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International Journal of Production Research, 2014
http://dx.doi.org/10.1080/00207543.2014.951092

An application of hybrid life cycle assessment as a decision support framework for green supply chains

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(*Received 14 October 2013; accepted 27 July 2014*)

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; life cycle 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, Seuring, and Beske 2010; Bai and Sarkis 2014; Gunasekaran and Irani 2014). Sustainability-related constructs have thus emerged in the broad literature of SCM (Seuring and Müller 2008; Linton, Klassen, and Jayaraman 2007).

Sarkis (2003) and Srivastava (2007) describe the framework of green supply chain management (GSCM) from a product life cycle and operational perspective. Often, these two perspectives within GSCM are mutually exclusive as there is a lack of integration between product life cycle 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, Heiser, and Cook 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 prioritise 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 life cycle assessment (LCA) (Acquaye et al. 2014). However, a review of extant literature suggests that (see, for AQ2 instance, Wang, Chan, and White 2014), 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

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AQ3 the opportunity to use SC knowledge and information on product life cycle 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, Cozzi, and Perona 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, Lenny Koh, Bruno, et al. 2013. AQ4

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 hybridised 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 *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 life cycle perspective. Sarkis (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 decarbonise supply chains. AQ5

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, Singhal, and Wassenhove 2005; Gimenez, Sierra, and Rodon 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 (Reich-Weiser and Dornfeld 2009; Sinden 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 (IO) LCA into a hybridised 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, Brent, and Van Erck 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 IO LCA) together in order to overcome the truncated system boundary problems in process LCA and the lack of specificity and accuracy in environmental IO LCA (Crawford 2008; Acquaye, Duffy, and Basu 2011).

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, Chan, and White (2014) 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 (Heijungs et al. 2006; Bani et al. 2009), methodological challenges (Guinee et al. 2010), complexity of SC systems (Suh et al. 2004; Deng, Babbitt, and Williams 2011) 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, emphasising 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 means 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*

AQ6 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.

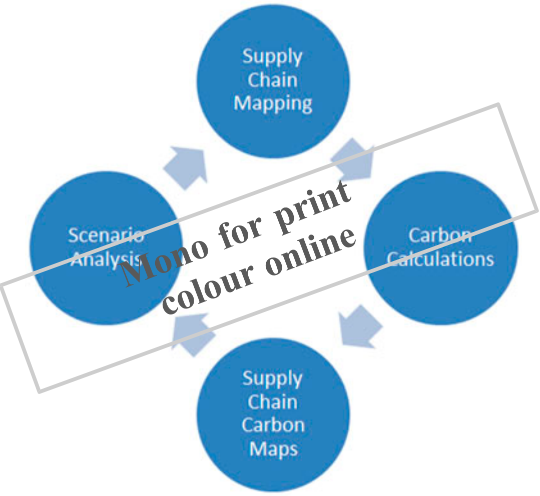


Figure 1. Methodological framework.

- *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.

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) life cycle 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 IO tables used to construct the hybridised LCA was sourced from the UK and ROW MRIO table expanded upon by Wiedmann et al. (2010). Appendix 3 provides the detailed breakdown of IO 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, forms 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 two-region UK-ROW MRIO framework. A generalised hybrid LCA (Rowley, Lundie, and Peters 2009) consists of a process LCA (Sinden 2009) and IO-based LCA (Su, Ang, and Low 2013) integrated together into one consistent framework.

The hybridised 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 hybridised framework (specifically, as a two-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, Benders, and Moll2006; Rueda-Cantuche and Ten Raa 2007). As reported by Eurostat (2008), the advantages of Supply and Use IO 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.

A_p being the matrix representation of the production system characterised using process LCA approach, 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,

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

For n different types of SC inputs into the process production system, A_p would be of dimension $(n+1) \times (n+1)$; 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 2 is integrated into the IO framework specifically characterised below as a two-region (UK-ROW) MRIO framework using the Supply and Use format.

3.3.2 *IO framework*

An 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 IO analysis is extensively described in literature (Suh 2009; Acquaye et al. 2011; 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 the 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:

AQ7

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

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 and services) required to produce a unit output. In IO 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 and 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, Pakarinen, and Sokka 2010; Wiedmann et al. 2011). As a result, the whole life cycle 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. *MRIO framework.* In this paper, the generalised IO approach presented in Section 3.3.2 is extended to a MRIO framework to specifically characterise 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 two-region (UK and ROW) model shown below.

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

where A_{io} becomes the two-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 × 224; hence, A_{io} is, therefore, of dimension 896 × 896. Refer to Appendix 3 for the detailed breakdown.

The technical coefficient matrix for UK Imports from ROW, $A_{(UK)IMP}$, for example, is defined as:

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

where $q_{ij}^{(ROW,UK)}$ represents elements of UK imports IO 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 hybridised 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 IO LCA can therefore be defined in a generalised form as:

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

However, in a generalised hybrid LCA, the pure IO 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. (2011) and Wiedmann et al. (2011).

$$\text{Total CO}_{2\text{-eq}}\text{ emissions} = \begin{bmatrix} \widehat{E}_p & 0 \\ 0 & \widehat{E}_{io} \end{bmatrix} \begin{bmatrix} A_p & -D \\ -U & (I - A_{io}) \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix} \tag{6}$$

where the total carbon emissions consist 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, $\widehat{E}_{\text{io}}$ is also presented in the Supply and Use format. $\widehat{E}_{io}$ which has unit (kg CO_2-eq/£) is a diagonalised $CO_{2\text{-eq}}$ intensity vector of UK-ROW industries.

$$\widehat{E}_{io} = \begin{bmatrix} \widehat{E}_{UK} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \widehat{E}_{ROW} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

$\widehat{E}_p$ (kg CO_2-eq/unit) denotes the diagonalised $CO_{2\text{-eq}}$ intensity vector of processes in the initial process production system A_p. $\widehat{E}_p$, 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, $E_p = [\widehat{e}_n]$; 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 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. 2011).

y is the functional unit denoting the output of the initial process system. Within the hybridised framework, the functional unit is linked to the initial process production system A_p already described in Section F has a dimension of $(n+1) \times (n+1)$; 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 2 for the process production matrix A_p, the $CO_{2\text{-eq}}$ intensity vector of processes in the initial process production system $\widehat{E}_\mathrm{p}$ 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 IO tables into a two-region MRIO framework, the hybrid LCA can overcome the complexity of product SC as a result of the globalised 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 requirements 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 3, and, for ease of presentation, aggregated across 18 economic segments as shown in the Concordance Table presented in Appendix 4.

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 life cycle emissions); High (Orange, 5–10%); Medium (Yellow, 1–5%); Low (Green, Less than 1%). The SC carbon maps reaffirm the fact that inputs having significant emissions impact 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, 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 prioritised in terms of de-carbonisation 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, Zhu, and Lai 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

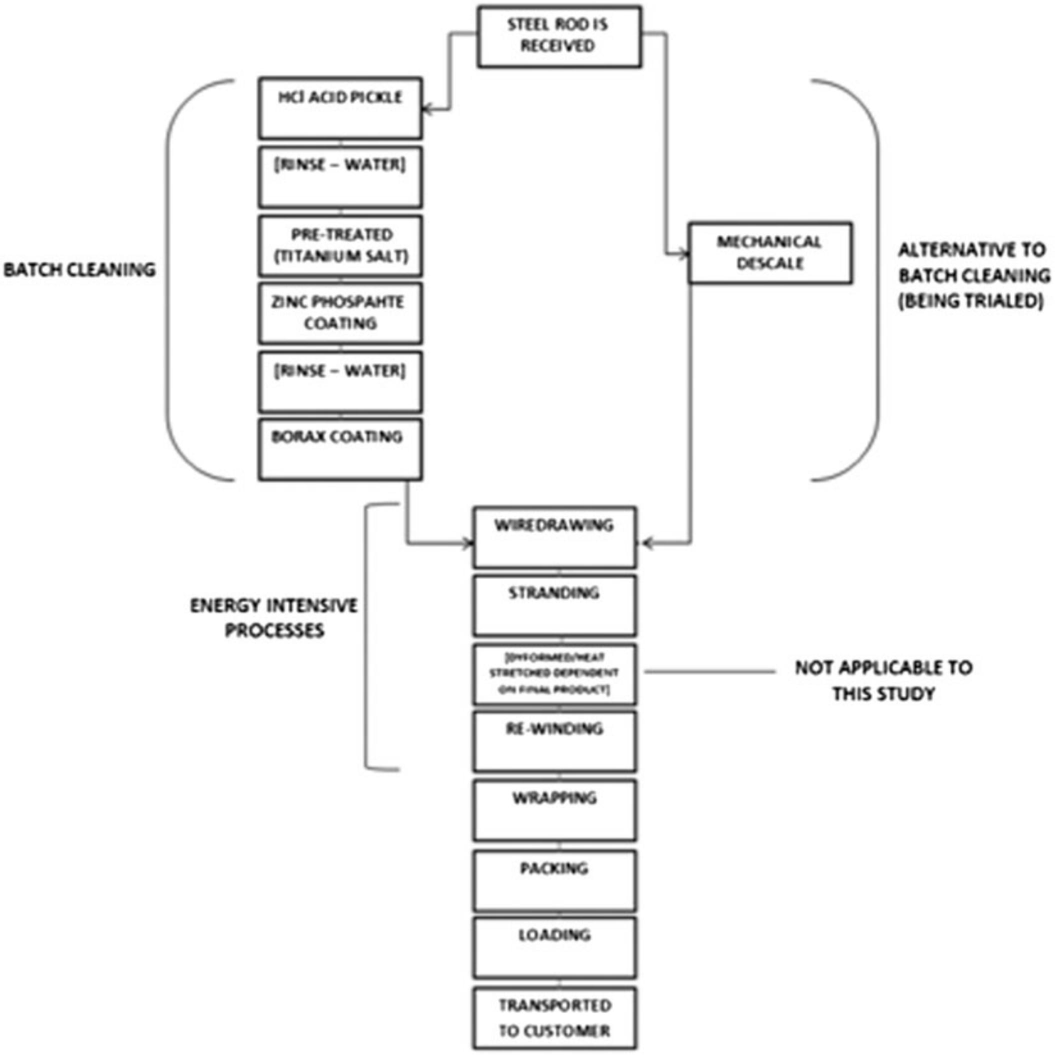
The decision support framework, based on the hybrid LCA methodology presented in Section 3, forms the basis for performing the environmental analysis of the selected SC.

