A comparison between linear and circular supply chains:
A case study from the construction industry

Abstract

In the last decades, green and sustainable supply chain management practices have been developed, trying to reduce negative consequences of production and consumption processes on the environment. In parallel to this, the circular economy discourse has been propagated in the industrial ecology literature and practice. Circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth. Therefore, circular economy is not just concerned with the reduction of the use of the environment as a sink for residuals but rather with the creation of self-sustaining production systems in which materials are used over and over again.

In this paper, through a case study from the construction industry, the performances of traditional and circular production systems will be compared. The paper asserts that an integration of circular economy principles within sustainable supply chain management can provide clear advantages from an environmental point view. Emerging supply chain management challenges and market dynamics are also highlighted and discussed.

1. Introduction

Over the past few decades, individual and corporate entities have become increasingly aware of the greater roles they need to play in improving environmental conditions and preserving natural resources. It has also been established that economic and production systems cannot be separated from the environment, with contemporary ecological economic theory emphasising the increasing impacts of human activities on the natural environment (Harte 1995). As a result, the emphasis on sustainability has become even more important in the present time. As such, sustainability has forced the redefinition of the operations function (de Burgos Jiménez and Lorente 2001). Additionally, sustainable supply chain management has become a strategic process enabling firms to create competitive advantage (Sivaprakasam 2014).

Within this context, in the last decades, sustainable supply chain management theories have been emerging (*inter alia:* Walton et al. 1998; Seuring and Müller 2008; Sarkis et al. 2011), suggesting that the requirement to take a holistic view of the whole product supply chain is a fundamental step for establishing greener and more sustainable production systems (Genovese et al. 2013) Such models could be based on the paradigm of *cradle-to-cradle*, encouraging the use of raw materials known as technical and biological nutrients, which do not have a negative impact on the environment, have an entirely beneficial impact upon ecological systems and return to the ecosystem without treatments (Braungart et al. 2007).

Interestingly, the concepts of green and sustainable supply chain management have been developed in parallel (although there are some fundamental differences in principles) to the circular economy discourse, which has been propagated in the industrial ecology literature and practice for a long time (Ehrenfeld 1995). In fact, sustainable supply chain management seeks to integrate environmental concerns into organisations by minimizing materials' flows or by reducing unintended negative consequences of production and consumption processes (Srivastava, 2007; Srivastava, 2008; Sarkis et al. 2011; Dong et al. 2014). On the other hand, as described by McDonough et al. (2002), circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth (Francas and Minner, 2007). This is achieved by creating a paradigm shift in the redesign of material flows based on long-term economic growth and innovation (Braungart et al. 2007). It is implied that circular economy is not just concerned with the reduction of the use of the environment as a sink for residuals (Andersen 2006) or with the delay of cradle-to-grave material flows (as sustainable supply chain management suggests) but rather with the creation of metabolisms that allow for methods of production in which materials are used over and over again (McDonough and Braungart 2000).

Finding ways to align sustainable supply chain strategies to circular economy principles, and understanding environmental and economic implications for this has therefore become important if the boundaries of environmental sustainability are to be pushed, especially in carbon-intensive industries.

To investigate these issues, a case study from the construction industry is analysed. This industry was chosen as there have been numerous claims that the construction sector is directly responsible for a relevant quota of global greenhouse gas emissions, solid waste generation, high-energy consumption and resource depletion (Griffiths et al., 2003; Ortiz, Castells and Sonneman, 2009). Specifically, this research will encompass the supply chains of two different types of insulation materials (a crucial component in the industry), by comparing a product resulting from a circular supply chain (in which waste is utilised as a raw material) to a product deriving from a traditional linear production system (in which virgin resources are utilised as input).

By using Life-Cycle Analysis, the main aim of this study is to assess the environmental impacts associated with the two supply chains, also understanding the market dynamics, policy and societal implications that could arise by the implementation of circular production systems.

To this aim, the study will be divided into four main parts. Firstly, a literature review will be presented, illustrating the principles of green supply chain management, circular economy, and generalities about frameworks for evaluating the environmental performance of supply chains. Section 3 presents the methodological notes about the employed LCA approach; also, generalities about the case study are provided. Section 4 analyses the results of the research. In Section 5, an analysis of different scenarios is performed, and then some conclusions are drawn.

2. Literature Review

2.1 Green Supply Chain Management

The production of products and services involve the movement of materials through a number of stages or involving single or multiple organisations. Supply chain management allows the design and management of flows of products, information and financial resources throughout these complex production systems (Sanders, 2012). Studies in the early twentieth century have shown the increased awareness in the importance of efficiently managing supply chains, with the emergence of modern practices such as lean and just-in-time (JIT) manufacturing (Svensson, 2001; Sarkis et al., 2011).

Within this context, thanks to the ever-growing consciousness within the society about the environment, sustainability has become a key priority in the design and operation of supply chains (Chopra and Meindl, 2007). Over the years, there are many variations in the definition and terminologies used to describe sustainable or green supply chain management; however, in general, principles of green and sustainable supply chain management concepts are largely aligned to an *utilitarian* environmentalist perspective, where the integration of environmental concerns in organisations are conducted by minimising material flows or by reducing negative impacts of production and consumption processes (Srivasta, 2008; Sarkis et al., 2011).

Green supply chain management practices ensure that green and environmental objectives are aligned with operational supply chain objectives. Early studies on the topic can be traced as early back as in the work of Ayres and Knees (1969), which addressed issues of material balancing and the roles of production and consumption in the supply chain. A rising number of papers, such as those from Seuring and Muller (2008) and Linton et al. (2007), address the loopholes from previous literatures such as that of De Burgos and Lorente (2001) which deal with environmental performance as an operations management objective, while supply chain issues are only secondarily addressed. Koh et al. (2013) supported this argument by identifying that some common themes within the sustainable supply chain literature have started to emerge. Moreover, recent studies have clearly shown the interconnection between supply chain strategies and their environmental consequences, hence underlining the fundamental importance of aligning an organisation's supply chain with its environmental targets (Hervani et al., 2005; Handfield et al., 2005).

