Developing sustainable supply chains in the UK construction industry:

A case study

Abstract

In recent years, increased concerns over greenhouse gas emissions have initiated a wave of policy change in both governmental, industry and non-governmental organisations in order to reduce the overall environmental impact and ensure a sustainable future. The UK Green Building Council for instance has identified construction as one of the most emission-intensive industries, accounting for around 50% of greenhouse gas production in UK. In this study, a hybrid life cycle assessment (LCA) technique is used to analyse the plasterboard supply chain; the most commonly used product in the UK construction industry of one of the Europe’s leading distributor and contractor of building materials. This study demonstrates how emission ‘hotspots’ across the lifecycle of products can be identified and analysed using different intervention options in the supply chain in an attempt to reduce greenhouse gas emissions. For the plasterboard supply chain, the implementation of cross-docking principles and use of renewable sources of energy in warehousing were determined to be major decarbonzation interventions.

Keywords**:** Sustainable supply chain, Life cycle assessment, Greenhouse gases, Construction industry, Case study.

1. Introduction

Business communities across the globe are facing increased concerns over rising carbon emissions, climate change, scarcity of resources and waste generation. In current business environment, companies are facing major challenges arising from resource constraints; furthermore, rising energy and fuel prices causing irreparable damage. In UK, central government has set an ambitious target to reduce the overall carbon emissions by 50% till 2025. The role of the UK construction sector within this target cannot be overemphasised given that it has been estimated that construction can potentially influence 47% of total UK carbon emissions (HM Government, 2010). However, a number of economic and political challenges exist to decarbonize the economy whilst alleviating the ongoing impacts from current financial crises. Although these challenges seem divergent, improving one aspect can inherently lead to improvements in other. For most organizations, as the budget tightens, their priorities will change to cut costs, improve sales and increase the market base. Developing greener supply chains can add to revenue generation by cutting carbon emissions, making processes more efficient and decreasing surplus consumption bills. To strengthen its stand on low carbon economy, the UK government has recently announced that all companies listed in the London Stock Exchange have to report their carbon footprint in their annual reports (Scott, 2012).

Green Supply Chain Management (GSCM) is a growing practice among industries that seek improvements in their environmental performance. In general, the introduction of GSCM could be either ethical (values driven by managers) and/or commercial (to gain competitive advantage in the market). In the last decade, an increased number of studies have been published in academic literature about GSCM and its benefits focusing on several aspects of environmental practices. For example, Zhang et al. (1997) reviewed green design; Bras and McIntosh (1999) described production planning and control for remanufacturing; Gungor and Gupta (1999) reviewed the issues related to green manufacturing and product recovery; Carter and Ellram (1998) researched about reverse logistics; and Jayaraman et al. (2003) reviewed the importance of logistics network design for greener supply chains.

According to the Carbon Trust (2006), carbon reporting and auditing is the first step towards reducing carbon emissions which may positively influence unnecessary resources consumption. Companies can benefit from carbon measurement and reporting to set their carbon management initiative in place for a carbon neutral future. A report by the Department of Environment, Food and Rural Affairs (DEFRA, 2009) estimates that a saving of 4 million tonnes of carbon emission by 2021 will be achieved using emission reporting. These regulations on reporting will directly or indirectly require companies to develop strategies to work towards a carbon neutral future. In a green supply chain, companies need to review their strategies to connect and collaborate with each member in the chain. In recent years companies are becoming more proactive and are addressing the emissions out of their direct control, referred as Sustainability 2.0 (Ranconteur 2012). Therefore, collaborating at the supply chain (SC) level will help to manage risks and integrate sustainable practices in business processes.

Measuring and controlling carbon emissions is challenging for any company's supply chain. This study seeks to measure the direct and indirect lifecycle greenhouse gas emissions of the plasterboard supply chain of a leading European distributor of building materials with the help of a hybrid life cycle assessment (LCA) technique. The supply chain of plasterboard is mapped to identify total lifecycle emissions from manufacturing, storing and transportation. This helps to improve the visibility, transparency and understanding of carbon emissions in the supply chain network. Later, carbon emissions hotspots are identified and a series of scenario analyses presented to understand the possible interventions that could cut down the lifecycle carbon emissions. This study further offer recommendations to the company for consideration in future strategies.

The remainder of the paper is structured as follows: Section 2 presents the background information related to green supply chain and sustainability in construction sector. Section 3 proposes the hybrid LCA framework to evaluate the carbon emission in the supply chain. Section 4 discusses the implementation process of the hybrid LCA framework and presents the case study of the plasterboard supply chain in context of UK construction sector. Section 5 evaluates multiple scenarios in an attempt to lower the carbon emission of the supply chain. Section 6 provides a discussion over the findings and recommendations to the industry, while Section 7 concludes the paper.

2. Background

2.1 Green supply chain management

Previous work (see, for instance: Mefford (2011), Winkler (2011), Sarkis et al., 2011) have identified GSCM as a key business value driver. Porter (2008) also emphasises that such sustainable frameworks provides a strategic process which can enable organisations to create competitive advantages. Lake et al (2014) provides insight into how decision support systems based on the concept can be developed to aid businesses in developing supply chain strategies. Srivastava (2007) also states that the lack of integration of sustainable practices in upstream and downstream supply chain partners may lead to reduction in profits. This means that specific criteria such as environment responsibility and social behaviour need to be applied by all supply chain members for greater and more long-term benefits. Studies show that GSCM not only reduces the environmental and social impact but also improves the operational effectiveness in following ways:

- Green design: designing products to reduce the environmental impact over the full life cycle from the starting stage of developing new product and production processes (Fiksel, 1998).
- Green Operations: covering all aspects of greening the product by remanufacturing, handling, re - usage, logistics and waste management after the design phase
 (Lund, 1984; Srivastava, 2007).
- Green Manufacturing: reducing environmental impact by selecting recycled or reused products or products which have been refurbished/remanufactured (Srivastava, 2007; Lund, 1984).
- Green Packaging: utilizing less materials resulting in small, thin and light packages. This packaging can be recycled and also occupies less space during storage and transportation (Kassaye and Verma, 1992).
- Waste Minimization: from production and operations (Lund, 1984).
- Reverse Logistics: defined as "the process of planning, development and efficient control of the flow of materials, products and information from place

of origin to that of consume as to meet customer needs, recovering the residue obtained and managing it so that possible reintroduction in the supply chain, giving added value and /or proper disposal of it" (Tibben-Lembke and Rogers, 1998)

Different stages of GSCM involve activities including product safety, environmental risk management, occupational health and safety, pollution prevention, conservation of resources, cradle to grave product lifecycle analysis and waste management (Srivastava 2007; Zhu et al., 2008). Managing these activities systematically in the supply chain helps companies to integrate their discrete activities resulting in increased efficiencies, reduction of costs, promotion of economies of scale, better management of risks and improvement in operational effectiveness.

In the current global competitive environment, businesses are facing ever-increased challenges to satisfy the ever-rising expectations of their customers and seek ways to reduce costs, improve quality and meet their sustainability goals. To meet these goals, many of them have identified GSCM as an area to gain the competitive advantage in the long term (Zhu and Sarkis 2004; Genovese et al., 2013b). Every stage of the supply chain contains energy consumption, waste elimination and carbon emissions, and therefore, the SC needs to be restructured to reduce the waste and carbon emissions by re-engineering, re-manufacturing, re-furbishing and re-usage (Koh and Aaoshima, 2001). Bernon and Cullen (2007) also explain the necessity to measure SC performance of reverse logistics and closed loop supply chains in both environmental and financial profitability. Many companies face problems in implementing environmental management systems due to internal and external barriers.

2.2 Sustainability in Construction Industry

The UK government is committed to rebuilding the economy as it recovers from recession, and believes that mainstream sustainable development policies will result in long-term improvement in well-being and economic prosperity. According to Kolk and van Tulder (2005), Scherer *et al.* (2006) and Moon (2007), industries may play a significant role in shaping the policies for a sustainable future. According to a report by UK Green Building Council (2008), the construction of buildings accounts for the 50% of the greenhouse gas emissions in UK.

Plasterboard is one of the notable products utilised in the construction industry. The construction industry consumes approximately 3 million tonnes of plasterboard for construction in UK each year. Detailed statistics from the Department for Environment, Food & Rural Affair (DEFRA, 2009) show that around 300,000 tonnes of plasterboard waste are generated from new construction activities each year. Moreover, it is difficult to quantify the amount of plasterboard waste arising from demolition and refurbishment projects; estimates however show this lies in the range of around 500,000 tonnes to more than 1 million tonnes per year. From an environmental perspective, climate change is the main impact associated during manufacturing due to the energy consumption at several stages of production (namely 'calcinations' and drying of the plasterboard) (DEFRA, 2009). As discussed in the DEFRA report, other impacts include the cost of disposal of plasterboard at the end of the life cycle (economic impact) and the potential health risks emanating from the manual handling of plasterboard sheets in construction sites (social impact).

