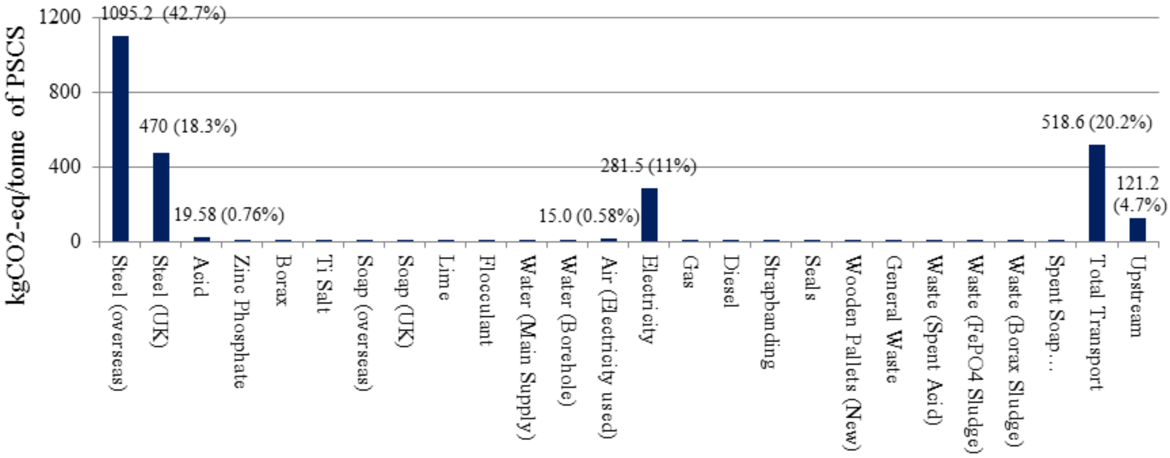

Figure 4: The Pre-Stressed Concrete Strand lifecycle emissions

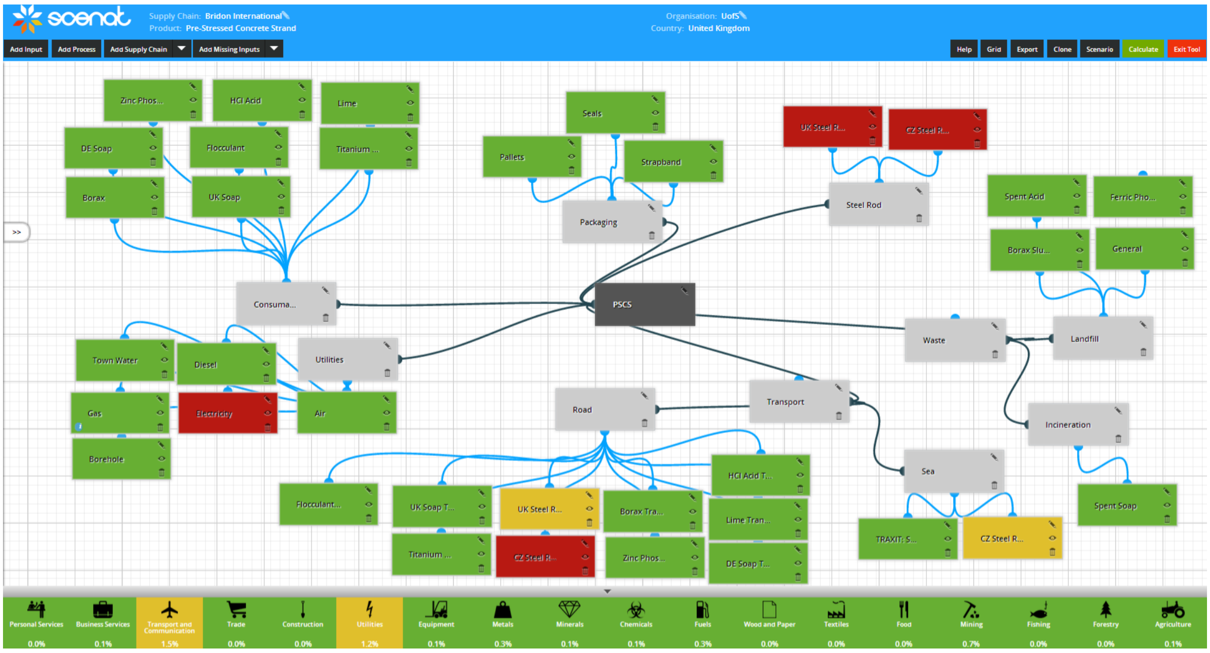

Figure 5: Upstream and Process Carbon emissions breakdown