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 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.

There are four main forms which the PSCS final product can take: 'not sheathed/not dyformed', 'sheathed/not dyformed', '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 1). 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.



AQ27 Figure 2. Process map for PSCS production.

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 hybridised LCA was sourced from the UK and ROW MRIO table expanded upon by Wiedmann et al. (2010). Appendix 3 reports the detailed breakdown of IO 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 AQ9 and Ecoinvent (2012) life cycle 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.

Although Ecoinvent (2010) database has amassed an extensive set of life cycle 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 AQ10 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).

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

Type	Name	Unit[a]	Quantity	Unit cost
Raw material	Steel rod	Kilogramme	1057.0000	
	CZ		739.9000	£0.62
	UK		317.1000	£0.60
Consumable	Acid	Kilogramme	22.9522	£0.08
	Zinc phosphate		0.0072	£1.27
	Borax		0.6300	£0.59
	Ti salt		0.3528	£0.27
	Soap		3.7002	
	DE		1.4775	£2.38
	UK		2.2226	£1.43
	Lime		1.5084	£0.17
	Flocculant		0.0014	£4.38
Utility	Water	Kilogramme	26391.1140	
	Source: Town's water		4141.1700	£0.001
	Source: Borehole		22249.9440	£0.000001[b]
	Air (detracted from electricity)	kWh	25.2435	£0.09
	Electricity		474.6916	£0.09
	Gas		822.1624	£0.03
	Diesel	Litre	0.1620	£1.39
Packaging	Strap banding	Kilogramme	1.1466	£1.01
	Seals		0.107838	£1.36
	Wooden pallets (New)	Unit	0.25398	£4.12
Waste treatment/disposal	Landfill	Kilogramme	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	Kilogramme		
	Spent soap		3.114	£0.65

[a] Unit is determined by the unit in the ecoinvent database.
[b] Unit derived by dividing abstraction licence (£1434.97) by total water used in 2011.

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

An important part of the life cycle 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 life cycle greenhouse gas emissions are estimated to be 2562.62 kg CO_2-eq per tonne of PSCS (not sheathed/not dyformed) produced.

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.

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 pressurised air use (0.58%).

It is evident that the top five contributions to the total life cycle emissions include 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,

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	Kilogramme		
	CZ		1.482	Reinforcing steel
	UK		1.482	Reinforcing steel
Consumable	Acid	Kilogramme	0.85292	Hydrochloric acid, 30% in H$_2$O, at plant
	Zinc phosphate		2.8886	Zinc oxide, at plant
	Borax		1.6475	Borax, anhydrous, powder, at plant
	Ti Salt		4.1315	Titanium dioxide, chloride process, at plant
	Soap			
	DE		1.7105	Soap, at plant
	UK		1.7105	Soap, at plant
	Lime		0.98382	Quicklime, in pieces, loose, at plant
	Flocculant		5.8898	Sodium tripolyphosphate, at plant
Utility	Water	Kilogramme		
	Source: Town's water		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		0.59293	Electricity, at grid, high voltage, (GB)
	Gas		0.0019927	Natural gas, high pressure, at consumer (GB)
	Diesel	Litre	0.48624	Diesel, at refinery
Packaging	Strap banding	Kilogramme	1.482	Reinforcing steel
	Seals		1.482	Reinforcing steel
	Wooden pallets (New)	Unit	6.1595	EUR-flat pallet
Waste treatment/ disposal	Landfill	Kilogramme		
	General waste		0.0071333	Disposal, inert waste
	Spent acid		0.1851	Disposal, hazardous waste
	Ferric phosphate sludge		0.60391	Disposal, sludge from FeCl$_3$ production
	Borax sludge		0.32915	Disposal, sludge, NaCl electrolysis
	Incineration	Kilogramme		
	Spent soap		2.8526	Disposal, used mineral oil, 10% water, to hazardous waste incineration

acid, electricity and transportation) 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 life cycle 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).

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 life cycle emissions), utilities (producing 1.2% of total life cycle emissions), mining (producing 0.7% of total life cycle emissions), fuels and metals (both producing 0.3% of total life cycle emissions, and equipment, minerals, chemicals, agriculture and business services (each producing 0.1% of total life cycle 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.

SC carbon maps presented in this study provide a visualisation technique supporting decision-making. They consist 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 impact from the wider economy, aggregated in 18 economic segments presented at the bottom of the SC carbon map.

Table 3. Ecoinvent data providing the tonne–kilometre CO_2-eq/unit for the mode of distribution.

Type	Name	Transportation	CO_2-eq/unit	Description (ecoinvent)
Raw material	Steel rod			
	CZ (70% of supply)	Lorry	0.1057	Transport, lorry, >32t, EURO4
		Ship	0.046416	Transport, barge
	UK (30% of supply)	Lorry	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	0.46416	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

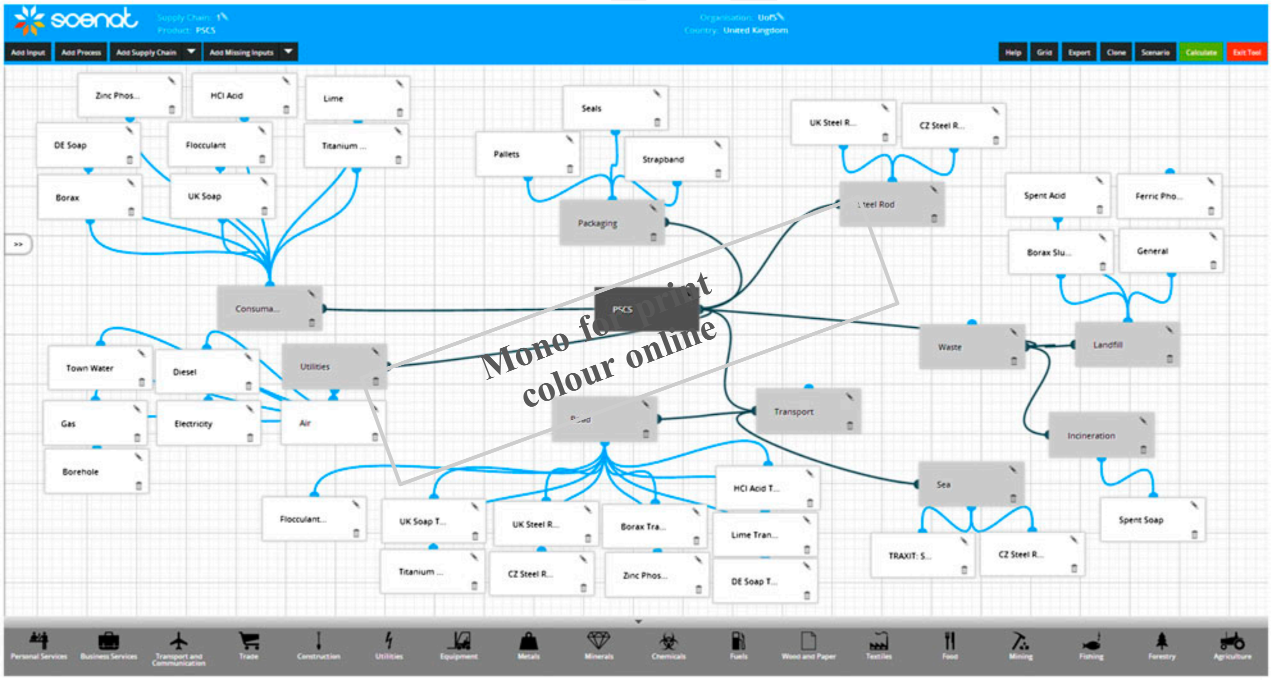


Figure 3. The PSCS supply chain map.