In July 2008, the government collaborated with industries to launch strategy for sustainable construction. This project was coordinated by DEFRA and plasterboard was identified as one of the 10 priority products in its programme on Sustainable Consumption and Production (DEFRA, 2010). Due to its high usage and environmental impact, Gypsum Products Development Association and DEFRA developed the Sustainability Action Plan to curb the impacts caused by Plasterboard throughout the product life cycle. The objectives incorporated into the plan include efficient manufacturing, safer handling, zero waste to landfill, utilizing materials and sustainable partnerships. This initiative by construction industry sets a good example to produce carbon neutral plasterboards and contribute to the control of climate change (DEFRA, 2010). Srivastava (2007) believes that creating awareness and collaborating with supply chain partners can influence directly or indirectly the sustainability plans such as for plasterboard supply chains. An exhaustive study by Carter and Easton (2011) identifies many areas of sustainable practices can be applied to the GSCM strategy for a greener future. It could be the materials used in manufacturing; location of vendors; transportation; or final consumption of the product. The environmental effect of a product can also be reduced by sustainable logistics (Varma and Clayton, 2010) and warehousing (Tan et al., 1998). Both are independent activities and, without consideration, can have harmful effects on the environment when magnified at multiple levels across the Supply Chain. Optimizing the transport routes and reducing the inventory level can also lead to better savings and improved efficiency (Gavirneni, 2005).

To this end, the paper aims to explore the development of sustainable supply chains in the UK construction sector using the supply chain for plasterboard products as a case study. Within this process, the greenhouse gas emissions are assessed throughout the product lifecycle using a Hybrid LCA methodology. The impact of logistics activities and multiple scenarios of the operations function of the supply chain such as cross-docking as an alternative storage solution are analysed in this paper.

3. Hybrid LCA Methodology

In this paper, the top-down environmental input-output methodology and the bottom-up process analysis methodology are integrated together to develop the hybrid LCA framework. The environmental input-output methodology is formulated on the concept of Multi-Regional Input-Output (MRIO) analysis based on the Supply and Use format. Because supply chains are generally complex with extended system boundary as a result of the globalized nature of all the interconnecting and theoretically infinite tier-level product, process and service inputs, the use of the MRIO framework enables the complexity issue to be resolved. Fundamentals of this methodology are described in the following.

3.1 General Input-Output Model

An input-output (IO) model records the flows of resources (products and services) from each industrial sector considered as a producer to each of the other sectors considered as consumers (Miller and Blair 2009). An IO model is therefore a matrix representation of all economic (production and consumption) activities taking place within a country, region or multi-region.

The general input-output approach has been well documented in literature (Albino et al., 2002; ten Raa, 2007; Ferng, 2009; Minx *et al.*, 2009). It can be shown that:

$$\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$$

Where: $\boldsymbol{A} = [a_{ij}]$ describes all the product requirements (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 supply chain inputs (including raw materials, machinery, energy, goods, transport, services, etc) required to produce a unit output (Barrett and Scott 2012). Vector $\underline{x}$ represents the total output in a given sector and is equal to the sum of those products consumed by other industries and those consumed by the final demand $\underline{y}$ (households, governments, exports, etc).

$(\boldsymbol{I}-\boldsymbol{A})^{-1}$ is referred to as the Leontief Inverse matrix and $(\boldsymbol{I}-\boldsymbol{A})^{-1}\cdot\underline{y}$ describes the total (direct and indirect) requirements needed to produce the total output, $\underline{x}$ for a given final demand $\underline{y}$ (Miller and Blair, 2009). Hence, in terms of supply chain visibility, the supply chain of a given product can be set up in such a way that not only direct inputs are captured, but also, irrespective of the origin of these inputs (domestic or imported), indirect supply chain input can also be captured in the analysis. This is as a result of the extended system boundary of the IO framework (Acquaye and Duffy 2010, Mattila *et al.* 2010, Wiedmann *et al.* 2011). As a result, the whole lifecycle perspective, which is a key principle of green supply chain management (Sundarakani et al., 2010; Carter and Easton, 2011), can be adopted based on the generalised ideas surrounding Multi-Regional Input-Output (MRIO) analysis (Wiedmann, 2009).

3.2 Multi-Regional Input-Output (MRIO) Hybridized Framework

The MRIO model used in environmental input-output analysis is usually presented as a 2-region model; see for instance McGregor *et al.* (2008) who used a two-region MRIO model to enumerate CO_2 emissions embodied in interregional trade flows between Scotland and the rest of the UK. In this paper, the Supply and Use format within a two-region (UK and the Rest of the World) IO framework is adopted. As reported by EUROSTAT (2008), the advantages of Supply and Use tables as an integral part of the national accounts lie in the fact that they have a stronger level of detail which ensures that there is a higher degree of homogeneity of the individual product and therefore better possibilities for determining categories of uses and consequently the environmental impacts. Additionally, it enables us to split emissions as a result of using supply chain inputs either sourced from the UK or from the rest of the world (ROW). The methodology encompassing this MRIO approach and developed within the integrated hybrid LCA methodology (Suh and Huppes, 2005) is presented below. The general equation is given by Equation 1 (see also Acquaye *et al.*, 2011)).

Equation 1:

$$\text{Total Emissions Impact} = \begin{bmatrix} \mathbf{\hat{E}_p} & \mathbf{0} \\ \mathbf{0} & \mathbf{\hat{E}_{io}} \end{bmatrix} \begin{bmatrix} \mathbf{A_p} & -\mathbf{D} \\ -\mathbf{U} & (\mathbf{I} - \mathbf{A_{io}}) \end{bmatrix}^{-1} \begin{bmatrix} \frac{y}{0} \end{bmatrix}$$

Where:

Where:

$\mathbf{A_p}$ represents the square matrix representation of process inventory (dimension: s × s)

$\mathbf{A_{io}}$ represents the MRIO technology coefficient matrix (dimension: m × m)

I represents an identity matrix (dimension:m × m)

U provides the matrix representation of upstream cut-offs to the process system (dimension:m × s)

D reproduces the matrix of downstream cut-offs to the process system (dimension: s × m)

$\mathbf{E_p}$ represents the process inventory environmental extension matrix. CO_2-eq emissions are diagonalised (dimension:s × s)

$\mathbf{E_{io}}$ represents the MRIO environmental extension matrix. CO_2-eq emissions are diagonalised (dimension:m × m)

$\begin{bmatrix} \frac{y}{0} \end{bmatrix}$ represents the functional unit column matrix with dimension $(\mathrm{s}+\mathrm{m}, 1)$ where all entries are 0 except y

The following sub-sections details how each part of the MRIO model is set-up.

3.2.1 Process LCA

Referring back to Equation 1, A_p describes the matrix representation of the Process LCA system following developments made by (Suh and Huppes, 2005). For n different types of supply chain inputs accounted for in the Process LCA system, $\mathrm{A_p}$

would be of dimension $(n+1)$ by $(n+1)$; where there are n supply chain product inputs and 1 main product output. Let q_n represent the quantity of supply chain inputs used for any given input, n and $\mathrm{A_p} = [k_{rc}]$; r (rows) represents inputs and c (columns) processes in the process LCA system. The mathematical formulation of the Process LCA system becomes:

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

3.2.2 Input-Output LCA System, A_{io}

Following on from Equation 1, the input-output LCA system in this paper is setup as a multi-regional input-output LCA system ($\mathrm{A_{io}}$) presented in the Supply and Use format. In Matrix representation, this becomes

$$\mathbf{A_{io}} = \begin{bmatrix} \mathbf{0} & \boldsymbol{A}_{(\boldsymbol{UK})\boldsymbol{U}} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{A}_{(\boldsymbol{UK})\boldsymbol{s}} & \mathbf{0} & \boldsymbol{A}_{(\boldsymbol{UK})\boldsymbol{EXP}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{A}_{(\boldsymbol{ROW})\boldsymbol{U}} \\ \boldsymbol{A}_{(\boldsymbol{UK})\boldsymbol{IMP}} & \mathbf{0} & \boldsymbol{A}_{(\boldsymbol{ROW})\boldsymbol{S}} & \mathbf{0} \end{bmatrix}$$

Where $\mathrm{A_{io}}$ becomes the 2-region MRIO technical coefficient matrix. This includes the following technical coefficient matrices:

- $\boldsymbol{A}_{(UK)U}$, representing the UK Domestic Use.
- $\boldsymbol{A}_{(UK)S}$, representing the UK Domestic Supply.
- $\boldsymbol{A}_{(UK)EXP}$, representing the UK Export to ROW.
- $\boldsymbol{A}_{(ROW)U}$, representing ROW Use.
- $\boldsymbol{A}_{(UK)IMP}$, representing UK Imports from ROW.
- $\boldsymbol{A}_{(ROW)S}$, representing ROW supply to ROW.