For corporate entities, the transition towards green supply chains needs to be supplemented and informed by robust green supply chain research (Burritt et al., 2002). The measuring and benchmarking of the company's environmental performance with respect to the supply chain remains a challenging proposition. Difficulties may arise due to a number of factors such as the complexities of the supply chains (Beamon, 1999) as well as non-standardised data and geographical differences (Hervani et al., 2005). Furthermore, the frontiers of environmental sustainability within the supply chain are now pushed by the idea that there are workable relationships between industrial ecological systems and economic growth (Francas and Minner, 2009; Genovese et al., 2015).

2.3 Circular Economy

According to WRAP (2015), circular economy is defined as an economic paradigm where resources are kept in use as long as possible, with maximum value extracted from them while in use. The paradigm has its conceptual root in industrial ecology, emphasising the benefits of recycling waste materials and by-products (Jacobsen, 2006). The principles of circular economy thus extend the boundary of green supply chain management by devising methodologies to continuously sustaining the circulation of resources and energy within a quasi-closed system. This consequently reduces the need for new material inputs into production systems as well as minimising the use of virgin materials for economic activity (Andersen, 2006; Genovese et al., 2015).

In the European Union (EU), the European Commission had recently launched a consultation to cut waste and boost reuse of raw material. This consultation will be able to address the conclusion made by the Ellen Macarthur Foundation (2015) that the European economy operates in a linear take-make-dispose resource model that generates significant waste. The consultation seeks to find out measures that could be taken at EU level to overcome barriers in development of circular economy during manufacture and consumption of products (Early, 2015a). In response to the consultation, the European Parliament will consequently vote on proposals for a target to increase resource efficiency by 30 percent and to recycle 70 percent of waste by the year 2030 (Early, 2015b).

In essence, the concept of circular economy pushes for a *closed-loop* supply chain design, enabling any products at the end of their life cycle to re-enter the supply chain as a production input. As discussed by Chopra and Meindl (2007), although firms may produce recyclable products, it would not be sufficient without the support of the supply chain. In order to effectively enable recyclable products to be recycled, the concept of *Reverse Supply Chain Management* has been introduced (Li et al., 2014). It is defined by Guide Jr. and Wassenhove (2002) as a series of activities that are required in order to retrieve a used product from a customer and either dispose of it or reuse it. Guide Jr. and Wassenhove (2002) have also inferred that in general, companies that have been most successful with their reverse supply chains are those that are able to closely coordinate their reverse with their forward supply chains, creating a closed-loop system, hence maximising value creation over the entire life cycle of the product. However, it shall also be noted that reverse supply chains can also be *open-loop* where materials are recovered by parties other than the original producers and used in the production of different products (Genovese et al., 2015).

The idealistic paradigm of the circular economy might also be its Achilles heel; some have argued that in the European context, mainly dominated by free-market and neo-liberal ideologies, companies are already capturing most of the economically attractive opportunities to recycle, remanufacture and reuse. This leads them to claim that reaching higher levels of circularity may involve an economic cost that Europe cannot cope, especially as companies are already struggling with high resource price (Ellen Macarthur Foundation, 2015). Hence, policy interventions are also required alongside innovative business models currently adopted by companies.

2.4 Life Cycle Assessment

Sanders (2012) defined Life Cycle Assessment as an approach that considers environmental stewardship by analysing the environmental aspects and potential impacts associated with a product, process or service. Hence, the use of LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle (SAIC, 2006). This has been emphasised by Murphy and Norton (2008) and Acquaye et al. (2011), who stated that management strategies increasingly include usage of LCA for identifying environmental impacts and inefficiencies in resource use throughout the lifecycle of a product.

Although continuous advancements are being made in the development of LCA as a tool, the International Organization for Standardization ISO 14000 series framework is generally the consensus used globally (Rebitzer et al., 2004). Specifically, ISO 14040 and ISO 14044 provide the principles, framework, requirements and guidelines for undertaking LCA. Traditional LCA methodology or also known as process LCA, works by creating a system boundary dictated by the aims of the study and accounts for individual impact assessments within the system (Genovese et al., 2015). As value judgements involve several steps - for instance, different choices of boundaries (Carlson-Skalak et al., 2000) - different approaches might lead to different results (Matos and Hall, 2007). These differences, according to Matos and Hall (2007) inevitably lead to criticisms regarding LCA reliability, although there are methods available to enhance the credibility of the analysis. It is also important to note that traditional process LCA suffers from a systematic truncation error due to the delineation of system boundary and the omission of contributions outside this boundary (Suh et al., 2004). This has led to this methodology being described as incomplete, primarily because it is not possible to account for the theoretically infinite number of inputs of every complex product supply chains into the LCA system (Crawford, 2008; Genovese et al., 2015).

Nevertheless, LCA remains a useful indicator of the environmental impacts associated with a product’s life cycle and can be a basis for eco-labelling requested by consumers, non-governmental organisations (NGOs) and national as well as international authorities (Jensen et al., 1997). In addition, if LCA is used optimally, it can be a decision support tool that helps businesses to ensure that their choices are environmentally sound.

2.5 The Construction Insulation Materials Industry

Several recent studies have shown that greenhouse gas mitigation is now a central policy of almost all developed economies (Acquaye et al., 2011). It is also stated by Acquaye et al. (2011) that buildings, in particular, account for approximately 40 percent to 50 percent of total emissions in these countries. In the United Kingdom, the UK Green Building Council has identified construction as the most emission-intensive industry; being responsible for around 50 percent of greenhouse gas production in the country (Dhadhich et al., 2015). Fraunhofer (2009) highlighted that more attention should be given to the environmental impact of the construction industry as the industry is responsible for 40 percent of overall waste production in the European Union (EU).