4.2 *Scenario analysis*

As the greenhouse gases 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 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 life cycle 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

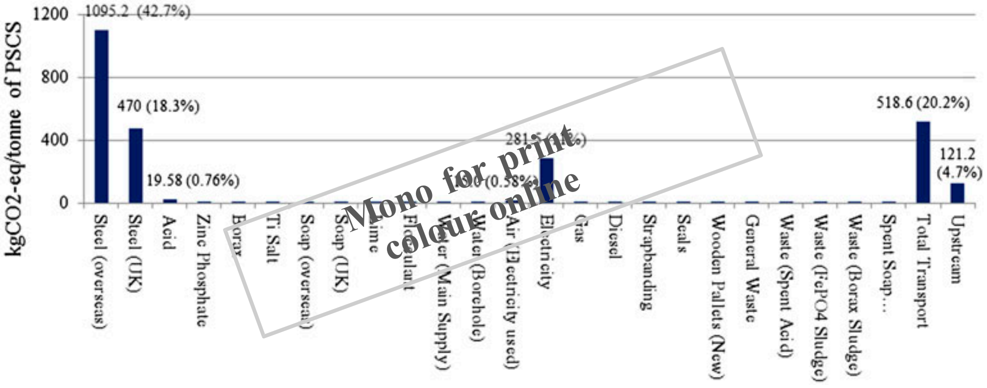
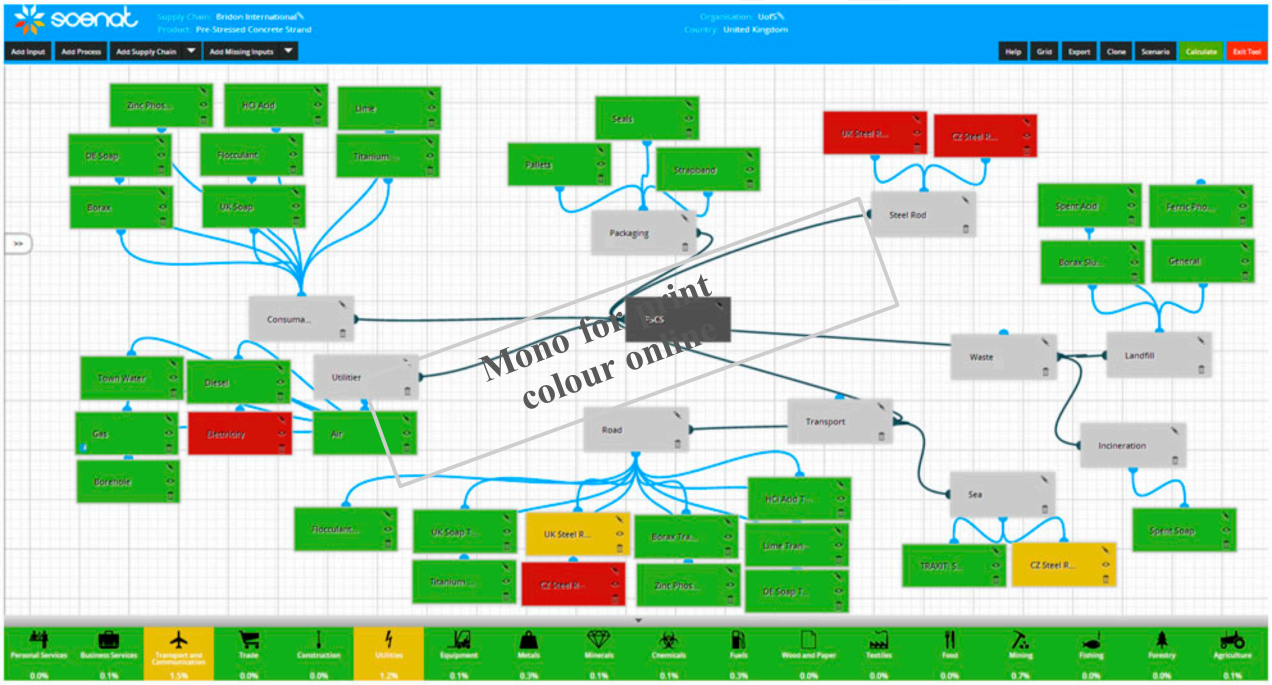


Figure 4. The PSCS life cycle emissions.



Supply Chain: Bridon International
Product: Pre-Stressed Concrete Strand
Organisation: UofS
Country: United Kingdom

Figure 5. Upstream and process carbon emissions breakdown.

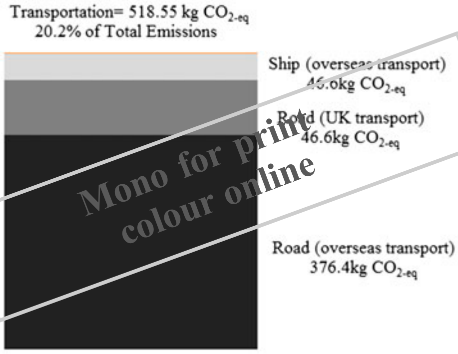
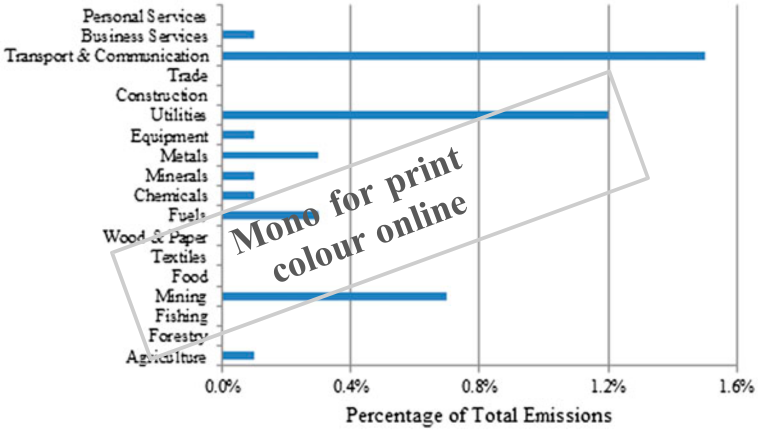


Figure 6. Transport-related carbon emissions breakdown.



AQ28 Figure 7. Upstream carbon emissions breakdown by macro-economic sector.

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 sources 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 life cycle emissions. This scenario will estimate the reduction in total life cycle 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/

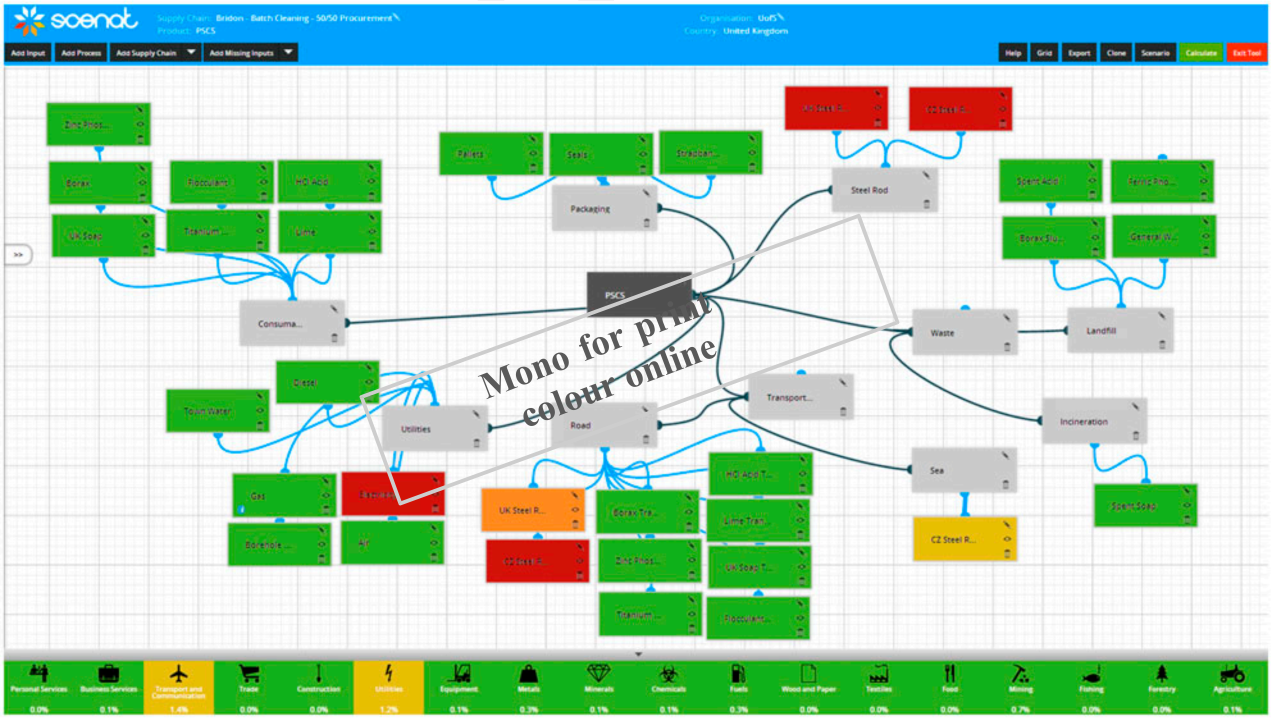


Figure 8. Scenario analysis carbon map: reducing overseas procurement.