All of the individual $\boldsymbol{A}$ matrices are of dimensions $224\ x\ 224$; hence, $\mathrm{A_{io}}$ and $\boldsymbol{I}$ (the Identity Matrix) are therefore of dimension $896\ x\ 896$.

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

$$\boldsymbol{A}_{(UK)IMP} = \left[\frac{q_{ij}^{(ROW,UK)}}{x_j}\right]$$

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

3.2.3 Upstream (U) and Downstream (D) Inputs

From Equation 1, the upstream inputs or Matrix U is assigned a negative sign because it represents inputs from the upstream supply chain (IO system) into the process system. Matrix D, is also assigned a negative sign, because it represents inputs from the process system into the background economy (IO system). Both Strømman *et al.* (2009) and Acquaye *et al.* (2011) explains that the downstream inputs from process LCA system into the wider economy or (IO system) can be considered negligible; hence matrix D set to zero. Using the basic principles of input-output analysis, Acquaye *et al.* (2011) provides details in estimating the upstream inputs U.

3.2.4 Final Demand $\underline{y}$

As shown in Equation 1, $\underline{y}$ represents the final demand; in this instance, the output of the hybrid LCA system. In matrix notation, $\underline{y}$ is a column matrix of dimension: $((n + 1 + 896)\ by\ 1)$; where n is the number of supply chain product inputs of the process LCA system, 1 represents the main product output and 896 the dimension of the MRIO matrix used in this paper. It is given as:

$$\underline{y} = [f_{d,1}];\text{ where } f_{d,1} = 1\ if\ d = n + 1\ and\ 0, \forall \text{ other } d$$

3.2.5 Environmentally Extended MRIO Hybridized Model

The MRIO component of the hybridized model can be extended to an Environmental MRIO lifecycle assessment (LCA) to generate results which can be used in the assessment of product supply chain emissions.

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

$$\underline{E} = \boldsymbol{E}_{io} \cdot \underline{x} = \boldsymbol{E}_{io} \cdot (\boldsymbol{I} - A_{io})^{-1} \cdot \underline{y}$$

Where $\boldsymbol{E}_{io}$ is the direct emissions intensity (kg CO_2-eq/£) of the IO industries and $\boldsymbol{E}_{io} \cdot (\boldsymbol{I} - \boldsymbol{A}_{io})^{-1}$ the total (direct and indirect) emissions intensities (kg CO_2-eq/£) of the IO industries.

By extension, the matrix $\boldsymbol{E}_{io}$ expressed in terms of the MRIO Supply and Use structure becomes:

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

Where $\widehat{\boldsymbol{E}}_{\boldsymbol{UK}}$ and $\widehat{\boldsymbol{E}}_{\boldsymbol{ROW}}$ are respectively the diagonalised direct emissions intensity (Sector emissions in kg CO_2-eq per total output in £) of each industrial sector in the UK and the ROW.

Similarly, the environmental extended component for the process LCA system $\boldsymbol{E}_p$ (Refer to Equation 1) is defined by a diagonalised matrix of the respective environmental values e_n of each input n into of the process LCA system. e_n is obtained by multiplying the quantity of each product inputs q and the respective emissions intensity e_{int}.

$$\boldsymbol{E}_p = [\hat{e}_n]$$

Where $\forall\ n$ into the process LCA system;

$$e_n = q_n \cdot e_{(int)_n}$$

This environmentally extended MRIO model (with each component described in Section 3.2) forms the basis for undertaking a robust comparative environmental impacts assessment (in terms of carbon emissions) and carbon hot-spotting analysis between the reverse supply chain management system and a linear production paradigm of the forward supply chain. Indeed, by interconnecting the domestic and ROW Supply and Use input-output tables into a 2-region MRIO table as shown, the model can overcome the complexity of product supply chains as a result of the globalized nature of all the interconnecting and theoretically infinite tier-level product, process and service inputs. This is so because in addition to direct inputs, the model captures all indirect upstream requirement that are needed to produce all the individual supply chain 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 evaluate carbon emissions across the supply chain.

3.2.6 Supply Chain Mapping

The output of the Hybrid LCA methodology will be organised and presented in tables (reporting supply chain inputs and related amounts, reference units, unit cost, emission intensities per reference unit, total emissions, emissions percentages over total and input category) and supply chain maps. 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) explains that the concept of a supply chain map can be used to provide clear understanding of the exact flow of materials and impacts along the supply chain and hence form the basis for managing and benchmarking the environmental performance of the supply chain. Specifically, supply chain inputs will be classified according to the following categories:

- *Transport to Plant*, involving the transport of raw materials and semi-finished goods to intermediate production stages and to the main manufacturing plant.
- *Materials from Supplier*, involving manufacturing activities related to the production of raw materials and semi-finished goods then utilised at the main manufacturing plant.

- *Utilities at Plant*, including the use of electricity, gas, fuels, water and other types of energy/utilities at the main manufacturing plant within the supply chain.
- *Transport to Warehouse*, representing logistical activities related to the transport of finished products from the main manufacturing plant to the distribution warehouse.
- *Transport inside Warehouse*, being related to loading, unloading and handling operations happening at the distribution warehouse (involving, for instance, the use of forklifts).
- *Utilities at Warehouse*, including the use of electricity, gas, fuels, water and other types of energy/utilities at the distribution warehouse.
- *Transport from Warehouse*, representing logistical activities related to the transport of finished products from the distribution warehouse to the final customer.

Inputs (and related aggregated categories) will be classified (in both tables and maps) according to their related emissions amount according to the colour-code and thresholds shown in Table 1.

<< Insert Table 1 here >>

4. Implementation

4.1 The Case Study

In this study, the implementation of the hybrid life cycle assessment (LCA) technique is demonstrated on the *plasterboard* supply chain of one of the Europe's leading distributors and contractors of building materials. The company offers an integrated supply chain solution to the construction industry and related markets. It maintains a fleet of over 1300 vehicles for supply chain operations in UK and the core products distributed by the company are interiors, exteriors, insulation and energy management. It has achieved ISO 14001 certification in 2006 and introduced the Low Carbon Business Policy which has resulted in gaining Carbon Trust Standard.

Plasterboards are a commonly used construction product due to its inherent qualities such as low flammability, acoustic benefits and ease of build. Approximately 270 million m^2 of plasterboard is produced, distributed and used in the UK every year (DEFRA, 2010). This high consumption also generates waste by the refurbishment and demolition of plasterboard at the end of the life cycle. Every year, over 2400 tonnes of plasterboard is produced and supplied to the case company warehouses. This study identifies the emission 'hotspots' across the lifecycle of the plasterboard and analyse different interventions in the supply chain in an attempt to reduce greenhouse gas emissions.

4.2 Data Collection

In this study, data has been collected using primary and secondary sources. The primary data is collected using a data collection protocol completed by the company, and through a number of interviews conducted during meetings with company managers. The data protocol is provided to the company listing the data requirements and the units of the primary dataset. The following specific information was provided by the company:

- The total energy usage (electricity, gas, petrol and diesel) by 1 tonne of plasterboard annually with their quantities and units.
- The total output of insulation plasterboard distribution annually.
- The percentage of total energy usage that can be allocated to Insulation plasterboard (through production, storage or transportation).
- All the inputs and related quantities and unit cost that goes into the production of 1 tonne of insulation plasterboard.
- The average distance (in km) travelled by 1 tonne of plasterboard for delivery of final product to customer.
- Details of the waste management service implemented during the production of plasterboard.

Relevant secondary data are collected from eco-invent; a widely used emission inventory database. In this study, Ecoinvent (2012) data provides the information about the emissions related to the activities involved in the manufacturing. The cumulative effects of emissions are represented using CO_2 kilogram equivalents ($kgCO_2$-eq) of the unit of input over a 100 year period. The secondary data for plasterboard supply chain inputs was retrieved from the Ecoinvent (2012) database version v2.2. It consists of more than 4000 up-to-date lifecycle inventory (LCI) datasets for a wide range of areas including: energy supply and production, agriculture, transportation, construction materials, packaging materials, metals, biofuels and bio materials, electronics and ICT and also waste treatment.