From a holistic point of view, the Code for Sustainable Homes (Department for Communities and Local Government, 2006) states that the construction of buildings should emphasize optimum energy efficiency and the use of natural, reclaimed and recycled materials. On a larger scale, EU policies, such as the Construction Products Regulation, Eco Design Directive and Green Public Procurement are steering the construction industry towards more sustainable production and operation (Paroc, 2014).

Insulation of buildings is a major element in providing an economical route to achieving the requirements of these various regulations, as heating energy can be saved, hence contributing to conservation of energy resources and lowering air pollution from the combustion of fossil fuels (Schmidt et al., 2004). There are many different types of insulation materials available in the market, each produced from different resources such as sheep wool, stone wool, glass wool and natural fibre. Regardless of the types of materials, the levels of thermal insulation required either for new buildings or refurbishment projects, which are set by building regulations, have to be met. These are mainly expressed as a *U*-value, which is a measure of heat loss. Although of the same type (i.e., stone wool), different brands of insulation may exhibit different thermal insulation performance and require different amount of material to achieve the required *U*-value. Therefore, the *U*-value often becomes a useful indicator for customers to select their preferred insulation product.

Just as many other building materials such as plasterboards, insulation materials, both excess insulation materials from completed construction projects and materials reaching the end of their service life will most likely end up in landfill. With the introduction of regulations such as the Landfill Tax (Gov.uk, 2015), there are economic benefits that can be gained on top of environmental benefits of rerouting these materials to other avenues such as reuse or recycling. The introduction of increasingly popular environmental certificates also underlines the importance of building material ecology (Reed et al., 2010).

2.6 Importance of the Study

It is important to understand the environmental implications of utilising sustainable alternatives in various contexts and applications. The increasing understanding and adoption of environmental paradigms such as the circular economy requires a holistic assessment approach in which environmental impacts are brought into one consistent framework, regardless of whether these impacts have occurred or will occur (Genovese et al., 2015).

The availability of LCA on insulation products will enable well-informed decisions to be made by key stakeholders in the construction industry, taking into account the full consequences and benefits of their construction material selection. Producers of insulation products and other construction materials may also re-evaluate their supply chain and place greater emphasis on the sustainability of their products and supply chains.

The study will therefore seek to understand the potential impact of switching from conventional insulation materials to insulation materials produced using recycled sources.

3. Methodology

The main aim of this research is to evaluate and compare the environmental impacts associated with the supply chain of building insulation projects obtained from recycled materials (circular supply chain) to those associated with traditionally manufactured products (linear supply chain). Both the products considered in this research generally serve the same function, which is mainly to contain heat within a building. As established in the literature review, a Life Cycle Assessment (LCA) provides a good understanding of the environmental impacts of supply chains. A comprehensive LCA enables the identification of production paths associated with high energy and resource usage, as well as pollution and emission of greenhouse gases (Genovese et al., 2015). Therefore, LCA will form the foundation of the research, supported by the presentation of results through various means.

3.1 Life Cycle Assessment

The life cycle assessment framework deployed for this study is based on ISO 14040 published international standards (International Organisation for Standardisation (ISO), 2006), where the method for LCA is articulated in four main steps: Goal and scope definition; Inventory analysis; Impact assessment; Interpretation (Figure 1). In addition to these steps, scenario analysis is integrated into the framework to model potential impacts of various recommendations that could be generated from the result of the LCA.

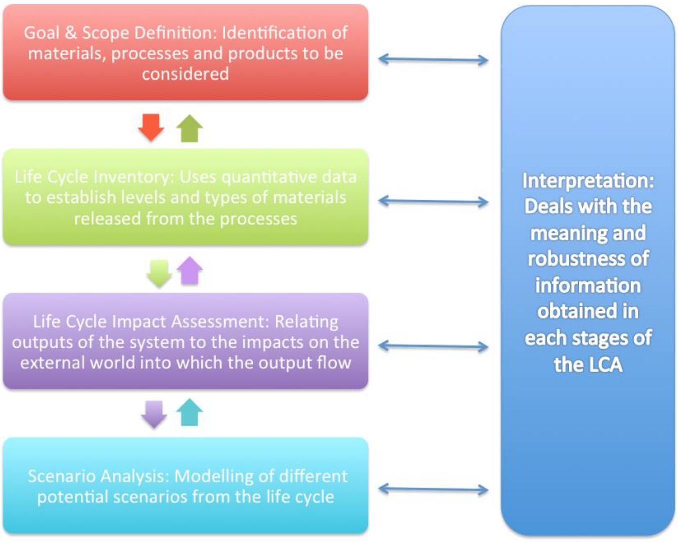

Figure 1: Adaptation of LCA standards according to ISO14040 (International Organisation for Standardisation, 2006) (Dadhich et al., 2015)

The environmental impact can be measured in many different ways depending on the chosen life cycle impact assessment (LCIA) method (Teehan and Kandlikar, 2012). One of the categories within the method as per the Intergovernmental Panel on Climate Change (IPCC) standard is the global warming potential over 100 years (GWP100) in kilograms of carbon dioxide equivalent (kgCO_2-eq). This method is adopted for this study due to the availability of data and because it has been used effectively in a large number of similar studies (Dadhich et al., 2015; Genovese et al., 2015; Acquaye et al., 2014; Teehan and Kandlikar, 2012).
It has to be noted that the study deploys *cradle-to-gate* analysis, where the assessment involves a partial product life cycle assessment from resource extraction (*cradle*) until it is packed at the factory, before it is transported to the customer (*gate*) (Guinee, 2002). Based on the aims of the study, the system boundary is determined in order to account for individual impact assessments within the system as highlighted in Table 1.