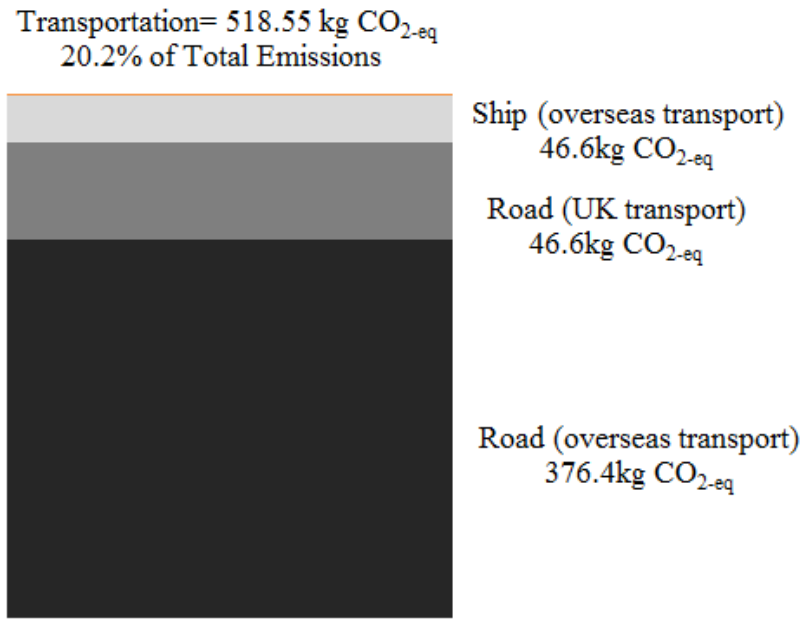

Figure 6: Transport-related Carbon emissions breakdown

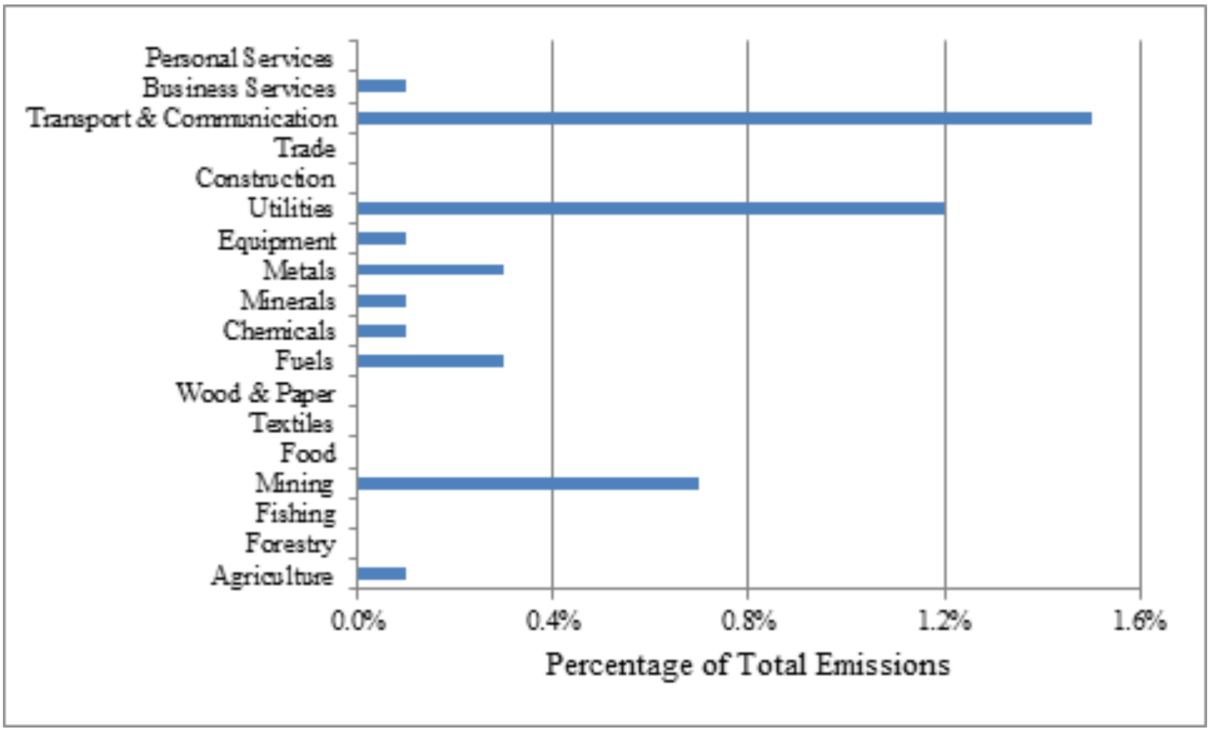

Figure 7: Upstream Carbon emissions