The data from both primary and secondary sources are used as inputs to the hybrid LCA methodology to calculate total lifecycle carbon emissions and develop the supply chain maps.

4.3 Data Analysis

4.3.1 Preliminary findings

The primary data supplied by the company are mainly related to their logistical (storage and transportation) activities, considering a distribution centre located in the North-West of England. Approximately 200 tonnes of plasterboards per month are produced by the suppliers, sourced and stored in the warehouse until distributed to the customers. The company transports plasterboard all around UK by road using its own fleet of 1,300 vehicles. The data sheet provided by the company includes the distance from a national distribution centre to the warehouse and from the warehouse to the customers. Based on primary data provided by the company, the average distance for customer deliveries was calculated to be 54 km to and from the warehouse (or 27km one way). On average, 255,477 kWh of electricity is consumed per year by one of the warehouses in UK. The total cost of water consumption in a month by the warehouse is £2,169. In the warehouse, 9 diesel forklifts operate for 42.5 hours per week and are used to load, unload and store the plasterboard in the warehouse.

Relevant secondary dataset used in the study is obtained from the Ecoinvent (2012) lifecycle inventory database, which is shown in Table 2. Data given in Table 2 show inputs as part of the production system supply chain of a typical plasterboard. The information on plasterboard's upstream supply chain is obtained from the GHG Scope 3 emission report by World Resources Institute and WBCSD (Greenhouse Gas Protocol, 2011). According to the report, Scope 1 emissions are the direct emissions that are controlled and owned by the companies while Scope 2 emissions are related to indirect use of energy (electricity, heat, steam). Scope 3 emissions are the indirect emissions that are not reported in the company's value chain. These potential Scope 3 emission activities are also analysed in this paper using the following upstream indirect inputs in the supply chain:

a. Travelling of employees by Air, Road and Rail
b. Construction of commercial buildings
c. Manufacturing of plasterboard
d. Machinery used in production
e. Extraction of gypsum
f. Collection and treatment of waste in the whole supply chain
g. Landfill of waste
h. Computer services

The primary data of the warehouse are converted according to the standard unit of 1kg of plasterboard and the emissions are calculated in $kgCO_2$. The carbon emission per unit weight of plasterboard due to inbound logistics, forklift trucks used in the warehouse, outbound logistics, and electricity and water consumption are summarised in Table 3.

<< Insert Table 2 here >>

<< Insert Table 3 here >>

4.3.2 Supply chain mapping

In this step, the data calculated from the primary and secondary resources are mapped and emissions are calculated to evaluate the environmental impact of the plasterboard supply chain based on the hybrid LCA methodology. Figure 1 presents the upstream and downstream carbon emission of the plasterboard supply chain.

Direct emissions identified in the plasterboard distribution are related to the production, transportation and warehouse activities. The indirect emissions include gas and electricity consumption where the company does not control the production process. In addition, Scope 3 indirect emissions produced as a consequence of ‘other’ activities. Table 4 reports the complete break-out of carbon emissions across the supply chain, including both direct and indirect emissions.

The total lifecycle carbon emission of the supply chain is estimated to be 0.7187 kg-CO_2 equivalent for per kilogram of plasterboard production. This analysis estimates that 90.47% of the total lifecycle emission is contributed by direct inputs, and 9.53% originates from the indirect emissions associated with the plasterboard supply chain. The indirect emissions in the supply chain are based on the inputs from different sectors such as, construction, trade, minerals, fuels, wood and papers, food, textiles, chemicals, fishing forestry, personal and business services, transport and communication, utilities and mining. In the case of plasterboard, the indirect emissions are linked to the operations related to Extraction of minerals (1.60%), Utilities (2.30%), Transport and Communication (1.10%), Mining (1.17%) and Construction (1.06%).

The Hybrid LCA model helps to identify the carbon ‘hotspots’ and quantify their impacts in the plasterboard supply chain. This is translated in a supply chain carbon map (as seen in Figure 1) aggregating the different direct emission inputs into identified categories identified in Table 4 and Table 5. In particular, the utilities consumption at the manufacturing plant account for 24.99% of the total emissions. Transport of finished products to the warehouse accounted for 18.68% of emissions, while materials received from suppliers and utilised at the manufacturing plant account for 16.02%. Utilities consumption at the warehouse estimated to account for 14.67% share of total emissions.

<< Insert Table 4 here >>

<< Insert Table 5 here >>

<< Insert Figure 1 here >>

<< Insert Figure 2 here >>

5. Scenario Analysis

In this section, different scenarios are modelled to identify the potential strategies to reduce the environmental impacts of the plasterboard supply chain. Scenario analysis is an important tool 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 (for example climate change) on possible interventions (Duinker and Grieg 2007).

During the production of plasterboard many of the raw materials used need to be utilized efficiently to cut down on environmental impacts. The impacts related to oil consumption, electricity and utilities are very high in production and manufacturing operations such as:

- *Gypsum Production* – Environmental impact due to the extraction of natural gypsum and production of Flue Gas Desulphurisation (FGD) is significant. Mining and extraction of minerals causes 2.77% of the total emissions (see Table 3).

- *Stucco Production* – Various stages in this process require energy to heat up to 150 degree Celsius using natural gas to convert calcium sulphate di-hydrate to calcium sulphate hemihydrate. The impact associated gets higher according to the quantity of fuels used.

- *Plasterboard Production* – During the formation of plasterboard slurry, hemihydrate is mixed with water, which is shaped between 'facing papers' and passed through a dryer at a moderate temperature to prevent re-calcination.

- *Disposal* – Emissions from the disposal of plasterboard are related to landfill and transportation.

In the warehousing activities, the highest carbon emissions arise from handling activities and electricity consumption. The use of 9 diesel forklifts within the warehouse presents both social and environmental impacts due to the release of carbon monoxide gas, which is a health related hazard for people working in the warehouse. The company could consider alternatives like electric or LPG forklifts to significantly reduce these impacts. Johnson (2008) identified that the carbon footprint of electric and LPG forklifts are almost the same while in use, however total lifecycle emissions of LPG forklift is smaller when compared to electric forklifts because the emissions related to charging the electric vehicle are higher.

5.1 Scenario 1: Implementation of Cross Docking principles

In this scenario, the cross-docking principle would be analysed in context of the warehouse activities at the case company. The hybrid LCA methodology would be used to estimate the carbon emission reductions after implementing the cross docking principles. In this activity, the inbound flow of plasterboard is synchronized with the outbound flow of plasterboard at a warehouse without moving them to the storage facility. Greater degree of coordination is required to implement the cross-docking activities smoothly; however it significantly reduces the inventory level (Kinnear 1997, Savasakan et al. 2004).

Cross docking will create a lean system facilitating distribution, which benefits both the company and their suppliers. The highly coordinated working environment will reduce warehouse usage and as a result will reduce the emissions associated with it due to the reduction in electricity usage. Savasakan et al. (2004) found evidence in their case company that the implementation of cross-docking principles reduces the inbound product order cycle time by 71% (decreasing from 7 days to 2 days), inventory levels reduced by 76% and the floor space required to store inventory at the plant reduced by up to 50%. However, for the successful implementation cross-docking, there is a need for advance information systems like Manufacturing Resource Planning (MRP 2) or Enterprise Resource Planning (ERP). These information systems drive the synchronization of deliveries related to cross docking and enable an enhanced information flow in the supply chain by integrating production, warehouse and distribution operations related to plasterboard.

After implementing the cross docking principle at the company, the total lifecycle emission of the SC is estimated to reduce from 0.71870 kg CO_2 to 0.61319 kg CO_2 equivalent per kilogram of plasterboard production (as shown in Tables 6 and 7). It means that the company would directly reduce the total lifecycle carbon emissions by 14.68% from its current plasterboard supply chain. Introducing the cross docking principle would also reduce emissions originating from electricity and water consumption at warehouse associated with the current supply chain model. Partnering with the suppliers distribution system would allow the company to reduce a significant proportion of emissions from inbound and outbound logistics. In the supply chain map, as shown in Figure 3, the aggregated carbon ‘hotspots’ are related to the manufacturing of raw materials at suppliers plant, utilities at manufacturing plant and transportation activities to the company warehouses (as shown in Table 7 and Figure 3). By implementing cross docking the plasterboard will not stay in the warehouse for more than 24 hours, therefore it can be safely assumed that emissions related to energy use would be reduced further. In addition, these emissions could be even further reduced by enhancing collaboration with suppliers to encourage the use of greener sources in the extraction of raw materials and in production (such as adopting energy-efficient machinery).