Table 1: Common material and activities included within the life cycle boundary (Altan and Timmis, 2011)

Raw Materials	Manufacturing
• All inputs used at any stage in the life cycle • Processes related to raw materials: -Mining/extraction -Pre-processing -Packaging -Storage -Transport • Account for the impact of raw materials	• All activities from collection of raw materials to distribution: -All production processes -Transport/storage related to production -Packaging -Site related emissions (e.g. lighting, ventilation, temperature) • All materials produced

3.2.1 Definition of a Functional Unit

The Functional Unit (FU) of the LCA is a measure of the function of the studied system and provides a reference to which the inputs and outputs can be related. According to ISO 14040 standards, the FU is defined as '*the quantified performance of a product system for use as a reference unit in a life cycle assessment study*'. In studies of thermal insulation products, the thermal resistance R, measured in m^2K/W, has been generally accepted as a meaningful and operational functional unit (Schmidt et al., 2004). The *R*-value is the measure of resistance to heat flow through a given thickness of material. Therefore, the higher the *R*-value, the more thermal resistance the material has and the better its insulating properties (Schmidt et al., 2004). In addition, it also gives information about the amount of insulation material that is required to achieve a certain thermal resistance within the product's lifetime. This consequently enables the comparison of two different products. This is arguably a very simplistic method to compare the performance of two insulating materials when the available information is the thickness of the material and the thermal conductivity. Heat moves in a number of different methods and the *R*-value only takes into account conduction. The *U*-value provides a more robust representation of the thermal insulation property of an insulation product. The calculation of *U*-value takes into account the three major ways in which heat loss occurs: conduction, convection and radiation. Nevertheless, the *R*-value is selected as the functional unit due to the availability of information for analysis and its adequate robustness as a meaningful and operational functional unit (Schmidt et al., 2004).

3.3 Supply Chain Mapping

The output of the LCA will be organised and presented in graphs reporting the total carbon emissions and the breakdown of the emission hotspots. In addition, tables (reporting the supply chain inputs, input category, related quantities, reference units, emissions intensities per reference units, total emissions, emissions percentage over total) for both the recycled insulation product (resulting from the circular supply chain) and stone wool one (resulting from the linear supply chain) will be presented in the Appendices section, while supply chain maps will visually represent the interaction between different entities (Dadhich et al, 2015). According to Koh et al. (2013), a supply chain map can be used to provide clear understanding of the flow of materials and the environmental impacts along the supply chain. This will then form the basis for benchmarking the environmental performance of the supply chains for both products and identify ways to manage the impacts.

The phases from upstream to downstream of the supply chain will be classified in the supply chain maps and their related emissions (e_n) amount will be colour-coded within thresholds shown in Table 2.

Table 2: Colour-code for emissions (Dadhich et al., 2015)

Impact	Interval	Colour-code
Low	$e_n \leq 1.00\%$	(green circle)
Moderate	$1.00\% \leq e_n \leq 5.00\%$	(yellow circle)
High	$5.00\% \leq e_n \leq 10.00\%$	(orange circle)
Very high	$e_n \geq 10.00\%$	(red circle)

3.4 Case study of insulation materials

Thermal and acoustics insulation materials represent one of the crucial components in the construction of new buildings and in renovation projects. In the United Kingdom (UK), the insulation market (exceeding £1 billion in 2008) forms a significant component of the construction industry (Murphy and Norton, 2008). With increasing emphasis on sustainable construction and green building, insulation plays a fundamental role in contributing to the environmental credentials of any construction projects; from how the insulation products are

manufactured and its supply chain, to the energy saving capability of the products through preventions of heat loss in buildings. One of the most commonly used insulation material within the construction industry is stone wool, which is produced using virgin raw materials from volcanic rock such as diabase or basalt, together with limestone and dolomite (Väntsi and Kärki, 2013); recently, alternative products, based on the recycling of used materials, have been proposed as an alternative to traditional materials.
This case study focuses on the environmental implications and performance of two insulation products that directly compete with each other in the same market segment. Commercial names of the products will not be disclosed for confidentiality reasons. The first product, resulting from a circular supply chain, is produced using recycled cottons (in the following, it will be indicated as P1); the second product – based on stone wool - is a common insulation type in the construction industry and produced from molten rock (in the following, it will be indicated as P2).
Data for the supply chain of P1 has been obtained from the UK distributor of the product, and are complemented with secondary data from Ecoinvent (2010). Similarly, Ecoinvent (2010) database was utilised to extract data related to the supply chain of P2. Due to the potentially diverse end-of-life scenarios for both types of insulation products, making direct comparison is very difficult. Even more so, the expected service life of many insulation products is relatively long, which is around 50 years (Murphy and Norton, 2008). Thus, the results from the LCA are considered for the *'cradle to gate'* part of the supply chain only. This includes the input of raw material, the production process, and up to but not including the distribution to final customer. The study also did not include the emissions associated with the installation of the product, its usage and disposal. The stages within the manufacturing of P1 up until the packaging at plant is shown in the process map in Figure 2.