breakdown by macro-economic sector

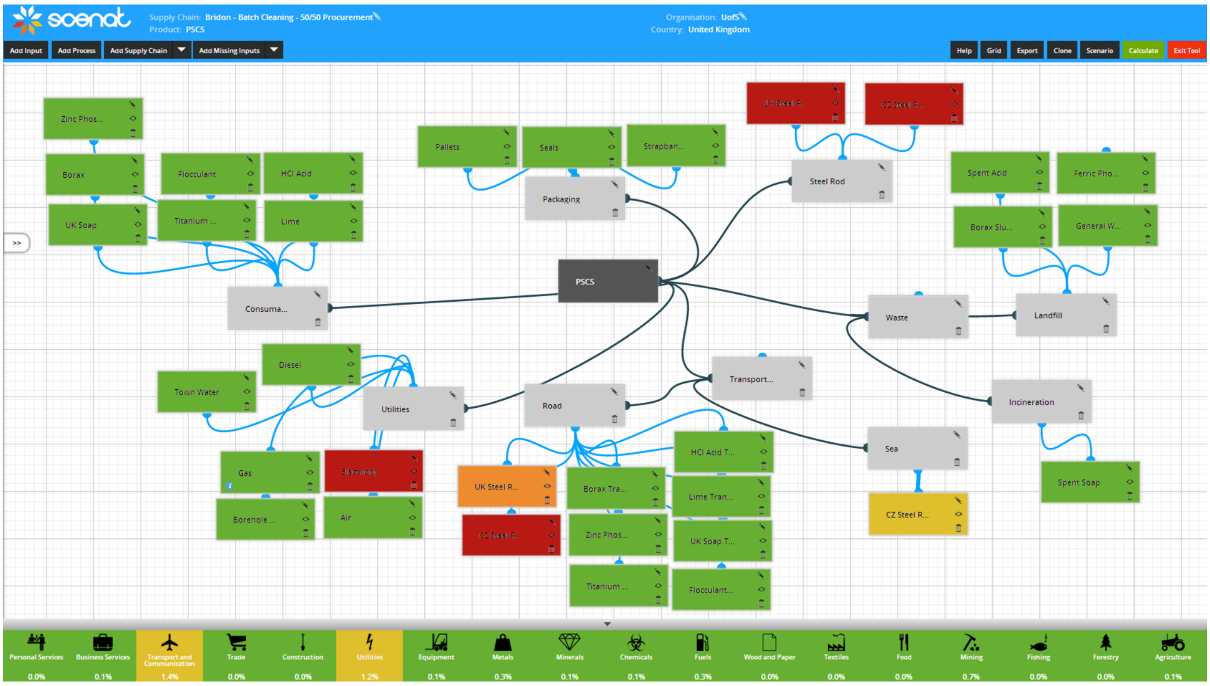

Figure 8: Scenario analysis carbon map: Reducing overseas procurement

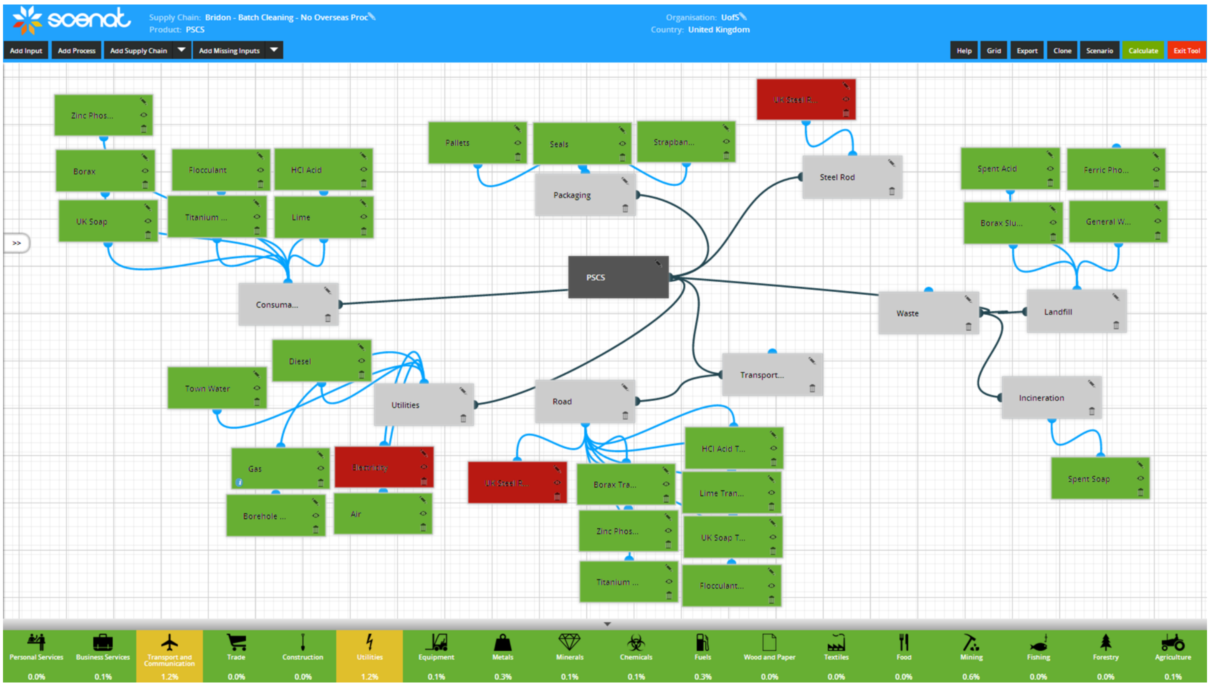