<< Insert Table 6 here >>

<< Insert Table 7 here >>

<< Insert Figure 3 here >>

5.2 Scenario Analysis 2: Implementation of Renewable Energy Sources

The European Union Directive on renewable energy states that at least 15% of gross energy consumption needs to be generated from renewable sources by 2015 and 25% by 2020 (European Commission, 2007). At present, onshore wind energy accounts for 28% of energy supplied by renewable sources in the UK and represent an economically attractive option compared to offshore and other renewable sources (DECC, 2011). According to a report by Deloitte (Boweyer et. al, 2009), UK has one of the best onshore and offshore wind energy resources in the world. In the past 35 years there has been a continuous flow of wind in this country. Although, this does not obligate the case company directly, the possible adoption of onshore wind energy provides a good solution for reducing carbon footprint of the firm.

In past, companies have voiced concerns regarding the initial investment required to implement onshore wind energy (mainly by installing a wind turbine and its associated transmission of energy to the facility). However, as discussed in Bassi et al. (2009), the following three factors must be considered to make an informed decision:

- The long-term costs of climate change and resource depletion associated with the continuing rate of energy consumption and carbon emissions.
- The costs expected from the rise of fuel prices.
- The comparison of cost with the long-term benefits of renewable energy (in particular the reduced costs of procuring electricity from this source)

Moreover, to understand the costs associated with various sources of energy, a life-cycle cost perspective needs to be taken into account. This cost includes the fuel, operation, maintenance and supply of energy over the period of the economic life of power plant. Given the economic and environmental trade-offs, a report by the Committee on Climate Change (CCC, 2011) state that onshore wind energy is a feasible solution compared to other non-renewable sources as it provides a more stable and reliable source of energy generates less financial impacts over the long-term, such as costs involved in mining to obtain fuel, water consumption and the disposal of waste products (IPCC, 2011).

The scenario analysis is performed to analyse the reduction in the lifecycle emissions of plasterboard SC by implementing wind energy. Sourcing electricity from wind energy suppliers or installing a wind energy turbine to sustain the company's needs of heat and electricity would reduce the carbon emissions of the case company. The analysis of the plasterboard SC is shown in Figure 4 after using renewable energy from wind turbine at warehouse and production facilities of the plasterboard. Reduction of 22.14% of carbon emission is estimated in the supply chain, which will result in the total emission of 0.55956 kg-CO_2 equivalent. This intervention will remove electricity inputs (and the aggregated category of utilities) as main 'hotspots'; and the hotspots in the lifecycle would then be shifted to transportation and manufacturing activities (see Tables 8 and 9 and Figure 4). Following this, the company can re-prioritize its decarbonzation efforts to these new hot-spots.

Although this scenario demonstrates that wind energy could significantly reduce lifecycle emissions of the plasterboard, it must be noted that using wind energy to meet 100% of overall consumption is probably unrealistic due to limitations in technology and capacity. However, the analysis of this scenario is important to provide an insight into the possibilities for emission reductions that could be achieved by implementing renewable energy sources, even for a proportion of current energy consumption. Based on the analysis of above scenarios, the most effective and reasonable interventions will be selected and utilised as a recommendation to the company for consideration in any future environmental decision-making.

<< Insert Table 8 here >>

<< Insert Table 9 here >>

<< Insert Figure 4 here >>

6. Discussion

Developing a sustainable supply chain is a complex process; it needs collaboration and integration of different activities with the supply chain partners. Measuring the life cycle emission of the product and monitoring the carbon intensive activities are important activities to be undertaken in order to encourage green practices. The proposed hybrid LCA methodology can be an effective means in evaluating the carbon emissions in the supply chain and assessing the impact of potential intervention options on the life cycle emissions. The successful implementation of green supply chain practices to reduce the carbon emissions, however, depends on a number of factors that will be discussed in the following.

6.1 Emission data sharing in the SC

Companies need to find innovative ways to reduce their carbon footprint, environmental impact and waste across the supply chain. However, it is an impossible task without building collaboration with the partners in both upstream and downstream of the SC (Vachon and Klassen, 2008; Genovese et al., 2013a). Collecting relevant emission data to understand the emission hotspots in the SC is an important task in order to decide appropriate strategies to reduce the environmental impact. Partners in the SC should share the emission data to evaluate the life cycle emission of the product. Transparency in data sharing should be encouraged to analyse the impact of potential green interventions on the SC. Long-term collaboration not only overcomes challenges in data sharing, but also provides innovative ideas to create win-win situation for all entities involved. Instead of designing separate policies, suppliers and customers of the product can collectively work on single policy to reduce overall environmental impact, increasing triple bottom line benefits for all involved.

In the above-mentioned case study, suppliers of the company are already engaged in the Plasterboard Sustainability Action Plan by DEFRA (DEFRA, 2010). However, the company can initiate further environmental collaboration to develop a transformational relationship with suppliers to mutually work to reduce the environment impact of plasterboard from cradle-to-grave.

6.2 Green Sourcing

The 'green' component in sourcing can act as a catalyst for the company by: building its green credentials, by developing better public image and reputation among stakeholders and allowing them to meet their cost reduction goals improving their financial results. Green sourcing is not just about finding new sustainable technologies or sourcing from green suppliers, it can also help in reducing waste throughout the whole supply chain by lowering the usage of raw materials and benefiting from the recyclable materials. This strategy should be adopted at every level of the SC.

6.3 Logistics Activities

The carbon assessment of plasterboard reports high emissions in inbound and outbound logistics. The company needs to look at the new opportunities available in the market to improve the fuel efficiency of the vehicles. Many companies are introducing aerodynamic and double trailer trucks in their transportation fleet. Volvo has launched the first parallel hybrid trucks in the UK market that are capable of carrying 26 tonnes and promises to reduce fuel consumption by up to 20% (Volvo, 2012). The case company operates a large feet of 1300 trucks and therefore, the investments in more efficient trucks could be considered as long term strategic investment. They can also make use of alternate modes of transportation such as railways to better fit the supply of plasterboard and lower the carbon emission. McKinnon (2006) suggests that increasing vehicle capacity, energy efficiency and reducing externalities can further reduce the CO_2 emissions. The company needs to benchmark the fuel efficiency of trucks and optimize routes to continuously improve their carbon emissions in long term.

6.4 Warehousing Activities

Results have shown that the influence of logistical activities on the overall carbon emissions figures for a typical product in the construction supply chain may not be negligible.

The scenario analyses showed that the best solution to reduce lifecycle emissions originating from warehousing activities is represented by the implementation of cross-docking principles. This will help to reduce carbon emissions related to electricity and water consumption. Other factors to reduce the environmental impact of the warehouse could include.

- *Adopting energy efficient practices*: Housekeeping (such as turning off lights when not in use) can save up to 50% of the direct energy used for the equipment, heating and lighting (Carbon Trust, 2006). Renewable sources of energy such as wind and solar energy could be used in the warehousing operations.

- *Maintaining the warehouse temperature*: The warehouse should be maintained at a satisfactory temperature condition to store the materials by controlling the maximum or minimum temperature level, however by reducing temperature by 1 degree Celsius, a saving of up to 10% can be achieved.

- *Appropriate lighting levels*: The carbon emission by using a single 400W high-pressure sodium light bulb when operated all year is approximately 1.69 tonnes of CO_2 (McKinnon et al., 2010). These bulbs can be replaced by Triphosphor tubular fluorescent lights resulting in cost savings of up to 20% and significant emission reductions.

- *Handling equipment*: With reference to the findings, diesel forklifts could be replaced with LPG forklifts which would reduce the carbon emissions.
- *Avoid Packaging*: Get rid of primary or extra packaging of plasterboard and find greener solution of packaging. A reusable common pallet can be used in the whole supply chain to stop the wastage of packing materials. This will help in reducing the cost as well as carbon emissions related to packaging.

6.5 Reverse Logistics

Responsible sourcing and ordering the right amount of materials helps in reducing the quantity of waste going to landfill. However, reverse logistics can play an important role in the reduction of waste disposal. According to the hybrid LCA analysis, the emission associated with waste is not a major concern for the current company. However, empty running of trucks is an issue. The company needs to collaborate and encourage reverse logistics with their suppliers to reduce fuel consumption from under-utilised routes. The company can look for opportunities to use the lorries and trucks on return journey to get both environmental and economic benefits. Also, the company can look at solutions for the reverse flow of the products after the end-of-life. Companies are becoming more proactive in achieving their sustainability goals through reverse logistics. They are looking forward to building carbon neutral buildings, which will involve green sourcing, recycling and re-usage of plasterboards. Companies can also collaborate with its customers to discover an innovative application of the reverse logistics principles. This will create a win-win situation for both the companies in reducing their carbon footprint by utilizing empty trucks and recycling plasterboard waste.