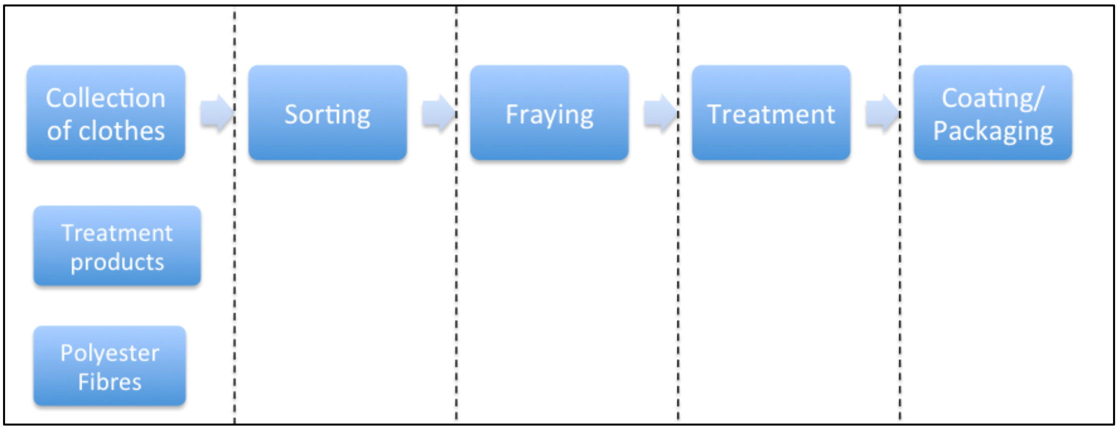

Figure 2: Supply chain of P1

As a direct comparison, the typical production process of P2 is shown in Figure 3.

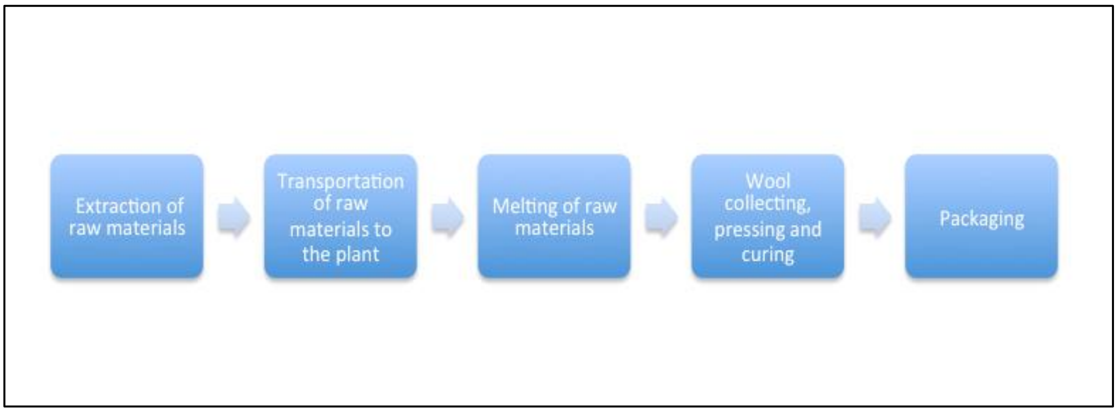

Figure 3: Typical supply chain for P2

The electricity source used in the processes for P2 manufacturing is based on the medium voltage electricity generated and transmitted for industrial use in the United Kingdom; for P1, the medium voltage electricity mix for France (where the product is primarily manufactured) is considered.

3.6 Data Collection

As mentioned in the previous section, the carbon emissions implications of the supply chain of the two types of insulation products being studied are obtained from both primary and secondary sources. The primary data is collected through direct communication with the company manufacturing P1 via face-to-face meetings, interviews, company reports and emails, while secondary data are sourced directly from Ecoinvent (2010) database. Ecoinvent is an online database with comprehensive Life Cycle Inventory (LCI) datasets, which have been used in a number of academic studies and corporate reports (Wiedmann et al., 2011). The following specific information was provided by for P1:

- The quantity of collected clothes for recycling and its proportion in terms of collection methods.
- The distance of transportation and types of transportation used for movement of materials in the supply chain.
- The quantity of energy consumption (electricity and gas) within the supply chain.
- Types and quantity of chemicals used in product treatment
- The process map of P1 production, from raw material to final product

From Ecoinvent (2010), the cumulative effects of emissions are presented using kilogram CO_2 equivalents (kgCO_2-eq) of the unit input over a 100-year period. For the stone wool (P2) insulation product, the quantity of materials for each Functional Unit (FU) is derived from Ecoinvent (2010) database. As for P1, the data given by the distribution company allows the quantity of each materials and processes required for the FU to be calculated. These quantities are multiplied with the emissions intensity per unit obtained from Ecoinvent (2010) and the total is summed up to give the total emissions of each product's supply chains.
The quantitative analysis from LCA is complemented by qualitative analysis through an interview with a P1 company representative. Interviews enable further in-depth details and information to be secured and supplement the quantitative data available. The interview was conducted face to face while the interview participant was selected from a list of personnel directly involved in the insulation industry. The main purpose of the interview was to dissect the cost elements of manufacturing the circular (P1) and linear (P2) and product alternatives, as well as identifying the market challenges associated with the implementation of circular

economy practices in the insulation materials industry. The majority of the questions asked in the interview were close-ended questions, set for exact and precise answers. Nevertheless, some open-ended questions were also laid out to gauge the dynamics of the insulation materials market, especially from the perspective of manufacturers adopting a circular supply chain.

4. Data Analysis

4.1 Preliminary findings

The functional unit for this research was defined according to a proposal from the Council for European Producers of Materials for Construction (CEPMC, 2000). The product lifespan is considered to be 50 years and an *R*-value of 1 m^2K/W. The same unit is used in the criteria for EU eco-labelling of insulation materials (Schmidt et al., 2004). It has to be noted however, that stone wool insulation materials come in a variety of brands and produced by different manufacturers. P1 has a thermal conductivity, λ, of 0.039 W/mk while the P2 stone wool insulation product chosen for this study has a thermal conductivity of 0.035 W/mK. Accordingly, the functional unit (FU) is defined as:

$$FU = R \cdot \lambda \cdot d \cdot A$$

Where:

- R is the thermal resistance to be obtained, assumed equal to 1 m^2K/W,
- λ is the thermal conductivity, which is 0.039 W/mK for P1 and 0.035 W/mK for P2;
- d is the density of the insulation products = 20 kg/m^3 for P1, 38 kg/m^3 for P2;
- A is the area of the insulation material to be considered (assumed equal to1 m^2).