Figure 9: Scenario analysis carbon map: Removing overseas procurement

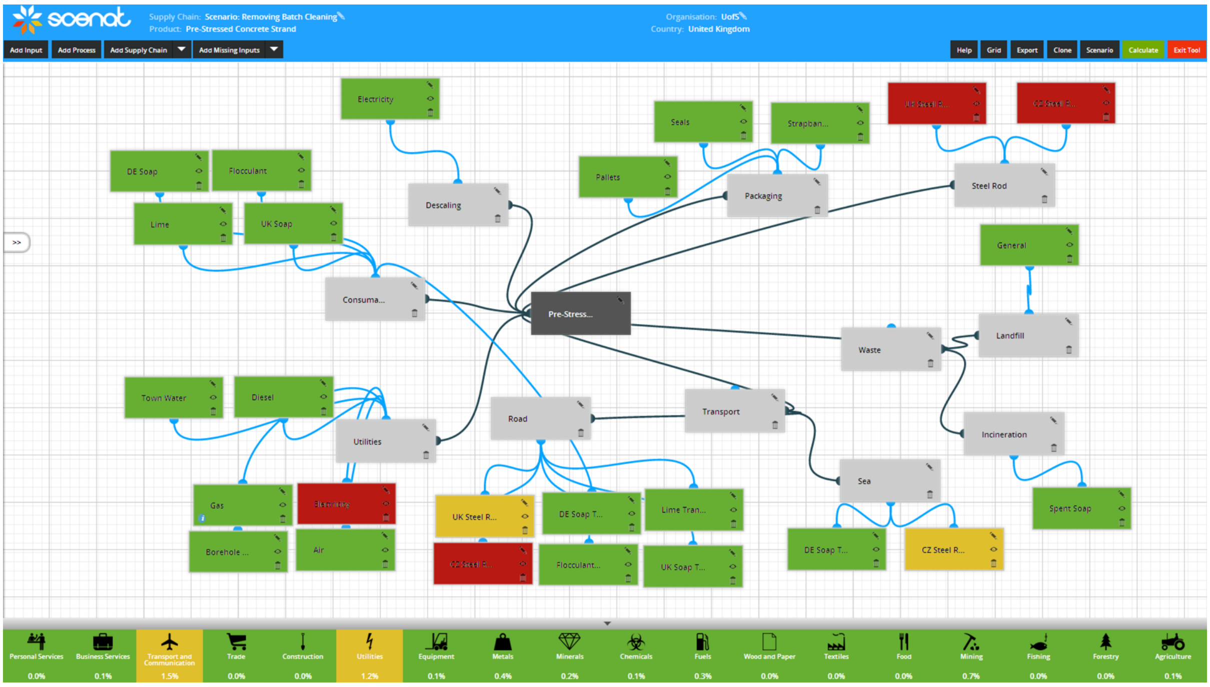

Figure 10: Scenario analysis – Replacing batch cleaning with mechanical descaling