30% between overseas and domestic suppliers to 50/50%, 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 and 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.

In scenario 1, a total life cycle 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 2562.62 kg). Regarding the carbon maps identification of greenhouse gas emitting 'hotspots', it can be clearly seen that, although total life cycle 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 life cycle emissions.

By reassigning 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 life cycle 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 life cycle 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 decarbonising domestic road transportation since that has now become a hotspot and hence a priority.

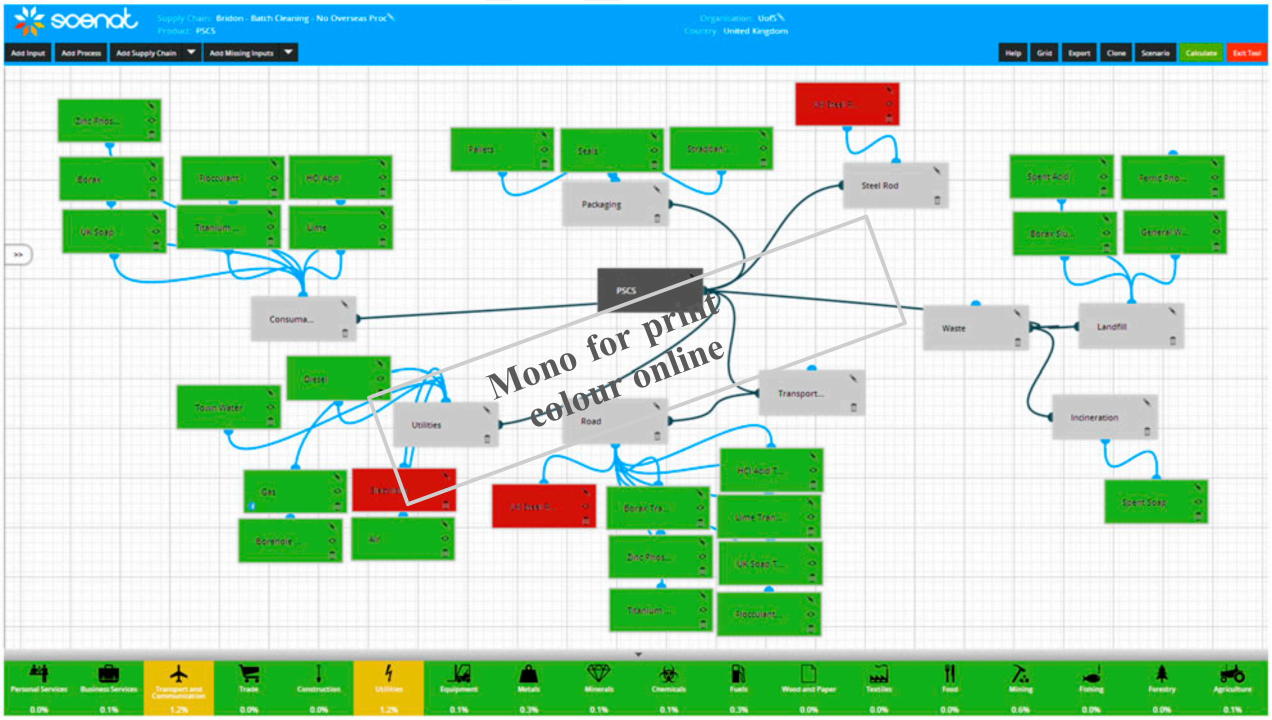


Figure 9. Scenario analysis carbon map: removing overseas procurement.

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.

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's 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 has already initialised a £3 million project to close their batch-cleaning facility and introduce a mechanical descaling 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 and Jarl (2006), who found that the descaling of 1 tonne of steel rods requires 7 kWh of electricity.

It can, therefore, be observed that in Figure 10, consumables such as borax, zinc phosphate and 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 life cycle 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 2562.62 kg $CO_{2\text{-eq}}$). Although at first glance this value seems relatively

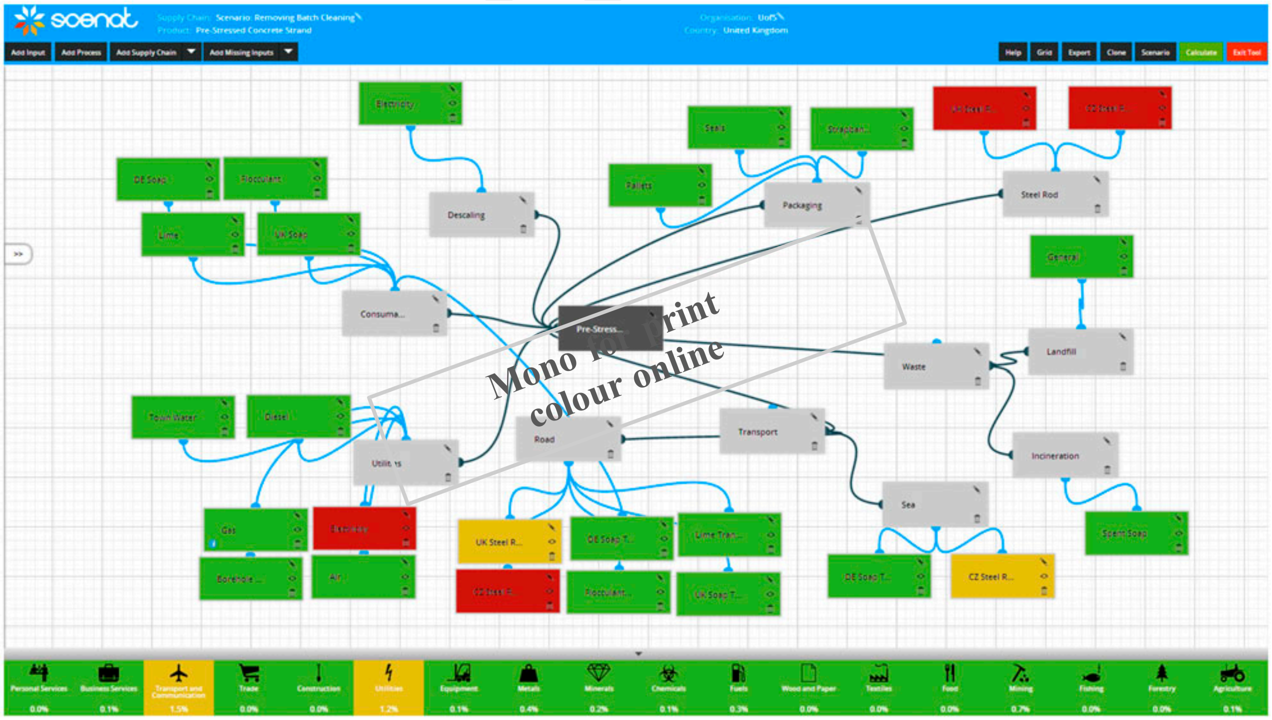

Supply Chain: Scenario: Removing Batch Cleaning
Product: Pre-Stressed Concrete Strand
Organisation: UofS
Country: United Kingdom

Figure 10. Scenario analysis – replacing batch cleaning with mechanical descaling.

insignificant in comparison with overall life cycle 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 life cycle 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.

Table 4 synthesises emission savings that can be obtained with the above-mentioned scenarios.