6.6 Logistics Network Optimisation

Logistics activities account for a significant share in the life cycle emission of the product. Traditional logistics models for manufacturing and distribution have focused on minimizing costs based on operational constraints but there is a need to consider the wider objectives linked with green objectives to optimize routes and gain environment benefits. Reducing the total distance will automatically provide environmental benefits as the vehicle will consume less fuel, emit less pollution and indirectly place less pressure on the road infrastructure. Redesigning logistics networks to optimise both economical and green objectives should be considered in collaboration with SC members. Mixed mode of transportation including the low emission options should also be considered along with network optimisation.

6.7 Aligning Sustainable Practices in SC

The strategic plan for reducing the environmental impact could be short-term, mid-term or long-term. However, the strategic planning should be properly aligned with the operational measures to ensure the implementation of the sustainable practices in the SC.

- *Strategic Planning*: Current sustainability goals of the SC can be examined to see how much they align with the future sustainability planning and goal setting. If the current goals are not promising enough then there is a need to work on the design of new goals and policies.

- *Sustainability Review*: As soon as the goals are defined, suppliers' evaluation should be performed to check the alignment with the sustainability goals of the SC. The evaluation process should identify and rank the suppliers on their alignment to the SC green goals. It could be the reduction of waste, implementation of reverse logistics, logistics route optimization, green packaging, JIT, energy efficient products or sustainable warehousing. A review of the progress made by the suppliers would be undertaken over a fixed period to check if the company is improving at the required pace.

- *Sustainability Standards*: Sustainability standards of the product and processes in the SC should be decided in collaboration with partners so that everyone understands the sustainability goal of the SC. This will increase awareness among the supply chain members and help in developing innovative ideas for sustainable practices.

- *Execution:* Execution of strategic goal needs efficient coordination and information sharing with suppliers. Due to the limited sharing of data with suppliers, sustainability goals will not be achieved. If required, training to suppliers to understand the execution process should be provided.

7. Concluding Remarks

In context to the problems related to climate change and global warming, this study discussed the need to consider sustainability goals in the supply chain. Hybrid LCA based methodology is proposed in the paper to measure the carbon emission in the supply chain and evaluate potential strategies to reduce the carbon emission. Plasterboards, the most commonly used product in the UK construction industry and responsible for a significant impact on the environment was use to exemplify developments made in the paper. The case study presented assess the carbon emissions at the SC level and analyses multiple interventions in an attempt to develop sustainable SC. Calculating and monitoring the emission level in the SC is a complex process. Therefore, collaboration along the SC is required to collect relevant data to identify the emission hotspots and implement strategies to reduce the emission level. The holistic view of SC considering the product life cycle would be appropriate for implementing the green practices in the SC.

Companies in the SC should focus on data sharing and collaboration with suppliers and customers to gain long-term sustainability benefits. Better collaboration and green sourcing are considered useful to achieve the target of zero waste to landfill. Introducing logistics principles like reverse logistics and cross docking can further support to achieve the sustainability targets. Supply chain members need to develop collaborative strategy and continuously monitor it against the sustainability goals in an attempt to develop sustainable supply chain.

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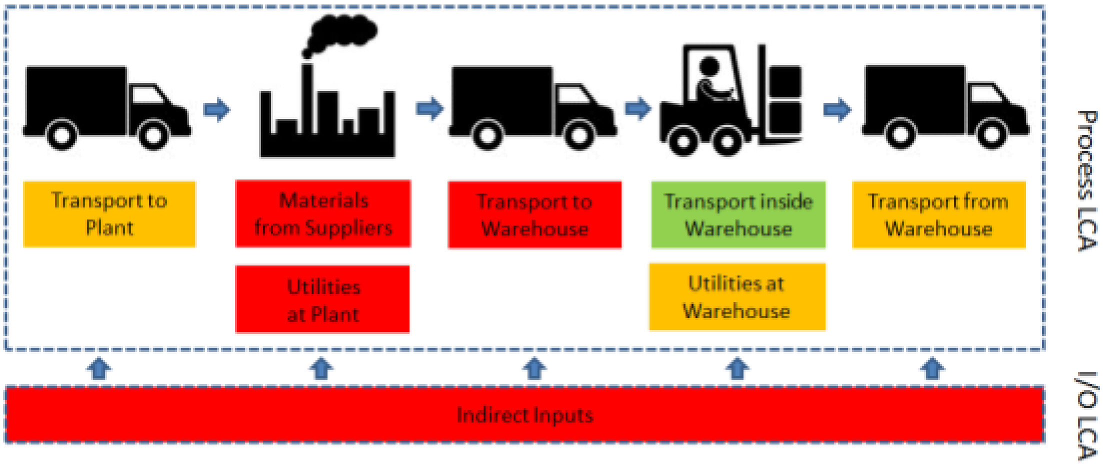

Figure 1: Plasterboard Supply chain mapping with upstream and downstream emissions

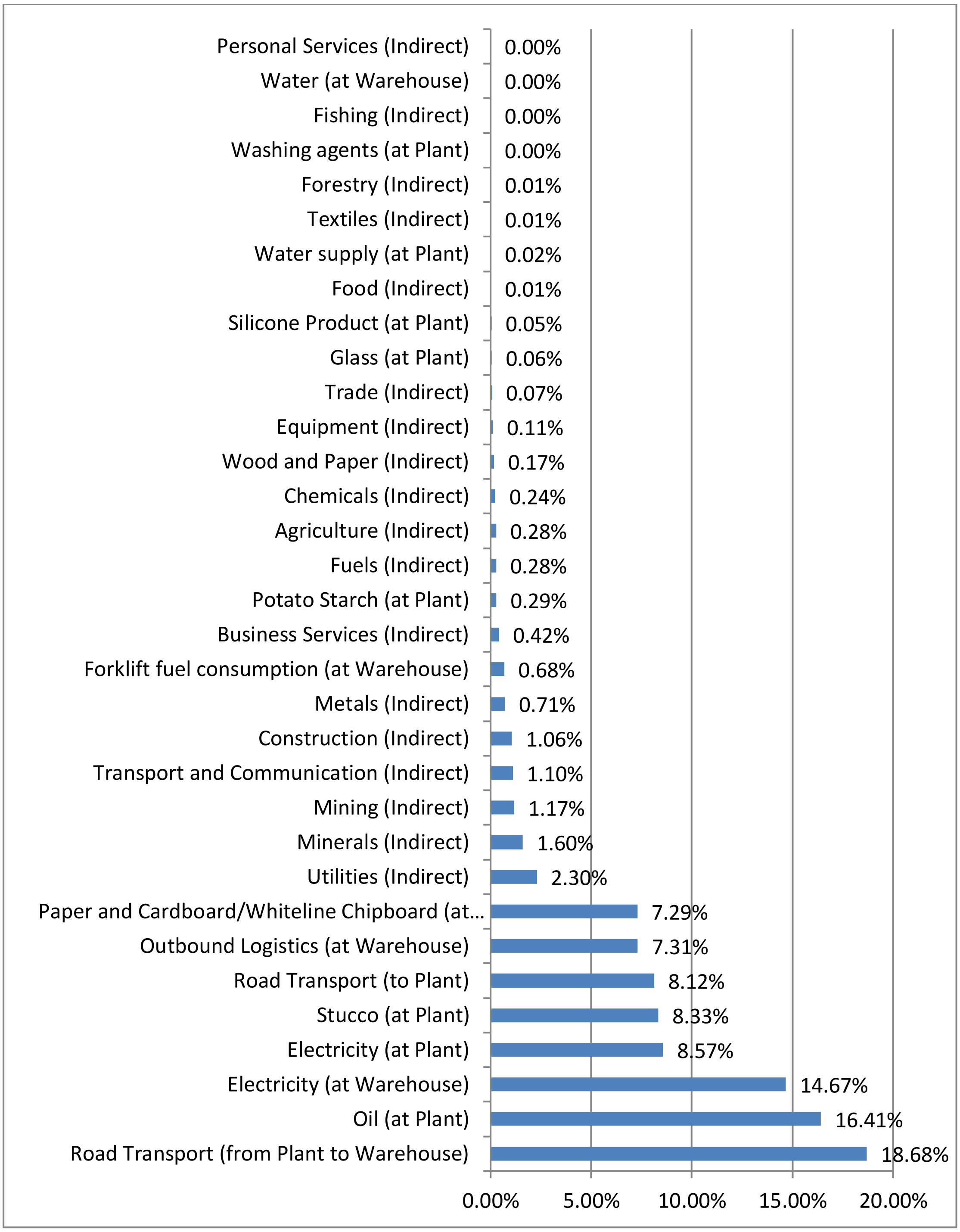

Figure 2: Distribution of life cycle emissions in plasterboard supply chain (base-case scenario).