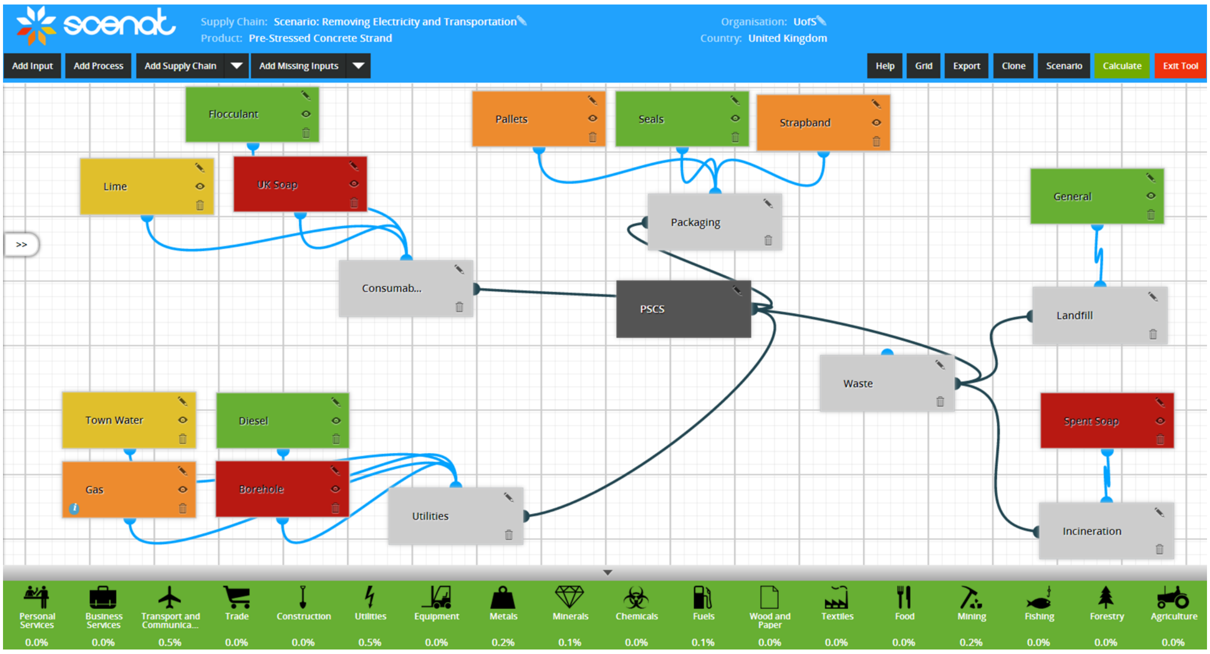

Figure 11: Scenario analysis – Identifying further hotspots

Appendix I: Data Collection Protocol

PLEASE NOTE: Save file after filling in the form.

Enter Date
dd- mm- yyyy

[1a] **Information and Data Transfer: Pre-Stressed Concrete Strand**

Information in the form of reports/diagrams/flow charts/company literature on detailed description of production process and supply chain of Pre-Stressed Concrete Strand has been arranged — Please Choose

[1b] Specify Functional Unit to be used (All data supplied should be scaled to the functional Unit) — 1 | tonne

[1c] What are your the roles in the Pre-Stressed Concrete Strand supply chain? — Please Describe:

[2] **Energy Usage (NB: Scaled to 1 tonne of Pre-Stressed Concrete Strand)**

Please list all the total energy used (example, electricity, gas, etc) per year used and their quantities and units

ENERGY	QUANTITY	Units
Electricity		
Gas		
Petrol		
Diesel		

(Add more if required)

Total Output and Allocation

[3a] What is the total ourput per year of Pre-Stressed Concrete Strand production — ____ Tonnes

[3b] What percentage of total energy usage can be allocated to Pre-Stressed Concrete Strand (through production or transportation)

Energy	Allocation [%]
Electricity	
Gas	
Petrol	
Diesel	

[4] **Inputs into Pre-Stressed Concrete Strand production process: Please NOTE-The Reference is to 1 tonne production of Pre-Stressed Concrete Strand**

Please list ALL inputs, Quantity Used, Units and Unit Cost that goes into the production of 1tonne of Pre-Stressed Concrete Strand