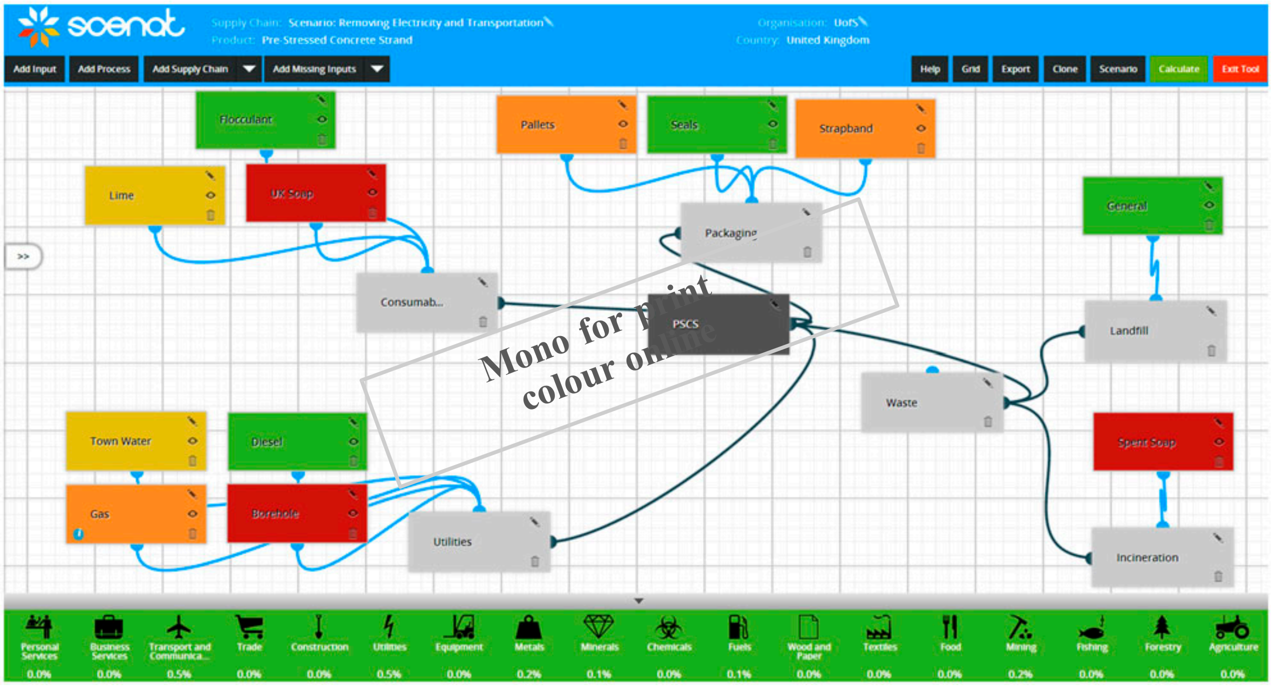
4.2.3 *Discovering further carbon hotspots*

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 life cycle carbon emissions have been calculated for remaining consumables, namely wire drawing 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 life cycle 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.

- *Reducing water and gas consumption*: The large proportion of total life cycle 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 kilogramme 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, Browne, and Whiteing 2012), could also reduce greenhouse emissions and total costs of

Table 4. Scenario analysis summary.

Intervention	Type	Mitigation potential	Δ%
Reducing overseas procurement	Green procurement	63.93 $kgCO_{2\text{-eq}}$/tonne	−2.49
Eliminating overseas procurement	Green procurement	223.29 $kgCO_{2\text{-eq}}$/tonne	−8.71
Removing batch-cleaning facility	Process innovation	27.02 $kgCO_{2\text{-eq}}$/tonne	−1.05



Supply Chain: Scenario: Removing Electricity and Transportation
Product: Pre-Stressed Concrete Strand
Organisation: UofS
Country: United Kingdom

Figure 11. Scenario analysis – identifying further hotspots.

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 of estimating 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 operationalise 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, multiple 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, Lenny Koh, Kumar, et al. 2013). AQ11 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 levels 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 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.

References

Acquaye, A. A., and A. P. Duffy. 2010. “Input–Output Analysis of Irish Construction Sector Greenhouse Gas Emissions.” *Building and Environment* 45 (3): 784–791.

Acquaye, A., A. Duffy, and B. Basu. 2011. “Embodied Emissions Abatement – A Policy Assessment Using Stochastic Analysis.” *Energy Policy* 39 (1): 429–441.

Acquaye, A., A. Genovese, J. Barrett, and L. Koh. 2014. “Benchmarking Carbon Emissions Performance in Supply Chains.” *Supply Chain Management: An International Journal* 19 (3). AQ12

Acquaye, A. A., T. Sherwen, A. Genovese, J. Kuylenstierna, S. C. Lenny Koh, and S. Mcqueen-Mason. 2012. “Biofuels and Their Potential to Aid the UK towards Achieving Emissions Reduction Policy Targets.” *Renewable and Sustainable Energy Reviews* 16 (7): 5414–5422.

Acquaye, A. A., T. Wiedmann, K. Feng, R. H. Crawford, J. Barrett, J. Kuylenstierna, A. P. Duffy, S. C. L. Koh, and S. Mcqueen-Mason. 2011. “Identification of ‘Carbon Hot-spots’ and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis.” *Environmental Science and Technology* 45 (6): 2471–2478.

Angerhofer, B. J., and M. C. Angelides. 2006. “A Model and a Performance Measurement System for Collaborative Supply Chains.” *Decision Support Systems* 42 (1): 283–301.

Bai, C., and J. Sarkis. 2014. Green Supply Chain Technology: A Comprehensive Evaluation and Justification Multiattribute Decision Modeling Approach. In *Supply Chain Management Under Fuzziness, Studies in Fuzziness and Soft Computing*, Vol. 313, edited by C. Kahraman and B. Öztayş, 655–679. Berlin: Springer-Verlag.

Bani, M., Z. Rashid, K. Hamid, M. Harbawi, A. Alias, and M. Aris. 2009. "The Development of Decision Support System for Waste Management; a Review." *Proceedings of World Academy of Science: Engineering & Technology* 49. AQ13

Barrett, J., and K. Scott. 2012. "Link between Climate Change Mitigation and Resource Efficiency: A UK Case Study." *Global Environmental Change* 22 (1): 299–307.

Bhattacharya, A., P. Mohapatra, V. Kumar, P. K. Dey, M. Brady, M. K. Tiwari, and S. S. Nudurupati. 2014. "Green Supply Chain Performance Measurement Using Fuzzy ANP-based Balanced Scorecard: A Collaborative Decision-making Approach." *Production Planning & Control: The Management of Operations* 25 (8): 698–714.

Bruno, G., E. Esposito, A. Genovese, and R. Passaro. 2012. "AHP-based Approaches for Supplier Evaluation: Problems and Perspectives." *Journal of Purchasing and Supply Management* 18 (3): 159–172.

Carter, C., and P. Easton. 2011. "Sustainable Supply Chain Management: Evolution and Future Directions." *International Journal of Physical Distribution & Logistics Management* 41 (1): 46–62.

Chan, F. T., and N. Kumar. 2007. "Global Supplier Development Considering Risk Factors Using Fuzzy Extended AHP-based Approach." *Omega* 35 (4): 417–431.

Cigolini, R., M. Cozzi, and M. Perona. 2004. "A New Framework for Supply Chain Management: Conceptual Model and Empirical Test." *International Journal of Operations & Production Management* 24 (1): 7–41.

Cordero, P. 2013. "Carbon Footprint Estimation for a Sustainable Improvement of Supply Chains: State-of-the-art." *Journal of Industrial Engineering & Management* 6 (3). AQ14

Crawford, R. H. 2008. "Validation of a Hybrid Life-cycle Inventory Analysis Method." *Journal of Environmental Management* 88 (3): 496–506.

Cullen, J. M., and J. M. Allwood. 2010. "Theoretical Efficiency Limits for Energy Conversion Devices." *Energy* 35 (5): 2059–2069.

De Benedetto, L., and J. Klemeš. 2009. "The Environmental Performance Strategy Map: An Integrated LCA Approach to Support the Strategic Decision-making Process." *Journal of Cleaner Production* 17 (10): 900–906.

Deng, L., C. W. Babbitt, and E. D. Williams. 2011. "Economic-balance Hybrid LCA Extended with Uncertainty Analysis: Case Study of a Laptop Computer." *Journal of Cleaner Production* 19 (11): 1198–1206.

Duinker, P. N., and L. A. Greig. 2007. "Scenario Analysis in Environmental Impact Assessment: Improving Explorations of the Future." *Environmental Impact Assessment Review* 27 (3): 206–219.

Ecoinvent (database ecoinvent data v2.2. Swiss Centre for Lifecycle Inventories; 2010).

Eisenhardt, K. M. 1989. "Building Theories from Case Study Research." *Academy of Management Review* 14 (4): 532–550.

AQ15 Emmett, S., and V. Sood. 2010. *Green Supply Chains: An Action Manifesto*. Wiley.