The resulting unit in kilograms necessary to provide a thermal resistance of 1 m^2K/W for a use period of 50 years (Schmidt et al., 2004) is therefore shown in Table 3.

Table 3: The functional unit (in kg) necessary to provide a thermal resistance of 1 m^2K/W for a use period of 50 years (Schmidt et al., 2004)

Material	Thermal conductivity, λ (W/mK)	Density (kg/m^3)	Functional Unit (kg)	Corresponding insulation thickness (mm)
P1 (Circular)	0.039	20	0.78	39
P2 (Linear)	0.035	38	1.33	35

The preliminary data supplied by the company distributing P1 provided a comprehensive overview of the entire supply chain of the product, from collection of denim cottons to the packing process of the finished products. Each year, an average of 11,000 tonnes of clothes are collected to be processed as inputs for the production of P1. The clothes are collected using various methods in two types of sacks:

i) Type 1 sacks are made of High Density Polyethylene (HDPE). The manufacturing companies, distributes 15,000 sacks each day for three times a week, with each sack weighing 12 grams.
ii) Type 2 sacks are made from HDPE and weighs 18.5 grams each.

The clothes are collected using three different methods. These are identified as:

i) *Door-to-door collection* – sacks are distributed to individuals and later collected from door to door.
ii) *Collection in container* – individuals deposit the clothes in different containers located in various locations in France.
iii) *Collection among local groups* – Annually, 730 tonnes out of the 11,000 tonnes of clothes used in the production of P1 are collected from local groups.

The main methods of transportation used in transporting materials between the main production locations are lorries ranging from 3 tonnes up to 24 tonnes. In some cases, small vans are also utilised, specifically in the collection of clothes as input material. Another mean of transport utilised in the production of P1 is sea freight, where the bi-composite polyester binder manufactured in South Korea are transported (for 19,663 km) from Busan port to Le Havre in France.
The electricity used in the manufacturing process comes from the *Électricité de France* (EDF) grid, converted to medium voltage for use in the manufacturing facilities. The electricity consumption in different stages of the manufacturing process ranges from 0.0018 kWh to 0.3787 kWh for each Functional Unit of insulation material produced.
A summary of the quantitative data collected for the manufacturing processes of P1 and P2, along with associated environmental impacts, is shown, respectively, in Appendices A and B.

4.2 Supply Chain Mapping
The results of the analysis directly compare the carbon emission implications of producing insulation material using recycled sources (P1) through a circular open-loop supply chain compared to the production of stone wool insulation material (P2) through a linear production system. Results are summarised in Figure 4 while detailed breakdown of the supply chain emissions for both products are reported in Appendices A and B.
Using the methodology discussed in Chapter 3, the analysis shows that the emissions from the supply chain of stone wool (1.5090 kgCO_2-eq) is 64.02% higher than that from the production of P1 (0.9200 kgCO_2-eq). This preliminarily indicates that the emissions of P1 (the insulation product produced from a circular open-loop supply chain) are significantly lower than that produced from a linear supply chain. In addition, as P1 is produced mainly from waste cottons, the emissions that would have been generated from waste disposal are also avoided.

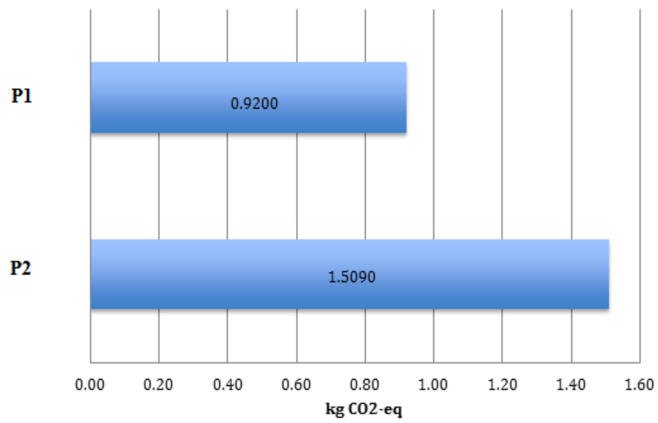

Figure 4: Comparative levels of emissions by P1 and P2 supply chains

The breakdown of CO_2-eq emissions for both P1 and P2 is presented in Figure 5.

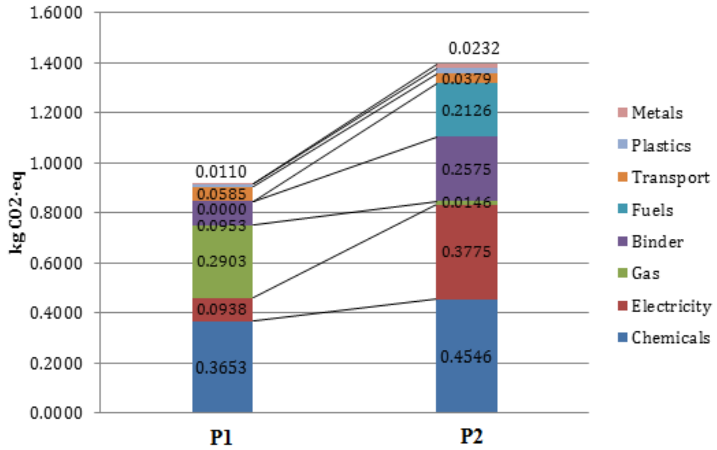

Figure 5: Breakdown of carbon emissions hotspots in P1 and P2 supply chains

It can be observed from the graph that within both supply chains, chemicals are the main "hotspots" for both P1 and P2 as there are a number of different chemicals used for product treatments. For P1, this contributes to 39.71% of the total emissions, which are caused by the chemicals used as treatment to add fire retardant properties and parasite resistance to the insulation materials. As for P2, the proportion of emissions contributed by chemicals is also significant at 30.12%; with phenol, urea and formaldehyde combining to a total of 27.75%; these are mainly the components for the binder (Pilato, 2010).