Input Material	Quantity Used	Unit	Approximate/Average Unit Cost [£/Unit]	Origin of Input Material	Transportation Mode

[5] **Transportation**

What is the average distance (km) travelled for delivery of final product to customer

[6] **Waste Management**

Outline waste management sevices implemented in the production process

[7] **Any Other Information**

Please detail any other relevant information

Appendix II: Process LCA system A_p for the production of 1 tonne of pre-stressed concrete strand

		Steel (Moravia)	Steel (Tata)	Acid	Zinc Phosphate	Borax	Ti Salt	Soap (Traxit-Germany)	Soap (Condat-Doncaster, UK)	Lime	Flocculant	Water (Main Supply)	Water (Borehole)	Air (detracted from Electricity)	Electricity	Gas	Diesel	Strapbandi ng	Seals	Wooden Pallets (New)	General Waste	Waste (Spent Acid)	Waste (Ferric Phosphate Sludge)	Waste (Borax Sludge)	Spent Soap (Incinerati on)	Road Tx (Moravia Steel)	Ship (Moravia Steel)	Road Tx (Tata Steel)	Road Tx Acid	Road Tx Zinc Phosphate	Road Tx Borax	Road Tx Ti Salt	Road Tx: Soap (Traxit-Germany)	Ship Tx: Soap (Traxit-Germany)	Road Tx: Soap (Doncaster , UK)	Road Tx Lime	Road Tx Flocculant	Pre-Stressed Concrete Strand
Raw Materials Inputs	Steel (Moravia)	739	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-739
	Steel (Tata)	0	317.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-317.1
	Acid	0	0	22.9522	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-22.9522
	Zinc Phosphate	0	0	0	0.0072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.0072
	Borax	0	0	0	0	0.63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.63
	Ti Salt	0	0	0	0	0	0.3528	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.3528
	Soap (Traxit-Germany)	0	0	0	0	0	0	1.4775	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4775
	Soap (Condat-Doncaster, UK)	0	0	0	0	0	0	0	2.2226	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.2226
	Lime	0	0	0	0	0	0	0	0	1.5084	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5084
	Flocculant	0	0	0	0	0	0	0	0	0	0.0014	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.0014
	Water (Main Supply)	0	0	0	0	0	0	0	0	0	0	4141.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4141.17
	Water (Borehole)	0	0	0	0	0	0	0	0	0	0	0	22249.944	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-22249.944
	Air (detracted from Electricity)	0	0	0	0	0	0	0	0	0	0	0	0	25.2435	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-25.2435
	Electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	474.6916	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-474.6916
	Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	822.1624	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-822.1624
	Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.162
	Strapbanding	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1466	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.1466
	Seals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.107838	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.107838
	Wooden Pallets (New)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25398	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.25398
	General Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7
	Waste (Spent Acid)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31.032	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-31.032
	Waste (Ferric Phosphate Sludge)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.214	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.214
	Waste (Borax Sludge)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.598	0	0	0	0	0	0	0	0	0	0	0	0	0	-5.598
	Spent Soap (Incineration)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.114	0	0	0	0	0	0	0	0	0	0	0	0	-3.114
Transportation Activities Input	Road Tx (Moravia Steel)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3560.7688	0	0	0	0	0	0	0	0	0	0	0	-3560.7688
	Ship (Moravia Steel)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1004.15	0	0	0	0	0	0	0	0	0	0	-1004.15
	Road Tx (Tata Steel)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	902.5459	0	0	0	0	0	0	0	0	0	-902.5459
	Road Tx Acid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1495	0	0	0	0	0	0	0	0	-0.1495
	Road Tx Zinc Phosphate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0023	0	0	0	0	0	0	0	-0.0023
	Road Tx Borax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0053	0	0	0	0	0	0	-0.0053
	Road Tx Ti Salt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0173	0	0	0	0	0	-0.0173
	Road Tx: Soap (Traxit-Germany)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9086	0	0	0	0	-0.9086
	Ship Tx: Soap (Traxit-Germany)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3838	0	0	0	-0.3838
	Road Tx: Soap (Doncaster, UK)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0249	0	0	-0.0249
	Road Tx Lime	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0146	0	-0.0146
	Road Tx Flocculant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0066	-0.0066
Final Product	Pre-Stressed Concrete Strand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Appendix III: Economic Classifications of the UK and Rest of the World Sectors used in MRIO