Eurostat. 2008. *Eurostat Manual of Supply, Use and Input–Output Tables*. European Commission. Accessed June 2013. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-RA-07-013/EN/KS-RA-07-013-EN.PDF

Ferng, J.-J. 2009. "Applying Input–Output Analysis to Scenario Analysis of Ecological Footprints." *Ecological Economics* 69 (2): 345–354.

Genovese, A., S. C. Lenny Koh, G. Bruno, and E. Esposito. 2013. "Greener Supplier Selection: State-of-the-art and Some Empirical Evidence." *International Journal of Production Research* 51 (10): 2868–2886.

Genovese, A., S. C. Lenny Koh, N. Kumar, and P. K. Tripathi. 2013. "Exploring the Challenges in Implementing Supplier Environmental Performance Measurement Models: A Case Study." *Production Planning & Control* 1–14.

Gillström, P., and M. Jarl. 2006. "Mechanical Descaling of Wire Rod Using Reverse Bending and Brushing." *Journal of Materials Processing Technology* 172 (3): 332–340.

Gimenez, C., V. Sierra, and J. Rodon. 2012. "Sustainable Operations: Their Impact on the Triple Bottom Line." *International Journal of Production Economics* 140 (1): 149–159.

Gold, S., S. Seuring, and P. Beske. 2010. "Sustainable Supply Chain Management and Inter-organizational Resources: A Literature Review." *Corporate Social Responsibility and Environmental Management* 17 (4): 230–245.

Grimm, D., D. Weiss, K. Erek, and R. Zarnekow. 2014. "Product Carbon Footprint and Life Cycle Assessment of ICT–Literature Review and State-of-the-art." In *2014 47th Hawaii International Conference on System Sciences (HICSS)*, 875–884. IEEE. AQ16

Guinee, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg. 2010. "Life Cycle Assessment: Past, Present, and Future†." *Environmental Science and Technology* 45 (1): 90–96.

Gunasekaran, A., and Z. Irani. 2014. "Sustainable Operations Management: Design, Modelling and Analysis." *Journal of the Operational Research Society* 65: 801–805.

Håkansson, H., and B. Wootz. 1975. "Supplier Selection in an International Environment-an Experimental Study." *Journal of Marketing Research (JMR)* 12 (1). AQ17

Health and Safety Executive. 2012. *Registration, Evaluation, Authorisation & Restriction of CHemicals (REACH)*. Accessed July 5, 2013. http://www.hse.gov.uk/reach/

Heijungs, R., A. Koning, S. Suh, and G. Huppes. 2006. "Toward an Information Tool for Integrated Product Policy: Requirements for Data and Computation." *Journal of Industrial Ecology* 10 (3): 147–158.

Horne, R. 2009. Life Cycle Assessment: Origins, Principles and Context. In *Life Cycle Assessment: Principles, Practice and Prospects*, 1. AQ18

Initiative for Global Environmental Leadership. 2012. *Greening the Supply Chain: Best Practices and Future Trends*. Accessed August 30, 2013. http://igel.upenn.edu/pdf/KW%20IGEL_Supply%20Chain%20Sustainability.pdf

Kaenzig, J., and R. Wüstenhagen. 2010. “The Effect of Life Cycle Cost Information on Consumer Investment Decisions regarding Eco-innovation.” *Journal of Industrial Ecology* 14 (1): 121–136.

Kagawa, S. 2012. “The Sustainability Practitioner’s Guide to Input–Output Analysis.” *Economic Systems Research* 24 (2): 225–227.

Kleindorfer, P. R., K. Singhal, and L. N. Wassenhove. 2005. “Sustainable Operations Management.” *Production and Operations Management* 14 (4): 482–492.

Koh, S. C. L., A. A. Acquaye, N. Rana, A. Genovese, P. Barratt, J. Kuylenstierna, and D. Gibbs. 2011. *Supply Chain Environmental Analysis (SCEnAT)-a New System for Delivering a Low Carbon Supply Chain*. Accessed May 2013. http://www.lowcarbonfutures.org/sites/default/files/2579_Low_Carbon_Report_Nov2011_1322663482.pdf

Kok, R., R. M. Benders, and H. C. Moll. 2006. “Measuring the Environmental Load of Household Consumption Using Some Methods Based on Input–Output Energy Analysis: A Comparison of Methods and a Discussion of Results.” *Energy Policy* 34 (17): 2744–2761.

Labuschagne, C., A. C. Brent, and R. P. G. Van Erck. 2005. “Assessing the Sustainability Performances of Industries.” *Journal of Cleaner Production* 13 (4): 373–385.

Lee, C.-H., and H.-W. Ma. 2013. “Improving the Integrated Hybrid LCA in the Upstream Scope 3 Emissions Inventory Analysis.” *The International Journal of Life Cycle Assessment* 18 (1): 17–23.

Linton, J. D., R. Klassen, and V. Jayaraman. 2007. “Sustainable Supply Chains: An Introduction.” *Journal of Operations Management* 25 (6): 1075–1082.

Löfgren, B., and A.-M. Tillman. 2011. “Relating Manufacturing System Configuration to Life-cycle Environmental Performance: Discrete-event Simulation Supplemented with LCA.” *Journal of Cleaner Production* 19 (17): 2015–2024.

Loiseau, E., G. Junqua, P. Roux, and V. Bellon-Maurel. 2012. “Environmental Assessment of a Territory: An Overview of Existing Tools and Methods.” *Journal of Environmental Management* 112: 213–225.

Lyon, T. P., and J. W. Maxwell. 2011. “Greenwash: Corporate Environmental Disclosure under Threat of Audit.” *Journal of Economics & Management Strategy* 20 (1): 3–41. AQ19

Markley, M. J., and L. Davis. 2007. “Exploring Future Competitive Advantage through Sustainable Supply Chains.” *International Journal of Physical Distribution & Logistics Management* 37 (9): 763–774.

Mattila, T. J., S. Pakarinen, and L. Sokka. 2010. “Quantifying the Total Environmental Impacts of an Industrial Symbiosis – A Comparison of Process-, Hybrid and Input−Output Life Cycle Assessment.” *Environmental Science and Technology* 44 (11): 4309–4314.

Mckinnon, A., M. Browne, and A. Whiteing. 2012. *Green Logistics: Improving the Environmental Sustainability of Logistics*. Kogan Page. AQ20

Miller, R. E., and P. D. Blair. 2009. *Input–Output Analysis: Foundations and Extensions*. Cambridge: Cambridge University Press.

Min, H., and G. Zhou. 2002. “Supply Chain Modeling: Past, Present and Future.” *Computers & Industrial Engineering* 43 (1–2): 231–249.

Minx, J. C., T. Wiedmann, R. Wood, G. P. Peters, M. Lenzen, A. Owen, K. Scott, et al. 2009. “Input–Output Analysis and Carbon Footprinting: An Overview of Applications.” *Economic Systems Research* 21 (3): 187–216.

Nansai, K., S. Kagawa, Y. Kondo, S. Suh, R. Inaba, and K. Nakajima. 2009. “Improving the Completeness of Product Carbon Footprints Using a Global Link Input–Output Model: The Case of Japan.” *Economic Systems Research* 21 (3): 267–290.

Porter, M. E. 1991. “America’s Green Strategy.” *Scientific American* 264 (4). AQ21

Porter, M. E., and M. R. Kramer. 2006. “The Link between Competitive Advantage and Corporate Social Responsibility.” *Harvard Business Review* 84 (12): 78–92.

Rebitzer, G. 2005. “Enhancing the Application Efficiency of Life Cycle Assessment for Industrial Uses.” *The International Journal of Life Cycle Assessment* 10 (6): 446–446.

Reich-Weiser, C., and D. Dornfeld. 2009. “A Discussion of Greenhouse Gas Emission Tradeoffs and Water Scarcity within the Supply Chain.” *Journal of Manufacturing Systems* 28 (1): 23–27.

Rowley, H., S. Lundie, and G. Peters. 2009. “A Hybrid Life Cycle Assessment Model for Comparison with Conventional Methodologies in Australia.” *The International Journal of Life Cycle Assessment* 14 (6): 508–516.

Rueda-Cantuche, J. M., and T. Ten Raa. 2007. Symmetric Input–Output Tables: Products or Industries? In *16th International Input–Output Conference of the International Input–Output Association (IIOA)*. Istanbul. AQ22

Sandin, G., G. Clancy, S. Heimersson, G. M. Peters, M. Svanström, and M. Ten Hoeve. 2014. “Making the Most of LCA in Technical Inter-organisational R&D Projects.” *Journal of Cleaner Production* 70: 97–104.

Saraei, M. H., and A. H. Zaree Farshad. 2009. “The Ecological Footprint (EF) as the Indicator of Societies Sustainability.” *Journal of Environmental Studies* 35 (50): 15–26. AQ23

Sarkis, J. 2003. “A Strategic Decision Framework for Green Supply Chain Management.” *Journal of Cleaner Production* 11 (4): 397–409.