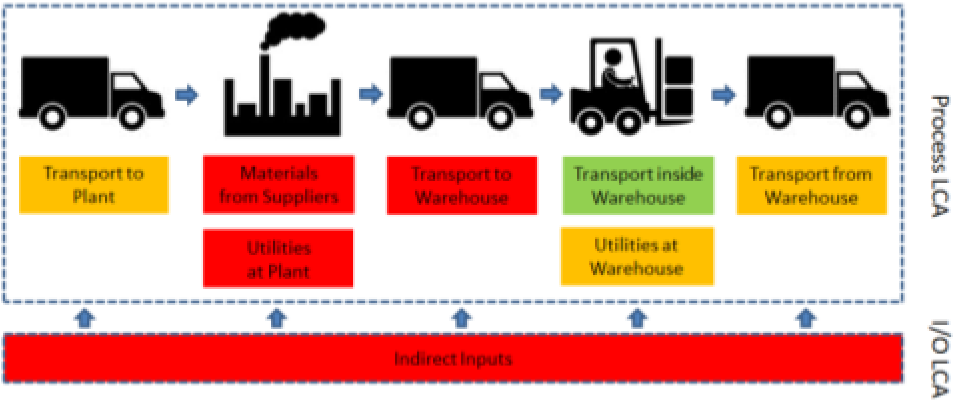

Figure 3: Scenario 1- Life cycle emissions after introducing cross- docking in Plasterboard Supply chain

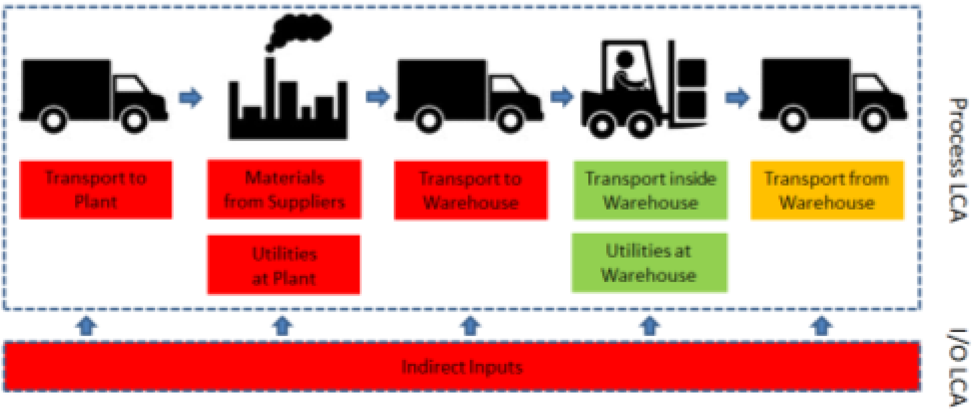

Figure 4: Scenario 2- Life cycle emissions after adopting wind energy

Table 1: Color-code for emissions

Impact	**Interval**	**Color-code**
Low	$e_n \leq 1.00\%$	
Moderate	$1.00\% < e_n \leq 5.00\%$	
High	$5.00\% < e_n \leq 10.00\%$	
Very High	$e_n \geq 10.00\%$	

Table 2: Relevant Secondary data retrieved from ECOINVENT

Supply Chain Input	Name	Quantity	Unit	Emissions in KgCo2	Cost (£)
washing agents	alkylbenzene sulfonate, linear, petrochemical, at plant	0.00001	kg	1.63090	0.4692
electricity/supply mix	electricity, medium voltage, at grid	0.09370	kWh	0.65700	0.082
glass/construction	glass fibre, at plant	0.00016	kg	2.63510	0.497
oil/heating systems	light fuel oil, burned in industrial furnace 1MW, non-modulating	1.36000	MJ	0.08670	0.0108
agricultural production/plant production	potato starch, at plant	0.00290	kg	0.71735	0.92
chemicals/inorganics	silicone product, at plant	0.00013	kg	2.71060	0.4692
construction materials/binder	stucco, at plant	0.81100	kg	0.07383	0.585
water supply/production	tap water, at user	0.36400	kg	0.00032	0.001
transport systems/road	transport, lorry 20-28t, fleet average	0.30000	tkm	0.19460	0.5
paper & cardboard/cardboard & corrugated board	whitelined chipboard, WLC, at plant	0.04840	kg	1.08300	0.1433

Table 3: Carbon emission data related to different operations in the warehouse

Activity	Quantity	Unit	Emissions in $KgCO_2$	Cost (in £)
Road Transport (from Plant to Warehouse)	0.69000	tkm	0.19460	0.50
Forklifts	0.00727	kg	0.67000	0.50
Outbound Logistics (at Warehouse)	0.27000	tkm	0.19460	0.50
Electricity	0.16044	kwh	0.65700	0.08
Water	0.00001	m3	0.65661	0.01

Table 4: Life-Cycle Analysis Calculation (Base Case)

Input Name	Amount	Reference Unit	Avg. Unit Cost	Emission Intensity	Carbon Emissions	Emissions %	Category
Road Transport (from Plant to Warehouse)	0.69000	tkm	£0.50	0.19460	0.13427	18.68%	Transport to Warehouse
Oil (at Plant)	1.36000	MJ	£0.01	0.08670	0.11791	16.41%	Utilities at Plant
Electricity (at Warehouse)	0.16044	KWh	£0.08	0.65700	0.10541	14.67%	Utilities at Warehouse
Electricity (at Plant)	0.09370	KWh	£0.08	0.65700	0.06156	8.57%	Utilities at Plant
Stucco (at Plant)	0.81100	kg	£0.59	0.07380	0.05985	8.33%	Materials from Supplier
Road Transport (to Plant)	0.30000	tkm	£0.50	0.19460	0.05838	8.12%	Transport to Plant
Outbound Logistics (at Warehouse)	0.27000	tkm	£0.00	0.19460	0.05254	7.31%	Transport from Warehouse
Paper and Cardboard/Whiteline Chipboard (at Plant)	0.04840	kg	£0.14	1.08300	0.05242	7.29%	Materials from Supplier
Utilities (Indirect)	N/A	N/A	N/A	N/A	0.01650	2.30%	Indirect
Minerals (Indirect)	N/A	N/A	N/A	N/A	0.01150	1.60%	Indirect
Mining (Indirect)	N/A	N/A	N/A	N/A	0.00840	1.17%	Indirect
Transport and Communication (Indirect)	N/A	N/A	N/A	N/A	0.00790	1.10%	Indirect
Construction (Indirect)	N/A	N/A	N/A	N/A	0.00760	1.06%	Indirect
Metals (Indirect)	N/A	N/A	N/A	N/A	0.00510	0.71%	Indirect
Forklift fuel consumption (at Warehouse)	0.00727	kg	£0.50	0.67000	0.00487	0.68%	Transport inside Warehouse
Business Services (Indirect)	N/A	N/A	N/A	N/A	0.00300	0.42%	Indirect
Potato Starch (at Plant)	0.00290	kg	£0.92	0.71740	0.00208	0.29%	Materials from Supplier
Fuels (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.28%	Indirect
Agriculture (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.28%	Indirect
Chemicals (Indirect)	N/A	N/A	N/A	N/A	0.00170	0.24%	Indirect
Wood and Paper (Indirect)	N/A	N/A	N/A	N/A	0.00120	0.17%	Indirect
Equipment (Indirect)	N/A	N/A	N/A	N/A	0.00080	0.11%	Indirect
Trade (Indirect)	N/A	N/A	N/A	N/A	0.00050	0.07%	Indirect
Glass (at Plant)	0.00016	kg	£0.50	2.63510	0.00042	0.06%	Materials from Supplier
Silicone Product (at Plant)	0.00013	kg	£0.47	2.70160	0.00035	0.05%	Materials from Supplier

Food (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.01%	Indirect
Water supply (at Plant)	0.36400	kg	£0.00	0.00030	0.00011	0.02%	Utilities at Plant
Textiles (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.01%	Indirect
Forestry (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.01%	Indirect
Washing agents (at Plant)	0.00001	kg	£0.47	1.63090	0.00002	0.00%	Materials from Supplier
Fishing (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
Water (at Warehouse)	0.00001	kg	£0.01	0.65510	0.00001	0.00%	Utilities at Warehouse
Personal Services (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
TOTAL					0.71870	100.00%	