1	Growing of cereals and other crops n.e.c. (except whe	76	Footwear	151	Electricity production - coal
2	Organic: Growing of cereals and other crops n.e.c. (ex	77	Wood and wood products, except furniture	152	Electricity production - gas
3	Growing of wheat	78	Pulp	153	Electricity production - oil
4	Organic: Growing of wheat	79	Paper and paperboard	154	Electricity production - nuclear
5	Growing of oil seeds	80	Articles of paper and paperboard (except paper statio	155	Electricity by hydro power (inland)
6	Growing of rice	81	Paper stationary	156	Electricity by wind power
7	Growing of sugar beet and sugar cane	82	Paper-based publishing, printing and reproduction	157	Electricity by biomass
8	Growing of fibre crops	83	Non paper-based publishing and reproduction of reco	158	Electricity by geothermal, solar, tidal or wave power
9	Growing of crops and plants for biofuels	84	Coke oven products	159	Electricity by waste incineration
10	Growing of crops nec	85	Motor spirit (gasoline)	160	Transmission of electricity
11	Conventional Growing of vegetables, fruits and other	86	Kerosene, including kerosene type jet fuel	161	Distribution and trade in electricity
12	Organic Growing of vegetables, fruits and other crops	87	Gas oils	162	Gas distribution
13	Growing of horticulture specialities and nursery prod	88	Fuel oils n.e.c.	163	Steam and hot water supply
14	Raising of diary cattle and production of raw cow mill	89	Petroleum gases and other gaseous hydrocarbons, ex	164	Collection, purification and distribution of water
15	Organic: Raising of diary cattle and production of raw	90	Other petroleum products	165	Construction (other than commercial and domestic buildings
16	Farming of cattle for meat	91	Processing of nuclear fuel	166	Construction of commercial buildings
17	Organic: Farming of cattle for meat	92	Industrial gases	167	Construction of domestic buildings
18	Raising of horses, equines and other animals; animal	93	Dyes and pigments	168	Sale, maintenance and repair of motor vehicles, and motor cy
19	Raising of sheep and goats; Production of raw wool,	94	Inorganic basic chemicals	169	Retail sale of automotive fuel
20	Organic: Raising of sheep and goats; Production of ra	95	Organic basic chemicals	170	Wholesale trade and commission trade, except of motor veh
21	Farming of swine	96	Fertilisers and nitrogen compounds	171	Retail trade, except of motor vehicles and motor cycles
22	Organic: Farming of swine	97	Plastics and synthetic rubber in primary forms	172	Repair of personal and household goods
23	Farming of poultry	98	Pesticides and other agro-chemical products	173	Hotels and accomodation
24	Organic: Farming of poultry	99	Paints, varnishes and similar coatings, printing ink an	174	Restaurants, cafes, bars etc.
25	Other farming of animals	100	Pharmaceuticals, medicinal chemicals and botanical p	175	Passenger transport by railways
26	Growing of crops combined with farming of animals (	101	Soap and detergents, cleaning and polishing preparat	176	Freight transport by inter-urban railways
27	Agricultural service activities; landscape gardening (	102	Other chemical products	177	Inter-city coach sevice
28	Animal husbandry service activities, except veterinar	103	Man-made fibres	178	Urban and suburban passenger railway transportion by und
29	Forestry, logging and related service activities (conve	104	Rubber products	179	Other scheduled passenger land transport n.e.c.
30	Forestry, logging and related service activities ('susta	105	Plastic plates, sheets, tubes and profiles, builders' wa	180	Taxi operation
31	Fishing	106	Plastic packing goods	181	Other passenger land transport
32	Fish farming (non-organic)	107	Glass and glass products	182	Freight transport by road
33	Fish farming (organic/sustainable)	108	Ceramic goods	183	Transport via pipeline
34	Mining of coal and lignite; extraction of peat	109	Bricks, tiles and other structural clay products for co	184	Sea and coastal water transportation services
35	Oil: Crude petroleum and services related to crude oil	110	Manufacture of cement	185	Inland water transportation services
36	Gas: Natural gas and services related to natural gas e	111	Manufacture of lime	186	Passenger air transport
37	Mining of uranium and thorium ores	112	Manufacture of plaster	187	Freight and other air transport
38	Mining of iron ores	113	Articles of concrete, plaster and cement; cutting, sha	188	Supporting and auxiliary transport activities: travel agencies
39	Mining of non-ferrous metal ores and concentrates	114	Basic iron and steel and of ferro-alloys; manufacture	189	Postal and courier services
40	Stone	115	Precious metals production	190	Telecommunications
41	Sand and clay	116	Aluminium production	191	Banking and financial intermediation, except insurance and p