Sarkis, J. 2012. “A Boundaries and Flows Perspective of Green Supply Chain Management.” *Supply Chain Management: An International Journal* 17 (2): 202–216.

Sarkis, J., Q. Zhu, and K.-H. Lai. 2011. “An Organizational Theoretic Review of Green Supply Chain Management Literature.” *International Journal of Production Economics* 130 (1): 1–15.

Sengupta, K., D. R. Heiser, and L. S. Cook. 2006. “Manufacturing and Service Supply Chain Performance: A Comparative Analysis.” *Journal of Supply Chain Management* 42 (4): 4–15.

Seuring, S. 2013. “A Review of Modeling Approaches for Sustainable Supply Chain Management.” *Decision Support Systems* 54 (4): 1513–1520.

Seuring, S., and M. Müller. 2008. “From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management.” *Journal of Cleaner Production* 16 (15): 1699–1710.

Sinden, G. 2009. “The Contribution of PAS 2050 to the Evolution of International Greenhouse Gas Emission Standards.” *The International Journal of Life Cycle Assessment* 14 (3): 195–203.

Srivastava, S. K. 2007. “Green Supply-chain Management: A State-of-the-art Literature Review.” *International Journal of Management Reviews* 9 (1): 53–80.

Strømman, A. H. 2009. “Dealing with Double-counting in Tiered Hybrid Life-cycle Inventories: A Few Comments – Response.” *Journal of Cleaner Production* 17 (17): 1607–1609.

Su, B., B. Ang, and M. Low. 2013. “Input–Output Analysis of CO$_2$ Emissions Embodied in Trade and the Driving Forces: Processing and Normal Exports.” *Ecological Economics* 88: 119–125.

AQ24 Suh, S., ed. 2009. *Handbook of Input–Output Economics in Industrial Ecology*. Springer.

Suh, S., and G. Huppes. 2005. “Methods for Life Cycle Inventory of a Product.” *Journal of Cleaner Production* 13 (7): 687–697.

Suh, S., M. Lenzen, G. J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, J. Munksgaard, and G. Norris. 2004. “System Boundary Selection in Life-cycle Inventories Using Hybrid Approaches.” *Environmental Science and Technology* 38 (3): 657–664.

Sundarakani, B., R. De Souza, M. Goh, S. M. Wagner, and S. Manikandan. 2010. “Modeling Carbon Footprints across the Supply Chain.” i 128 (1): 43–50.

Ten Raa, T. 2007. “The Extraction of Technical Coefficients from Input and Output Data.” *Economic Systems Research* 19 (4): 453–459.

Tillman, A.-M. 2000. “Significance of Decision-making for LCA Methodology.” *Environmental Impact Assessment Review* 20 (1): 113–123.

UK Steel. 2012. *About UK Steel*. Accessed August 25, 2013. http://www.eef.org.uk/uksteel/About-us/default.htm

UNEP and SETAC. 2011. *Global Guidance PrinciPles for Life Cycle Assessment Databases: A Basis for Greener Processes and Products*. Milan: Programme, U. N. E..

Wang, X., H. K. Chan, and L. White. 2014. “A Comprehensive Decision Support Model for the Evaluation of Eco-designs.” *Journal of the Operational Research Society* 65: 917–934.

Wiedmann, T. 2009. “A Review of Recent Multi-region Input–Output Models Used for Consumption-based Emission and Resource Accounting.” *Ecological Economics* 69 (2): 211–222.

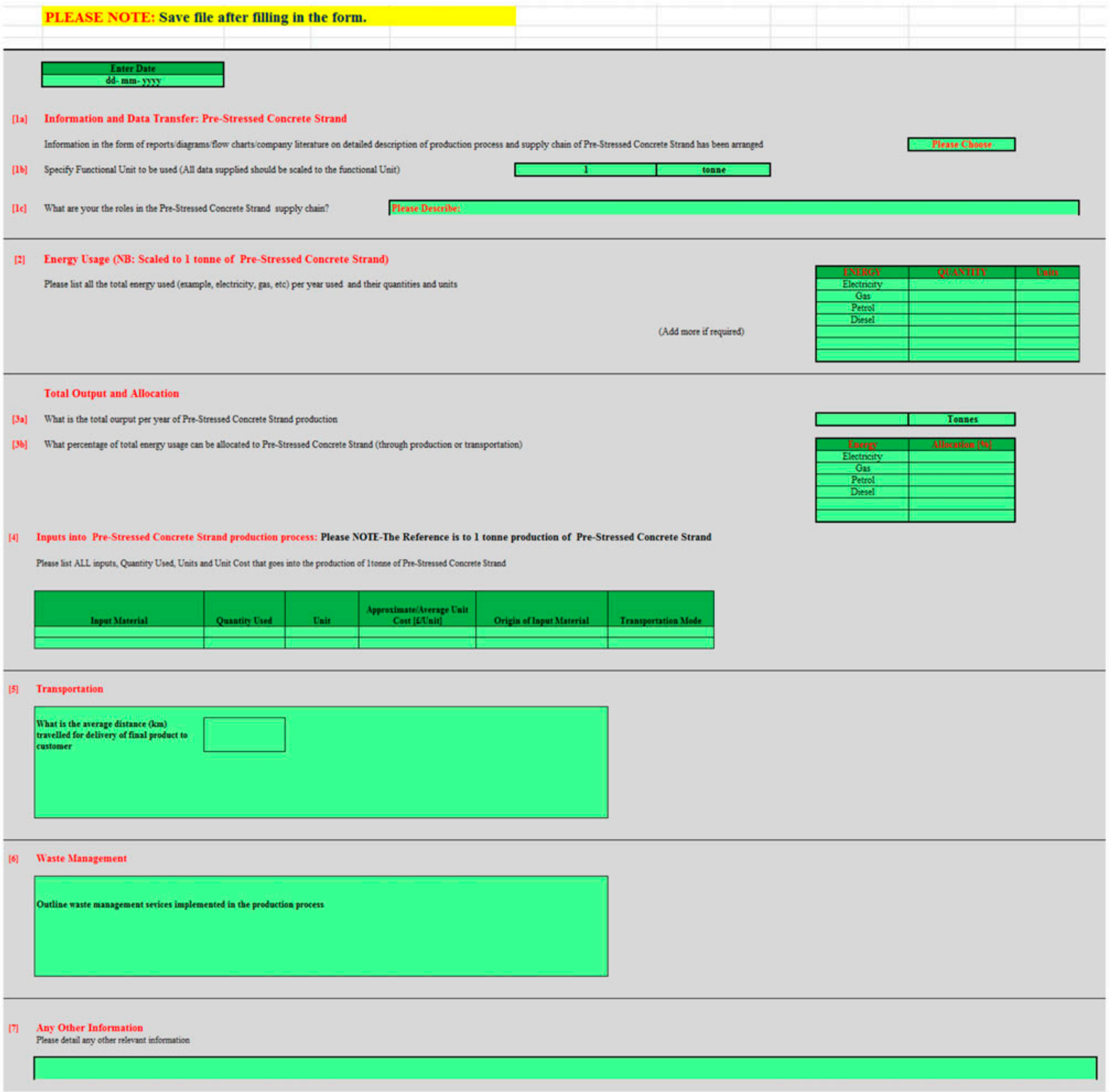
Wiedmann, T. O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, and K. Kanemoto. 2013. “The Material Footprint of Nations.” AQ25 *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.1220362110.

Wiedmann, T. O., S. Suh, K. Feng, M. Lenzen, A. Acquaye, K. Scott, and J. R. Barrett. 2011. “Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies – The Case of Wind Power in the UK.” *Environmental Science and Technology* 45 (13): 5900–5907.

Wiedmann, T., R. Wood, J. Minx, M. Lenzen, D. Guan, and R. Harris. 2010. “A Carbon Footprint Time Series of the UK – Results from a Multi-region Input–Output Model.” *Economic Systems Research* 22 (1): 19–42.

AQ26 Yin, R. K. 2009. *Case Study Research: Design and Methods*. Sage.