The environmental benefits from adopting circular supply chains can therefore be investigated in terms of the types of chemicals required for product treatment to produce insulation materials of identical thermal performances. The total emissions from chemicals required for treatment in the production of P1 is 0.3653 kgCO_2-eq, which is 19.64% lower than the emissions due to the chemicals used in product treatment for P2. This implies that the use of recycled cotton in the circular supply chain for P1 enables the input material to be treated with chemicals with lower environmental impact, compared to the linear supply chain.

Electricity is also a significant hotspot for both products' supply chains although it is much more prominent for P2 supply chain at 25.02% while the electricity emissions from P1 supply chain is 75.15% lower than P2 at 0.0938 kgCO_2-eq. This is due to the French electricity mix used in the production of P1. Further discussion on this aspect is provided in Section 5.

Transport is another major hotspot in P1 supply chain, forming 6.35% of the total carbon emissions. This is significantly higher than P2 where transport constitutes only 2.51 percent of the total emissions. The main proportion of the carbon emissions from the transport element of the P1 supply chain is from the clothing collection stage. As stated earlier, for P1, cotton clothing are collected from all around France using various methods with collection from containers forming 70.00% of the total annual input of clothes and consequently contributing to 4.01% of the total emission of P1. The average distance for collection from each container is 180 km, using 3 tonne lorries at average fill rate of 70%. This is another aspect that will be discussed further in Section 5.

The identification of carbon hotspots enables the impact of each phase of the materials' supply chain to be translated visually in supply chain carbon maps as seen in Figures 6 and 7.