42	Chemical and fertilizer minerals, salt and other mining	117	Lead, zinc and tin production	192	Insurance and pension funding, except compulsory social se
43	Processing and preserving of meat from cattle (beef)	118	Copper production	193	Auxiliary financial services
44	Organic: Processing and preserving of meat from catt	119	Other non-ferrous metal production	194	Real estate activities with own property; letting of own prop
45	Processing and preserving of meat from pigs	120	Casting of metals	195	Letting of dwellings, including imputed rent
46	Organic: Processing and preserving of meat from pigs	121	Structural metal products	196	Real estate agencies or activities on a fee or contract basis
47	Conventional poultry meat and poultry meat products	122	Tanks, reservoirs and containers of metal; manufactu	197	Renting of cars and other transport equipment
48	Organic poultry meat and poultry meat products	123	Forging, pressing, stamping and roll forming of metal	198	Renting of machinery and equipment, excl. office machinery
49	Meat products nec	124	Cutlery, tools and general hardware	199	Renting of office machinery and equipment including compu
50	Organic: Meat products nec	125	Other fabricated metal products	200	Renting of personal and household goods
51	Fish and fish products	126	Machinery for the production and use of mechanical	201	Computer services and related activities
52	Conventional Fruit and vegetables	127	Other general purpose machinery	202	Research and development
53	Organic Fruit and vegetables	128	Agricultural and forestry machinery	203	Legal activities
54	Vegetable and animal oils and fats	129	Machine tools	204	Accounting, book-keeping and auditing activities; tax consu
55	Dairy products (conventional)	130	Other special purpose machinery	205	Business and management consultancy activities; managem
56	Organic dairy products	131	Weapons and ammunition	206	Technical consultancy; technical testing and analysis; archi
57	Grain mill products, starches and starch products	132	Domestic appliances (e.g. white goods)	207	Advertising
58	Prepared animal feeds	133	Computers and other office machinery and equipment	208	Other business services
59	Bread, rusks and biscuits; manufacture of pastry goo	134	Electric motors, generators and transformers; manufa	209	Public administration (not defence); compulsory social secu
60	Organic bread, rusks and biscuits; manufacture of pa	135	Insulated wire and cable	210	Public administration - defence
61	Sugar	136	Electrical equipment not elsewhere classified	211	Primary, secondary and other education
62	Cocoa, chocolate and sugar confectionery	137	Electronic valves and tubes and other electronic com	212	Higher-level education
63	Other food products	138	Television and radio transmitters and line for telepho	213	Human health and veterinary activities
64	Alcoholic beverages	139	Television and radio receivers, sound or video record	214	Social work activities
65	Production of mineral waters and soft drinks	140	Medical, precision and optical instruments, watches a	215	Collection and treatment of sewage and liquid waste
66	Tobacco products	141	Motor vehicles, trailers and semi-trailers	216	Collection of waste
67	Preparation and spinning of textile fibres	142	Building and repairing of ships and boats	217	Incineration of waste
68	Textile weaving	143	Railway transport equipment, motorcycles, bicycles a	218	Landfill of waste
69	Finishing of textiles	144	Aircraft and spacecraft	219	Sanitation, remediation and similar activities
70	Made-up textile articles, except apparel	145	Furniture	220	Activities of membership organisations
71	Carpets and rugs	146	Jewellery and related articles; manufacture of musical	221	Recreational and cultural activities
72	Other textiles	147	Sports goods, games and toys	222	Sporting and other activities
73	Knitted and crocheted fabrics and articles	148	Miscellaneous manufacturing not elsewhere classifie	223	Dry cleaning, hair dressing, funeral parlours and other servic
74	Wearing apparel; dressing and dying of fur	149	Recycling of metal waste and scrap	224	Private households as employers of domestic staff
75	Tanning and dressing of leather; manufacture of lugg	150	Recycling of non-metal waste		

Appendix IV: Aggregation of 224 Sectors into 18 Economic Segments

Sectors No.	18 Aggregated Economic Segments
1-28	Agriculture
29-30	Forestry
31-33	Fishing
34-42	Mining
43-66	Food
67-76	Textiles
77-83	Wood & paper
84-91	Fuels
92-102	Chemicals
103-113	Minerals
114-121	Metals
122-150	Equipment
151-164	Utilities
165-167	Construction
168-174	Trade
175-190	Transport & communication
191-223	Business services
224	Personal services

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