Appendix 1. 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

(Add more if required)

ENERGY	QUANTITY	Units
Electricity		
Gas		
Petrol		
Diesel		

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

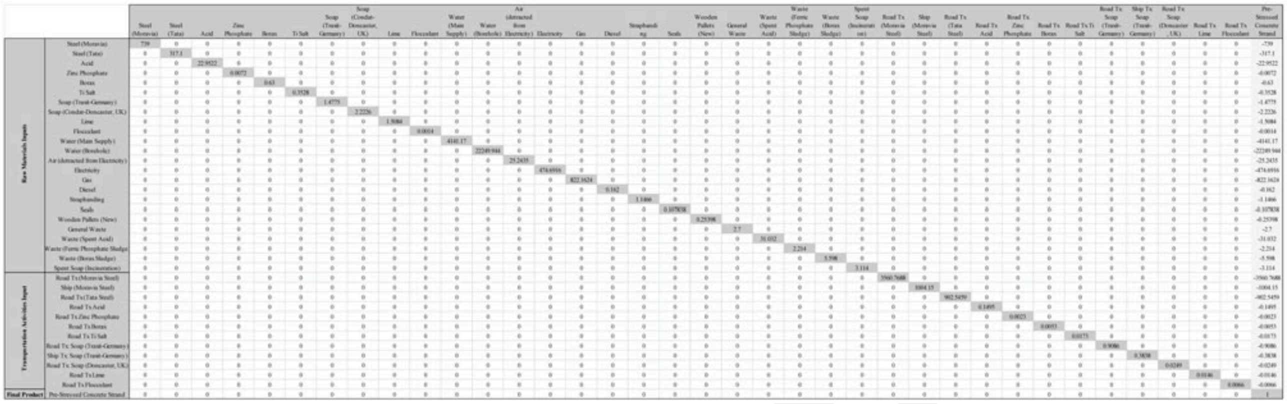
[6] **Waste Management**

Outline waste management sevices implemented in the production process

[7] **Any Other Information**

Please detail any other relevant information

Appendix 2. Process LCA system A_p for the production of 1 tonne of PSCS



		Steel (Moravia)	Steel (Tata)	Acid	Zinc Phosphate	Borax	Ti Salt	Soap (Trasit-Germany)	Soap (Condat-Doncaster, UK)	Lime	Flocculant	Water (Main Supply)	Water (Borehole)	Air (extracted from Electricity)	Electricity	Gas	Diesel	Strapbanding	Seals	Wooden Pallets (New)	General Waste	Waste (Spent Acid)	Waste (Ferric Phosphate Sludge)	Waste (Borax Sludge)	Spent Soap (Incineration)	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 (Trasit-Germany)	Ship Tx Soap (Trasit-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 (Trasit-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 (extracted 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 (Trasit-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 (Trasit-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 3. Economic classifications of the UK and ROW sectors used in MRIO

1	Growing of cereals and other crops n.e.c. (except wheat)	76	Footwear	151	Electricity production – coal
2	Organic: Growing of cereals and other crops n.e.c. (except wheat)	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 stationary)	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 recorded media	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 crops	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 products	88	Fuel oils n.e.c.	163	Steam and hot water supply
14	Raising of diary cattle and production of raw cow milk	89	Petroleum gases and other gaseous hydrocarbons, except natural gas	164	Collection, purification and distribution of water
15	Organic: Raising of diary cattle and production of raw cow milk	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		93	Dyes and pigments	168	

(*Continued*)

Appendix 3. (*Continued***).**

	Raising of horses, equines and other animals; animal hair				Sale, maintenance and repair of motor vehicles, and motor cycles; retail sale of automotive fuel
19	Raising of sheep and goats; Production of raw wool, sheep or goat milk	94	Inorganic basic chemicals	169	Retail sale of automotive fuel
20	Organic: Raising of sheep and goats; Production of raw wool, sheep or goat milk	95	Organic basic chemicals	170	Wholesale trade and commission trade, except of motor vehicles and motor cycles
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 and mastics	174	Restaurants, cafes, bars, etc.
25	Other farming of animals	100	Pharmaceuticals, medicinal chemicals and botanical products	175	Passenger transport by railways
26	Growing of crops combined with farming of animals (mixed farming)	101	Soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	176	Freight transport by inter-urban railways
27	Agricultural service activities; landscape gardening Change of title for SIC(2003)	102	Other chemical products	177	Inter-city coach service
28	Animal husbandry service activities, except veterinary activities	103	Man-made fibres	178	Urban and suburban passenger railway transportation by underground, metro and similar systems
29	Forestry, logging and related service activities (conventional)	104	Rubber products	179	Other scheduled passenger land transport n.e.c.
30	Forestry, logging and related service activities (‘sustainable’/FSC)	105	Plastic plates, sheets, tubes and profiles, builders’ ware of plastic and other plastic products (excl. plastic packing goods)	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 construction	184	Sea and coastal water transportation services
35	Oil: Crude petroleum and services related to crude oil extraction, excluding surveying	110	Manufacture of cement	185	Inland water transportation services
36	Gas: Natural gas and services related to natural gas extraction, excluding surveying	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, shaping and finishing of stone; manufacture of other non-metallic products	188	Supporting and auxiliary transport activities: travel agencies, cargo handling, storage, etc.
39	Mining of non-ferrous metal ores and concentrates	114	Basic iron and steel and of ferro-alloys; manufacture of tubes and other first processing of iron and steel	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 pension funding
42		117	Lead, zinc and tin production	192	

(*Continued*)

Appendix 3. (*Continued*).

	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.
43	Processing and preserving of meat from cattle (beef)
44	Organic: Processing and preserving of meat from cattle (beef)
45	Processing and preserving of meat from pigs
46	Organic: Processing and preserving of meat from pigs
47	Conventional poultry meat and poultry meat products
48	Organic poultry meat and poultry meat products
49	Meat products nec
50	Organic: Meat products nec
51	Fish and fish products
52	Conventional Fruit and vegetables
53	Organic Fruit and vegetables
54	Vegetable and animal oils and fats
55	Dairy products (conventional)
56	Organic dairy products
57	Grain mill products, starches and starch products
58	Prepared animal feeds
59	Bread, rusks and biscuits; manufacture of pastry goods and cakes (conventional)
60	Organic bread, rusks and biscuits; manufacture of pastry goods and cakes
61	Sugar
62	Cocoa, chocolate and sugar confectionery
63	Other food products
64	Alcoholic beverages
65	Production of mineral waters and soft drinks
118	Copper production
119	Other non-ferrous metal production
120	Casting of metals
121	Structural metal products
122	Tanks, reservoirs and containers of metal; manufacture of central heating radiators and boilers; manufacture of steam generators
123	Forging, pressing, stamping and roll forming of metal; powder metallurgy; treatment and coating of metals
124	Cutlery, tools and general hardware
125	Other fabricated metal products
126	Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines
127	Other general purpose machinery
128	Agricultural and forestry machinery
129	Machine tools
130	Other special purpose machinery
131	Weapons and ammunition
132	Domestic appliances (e.g. white goods)
133	Computers and other office machinery and equipment
134	Electric motors, generators and transformers; manufacture of electricity distribution and control apparatus
135	Insulated wire and cable
136	Electrical equipment not elsewhere classified
137	Electronic valves and tubes and other electronic components
138	Television and radio transmitters and line for telephony and line telegraphy
139	Television and radio receivers, sound or video recording or reproducing apparatus and associated goods
140	Medical, precision and optical instruments, watches and clocks
	Insurance and pension funding, except compulsory social security
193	Auxiliary financial services
194	Real estate activities with own property; letting of own property, except dwellings
195	Letting of dwellings, including imputed rent
196	Real estate agencies or activities on a fee or contract basis
197	Renting of cars and other transport equipment
198	Renting of machinery and equipment, excl. office machinery and computers
199	Renting of office machinery and equipment including computers
200	Renting of personal and household goods
201	Computer services and related activities
202	Research and development
203	Legal activities
204	Accounting, book-keeping and auditing activities; tax consultancy
205	Business and management consultancy activities; management activities; market research and public opinion polling
206	Technical consultancy; technical testing and analysis; architectural and engineering related activities
207	Advertising
208	Other business services
209	Public administration (not defence); compulsory social security
210	Public administration – defence
211	Primary, secondary and other education
212	Higher-level education
213	Human health and veterinary activities
214	Social work activities
215	Collection and treatment of sewage and liquid waste

(*Continued*)

Appendix 3. (*Continued*).

66	Tobacco products
67	Preparation and spinning of textile fibres
68	Textile weaving
69	Finishing of textiles
70	Made-up textile articles, except apparel
71	Carpets and rugs
72	Other textiles
73	Knitted and crocheted fabrics and articles
74	Wearing apparel; dressing and dying of fur
141	Motor vehicles, trailers and semi-trailers
142	Building and repairing of ships and boats
143	Railway transport equipment, motorcycles, bicycles and transport equipment n.e.c.
144	Aircraft and spacecraft
145	Furniture
146	Jewellery and related articles; manufacture of musical instruments
147	Sports goods, games and toys
148	Miscellaneous manufacturing not elsewhere classified; recycling
149	Recycling of metal waste and scrap
216	Collection of waste
217	Incineration of waste
218	Landfill of waste
219	Sanitation, remediation and similar activities
220	Activities of membership organisations
221	Recreational and cultural activities
222	Sporting and other activities
223	Dry cleaning, hair dressing, funeral parlours and other service activities
224	Private households as employers of domestic staff

(*Continued*)

Appendix 4. 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