Table 5: Life-Cycle Analysis Calculation (Base Case) - Emissions by Category

Category	**Carbon Emissions**	**Emissions %**
Materials from Supplier	0.11514	16.02%
Utilities at Plant	0.17958	24.99%
Transport to Warehouse	0.13427	18.68%
Utilities at Warehouse	0.10542	14.67%
Transport to Plant	0.05838	8.12%
Transport from Warehouse	0.05254	7.31%
Transport inside Warehouse	0.00487	0.68%
Total Direct Emissions	0.65020	90.47%
Total Indirect Emissions	0.06850	9.53%
Total Emissions	0.71870	100.00%

Table 6: Life-Cycle Analysis Calculation (Cross-Docking Adoption)

Input Name	Amount	Reference Unit	Avg. Unit Cost	Emission Intensity	Carbon Emissions	Emissions %	Category
Road (from Plant to Warehouse)	0.69000	tkm	£0.50	0.19460	0.13427	21.90%	Transport to Warehouse
Oil (at Plant)	1.36000	MJ	£0.01	0.08670	0.11791	19.23%	Utilities at Plant
Electricity (at Warehouse)	0.09370	kWh	£0.08	0.65700	0.06156	10.04%	Utilities at Warehouse
Stucco (at Plant)	0.81100	kg	£0.59	0.07380	0.05985	9.76%	Materials from Supplier
Road Transport (to Plant)	0.30000	tkm	£0.50	0.19460	0.05838	9.52%	Transport to Plant
Outbound Logistics (at Warehouse)	0.27000	tkm	£0.00	0.19460	0.05254	8.57%	Transport from Warehouse
Paper and Cardboard/Whiteline chipboard (at Plant)	0.04840	kg	£0.14	1.08300	0.05242	8.55%	Materials from Supplier
Utilities (Indirect)	N/A	N/A	N/A	N/A	0.01640	2.67%	Indirect
Minerals (Indirect)	N/A	N/A	N/A	N/A	0.01150	1.88%	Indirect
Mining (Indirect)	N/A	N/A	N/A	N/A	0.00840	1.37%	Indirect
Transport and Communication (Indirect)	N/A	N/A	N/A	N/A	0.00790	1.29%	Indirect
Construction (Indirect)	N/A	N/A	N/A	N/A	0.00760	1.24%	Indirect
Metals (Indirect)	N/A	N/A	N/A	N/A	0.00510	0.83%	Indirect
Forklift fuel consumption (at Warehouse)	0.00727	kg	£0.50	0.67000	0.00487	0.79%	Transport inside Warehouse
Business Services (Indirect)	N/A	N/A	N/A	N/A	0.00300	0.49%	Indirect
Potato Starch (at Plant)	0.00290	kg	£0.92	0.71740	0.00208	0.34%	Materials from Supplier
Fuels (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.33%	Indirect
Agriculture (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.33%	Indirect
Chemicals (Indirect)	N/A	N/A	N/A	N/A	0.00170	0.28%	Indirect
Wood and Paper (Indirect)	N/A	N/A	N/A	N/A	0.00120	0.20%	Indirect
Equipment (Indirect)	N/A	N/A	N/A	N/A	0.00080	0.13%	Indirect
Trade (Indirect)	N/A	N/A	N/A	N/A	0.00050	0.08%	Indirect
Glass (at Plant)	0.00016	kg	£0.50	2.63510	0.00042	0.07%	Materials from Supplier
Silicone Product (at Plant)	0.00013	kg	£0.47	2.70160	0.00035	0.06%	Materials from

							Supplier
Food (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Water supply (at Plant)	0.36400	kg	£0.00	0.00030	0.00011	0.02%	Utilities at Plant
Textiles (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Forestry (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Washing agents (at Plant)	0.00001	kg	£0.47	1.63090	0.00002	0.00%	Materials from Supplier
Fishing (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
Personal Services (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
TOTAL					0.61319	100.00%	

Table 7: Life-Cycle Analysis Calculation (Cross-Docking Adoption) - Emissions by Category

Category	**Carbon Emissions**	**Emissions %**
Materials from Supplier	0.11514	18.78%
Utilities at Plant	0.11802	19.25%
Transport to Warehouse	0.13427	21.90%
Utilities at Warehouse	0.06156	10.04%
Transport to Plant	0.05838	9.52%
Transport from Warehouse	0.05254	8.57%
Transport inside Warehouse	0.00487	0.79%
Total Direct Emissions	0.54479	88.85%
Total Indirect Emissions	0.06840	11.15%
Total Emissions	0.61319	100.00%

Table 8: Life-Cycle Analysis Calculation (Wind Energy Adoption)

Input Name	Amount	Reference Unit	Avg. Unit Cost	Emission Intensity	Carbon Emissions	Emissions %	Category
Road (from Plant to Warehouse)	0.69000	tkm	£0.50	0.19460	0.13427	24.00%	Transport to Warehouse
Oil (at Plant)	1.36000	MJ	£0.01	0.08670	0.11791	21.07%	Utilities at Plant
Stucco (at Plant)	0.81100	kg	£0.59	0.07380	0.05985	10.70%	Materials from Supplier
Road Transport (to Plant)	0.30000	tkm	£0.50	0.19460	0.05838	10.43%	Transport to Plant
Outbound Logistics (at Warehouse)	0.27000	tkm	£0.00	0.19460	0.05254	9.39%	Transport from Warehouse
Paper and Cardboard/Whiteline chipboard (at Plant)	0.04840	kg	£0.14	1.08300	0.05242	9.37%	Materials from Supplier
Utilities (Indirect)	N/A	N/A	N/A	N/A	0.01640	2.93%	Indirect
Minerals (Indirect)	N/A	N/A	N/A	N/A	0.01150	2.06%	Indirect
Mining (Indirect)	N/A	N/A	N/A	N/A	0.00840	1.50%	Indirect
Transport and Communication (Indirect)	N/A	N/A	N/A	N/A	0.00790	1.41%	Indirect
Construction (Indirect)	N/A	N/A	N/A	N/A	0.00760	1.36%	Indirect
Metals (Indirect)	N/A	N/A	N/A	N/A	0.00510	0.91%	Indirect
Wind Energy (at Warehouse)	0.16044	kWh	£0.03	0.03120	0.00501	0.89%	Utilities at Warehouse
Forklift fuel consumption (at Warehouse)	0.00727	kg	£0.50	0.67000	0.00487	0.87%	Transport inside Warehouse
Business Services (Indirect)	N/A		N/A	N/A	0.00300	0.54%	Indirect
Wind Energy (at Plant)	0.09370	kWh	£0.03	0.03120	0.00292	0.52%	Utilities at Plant
Potato Starch (at Plant)	0.00290	kg	£0.92	0.71740	0.00208	0.37%	Materials from Supplier
Fuels (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.36%	Indirect
Agriculture (Indirect)	N/A	N/A	N/A	N/A	0.00200	0.36%	Indirect
Chemicals (Indirect)	N/A	N/A	N/A	N/A	0.00170	0.30%	Indirect
Wood and Paper (Indirect)	N/A	N/A	N/A	N/A	0.00120	0.21%	Indirect
Equipment (Indirect)	N/A	N/A	N/A	N/A	0.00080	0.14%	Indirect
Trade (Indirect)	N/A	N/A	N/A	N/A	0.00050	0.09%	Indirect
Glass (at Plant)	0.00016	kg	£0.50	2.63510	0.00042	0.08%	Materials from Supplier

Silicone Product (at Plant)	0.00013	kg	£0.47	2.70160	0.00035	0.06%	Materials from Supplier
Food (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Water supply (at Plant)	0.36400	kg	£0.00	0.00030	0.00011	0.02%	Utilities at Plant
Textiles (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Forestry (Indirect)	N/A	N/A	N/A	N/A	0.00010	0.02%	Indirect
Washing agents (at Plant)	0.00001	kg	£0.47	1.63090	0.00002	0.00%	Materials from Supplier
Fishing (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
Water (at Warehouse)	0.00001	kg	£0.01	0.65510	0.00001	0.00%	Utilities at Warehouse
Personal Services (Indirect)	N/A	N/A	N/A	N/A	0.00000	0.00%	Indirect
TOTAL					0.55956	100.00%	

Table 9: Life-Cycle Analysis Calculation (Wind Energy Adoption) - Emissions by Category

Category	Carbon Emissions	Emissions %
Transport to Plant	0.05838	10.43%
Materials from Supplier	0.11514	20.58%
Utilities at Plant	0.12094	21.61%
Transport to Warehouse	0.13427	24.00%
Utilities at Warehouse	0.00501	0.90%
Transport inside Warehouse	0.00487	0.87%
Transport from Warehouse	0.05254	9.39%
Total Direct Emissions	0.49116	87.78%
Total Indirect Emissions	0.06840	12.22%
Total Emissions	0.55956	100.00%