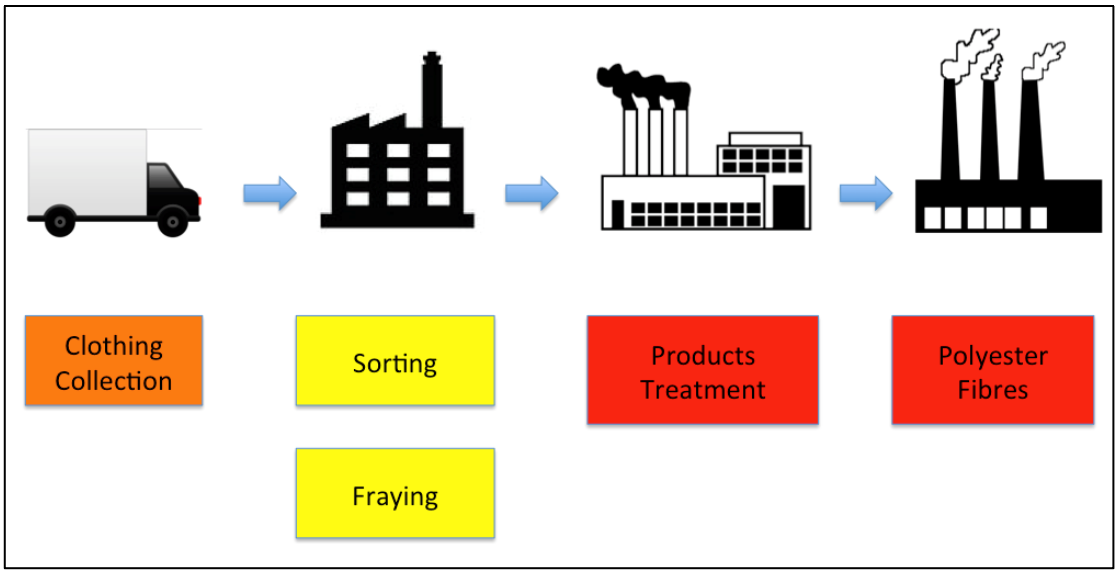

Figure 6: Supply chain Carbon Map for P1

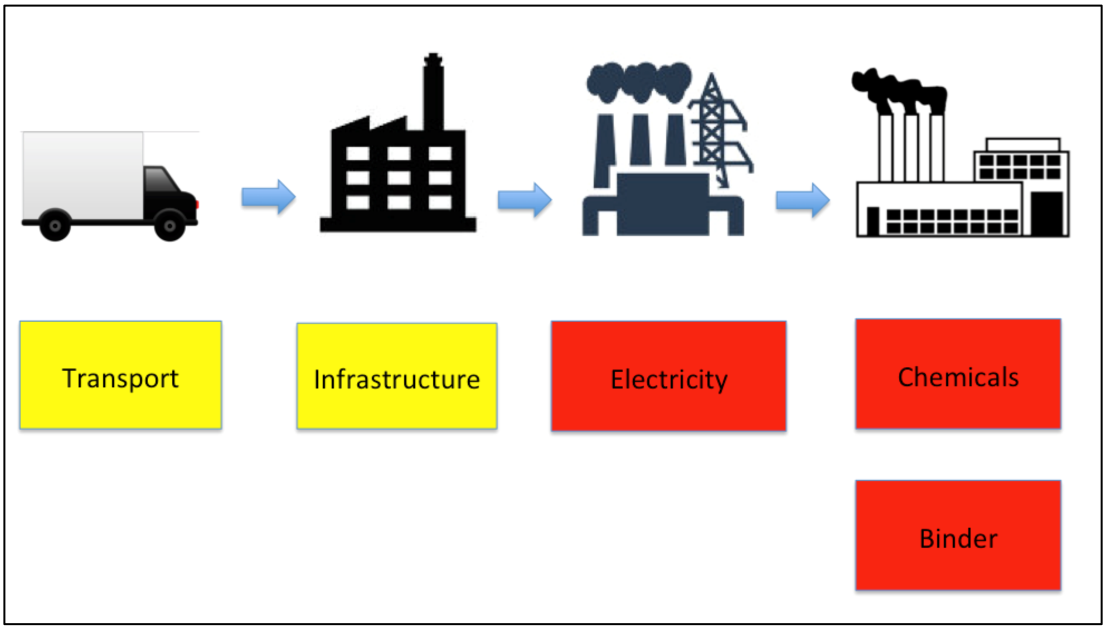

Figure 7: Supply chain Carbon Map for P2

The supply chain carbon map of P1 in Figure 6 presents the upstream and downstream carbon emissions of the product supply chain obtained using process LCA methodology. The main activities in the supply chain are the collection of clothing for recycling, sorting and fraying of the clothings, chemical treatment of the product and the manufacturing of the polyester fibres, which are used as binder for the material. Figure 6 reiterated the finding that product treatment activities and the manufacturing of bi-composite polyester binder are the main hotspots within the supply chain. This analysis estimates that product treatment activities contribute to 68.21% of the total lifecycle emissions while the manufacturing and transportation of binder accounts for 21.06% of the emissions. It has to be noted, however, that in both of these elements, the electricity used in the processes is also taken into account.
A slightly different approach was taken for the linear alternative, P2, where the electricity element is accounted separately. As shown in Figure 7, for P2, product treatment chemicals and binder material are the major carbon hotspots in the supply chain with each respectively

responsible for 30.12% and 17.06% of the supply chain carbon emissions. As it turns out, electricity is another major carbon hotspot, contributing to 25.02% of the carbon emissions. This is mainly attributed to the UK electricity grid, which still generates a major proportion of its electricity from non-renewable sources such as coal and natural gas.

4.3 Interview

An interview was conducted with the Director of the distribution company of P1 in the UK. The semi-structured interview was conducted face-to-face. The main issues and response from the interview are presented in Table 4.

Table 4: Main themes and response from interview

Issues	**Response**
Market condition	*Stone wool is the main product for conventional insulation. In the green segment, sheep wool has been introduced.*
Customers	*DIY people, home owners. Musicians, for their acoustic studios. Local authorities. Architects might specify it for customers who want green products. People who have some understanding on what makes something sustainable.*
Marketing challenge for P1	*People buy on price, full stop. When they buy insulation, they look for the cheapest. They might look for performance. They might not look for carbon emissions cost.*
Raw material	*There isn't any problem with it. It is easily accessible. We want to change the binder to bio binder. We are doing an R&D on that now. The denim cottons are collected in France. They have collection bins in France. They're getting it for free.*

Based on the interview, several have been identified by the company distributing P1 in the UK for further reducing the total emissions of the product. One of these is the change of the bi-composite polyester binder to a biological binder. This effectively corroborated with the findings of the analysis using supply chain mapping which identified the manufacturing of the binder as one of the major hotspots in the supply chain. The company believes that finding a binder that can provide optimum product performance while at the same time reducing the total carbon emissions from its life cycle will be the key to improving the environmental credentials of P1.

However, marketing a product manufactured through a circular supply chain presents major challenges in the industry, as the company believes that customers within the industry are more concerned with the price and performance of the insulation product, rather than the environmental credentials of its supply chain. The company distributing P1 is facing a tough challenge in making the price of their product competitive, as in the UK, many conventional insulation products receive subsidies from the government through several energy efficiency schemes operated by central and local government. These findings are consistent with results from Genovese et al. (2015), who stated that, in the current free-market economy, products resulting from circular supply chains may not be an economical alternative.

Also, it seems that the existing P1 customers already have some understanding and awareness on sustainable products. However, the company strongly believes that the general public should be better informed on the environmental credentials of the insulation products that they are using. This awareness can be cultivated from the provision of greater incentive from the government to encourage the purchase of products that can reduce the environmental impacts from activities such as new construction or renovation projects.

5. Discussion

In this section, further discussion on the implications of the results from the previous chapter will be provided. Different scenarios are modelled and potential strategies are identified to reduce the environmental impacts of the insulation materials supply chain. Two main scenarios are considered for the analysis: The electricity mix, and the configuration of the clothing collection methods (for product P1).

5.1 Scenario 1: The electricity mix

The worldwide energy demand is currently rising with some estimating that energy consumption will rise by 50 percent from 2005 to 2030; mainly due to rising population sizes and increased energy requirements of developing nations (U.S. Energy Information Administration, 2008). In many countries, the current energy demand is met mainly by using fossil fuels, which are in limited supply. The sources of energy, specifically electricity are therefore an important driver of environmental impacts that have to be considered when performing LCA (Bousquin et al., 2012; Teehan and Kandlikar, 2012).

In the data presented in Section 4, the scenarios considered in terms of electricity generation are based on the actual situation for production of both types of insulation products. P1 is manufactured and packed in France. Therefore, the emissions intensity figures considered for the electricity generation and transmission in the life cycle of P1 are based on France's energy mix (0.0946 kgCO_2-eq). Meanwhile, the production facilities of P2 are located in the United Kingdom, where the emission intensity for electricity is 0.6044 kgCO_2-eq. This is 538.90% percent higher than the emissions figure for France (Ecoinvent, 2010). This significant difference co-relates with the study by Holdway et al. (2010) shown in Table 5.

Table 5: Average CO_2 emissions from electricity generation (Holdway et al., 2010)

Country	Average emissions (g CO_2/kWh)
United States	605
United Kingdom	543
France	88

This difference in the figures can be interpreted through the proportions of electricity in the respective countries generated from fossil fuels. It was found that 66% of the electricity in the US, 62% in the UK and just 5% in France (U.S. Energy Information Administration, 2015; Department of Energy and Climate Change, 2014; Le réseau de l'intelligence électrique, 2015) are generated from fossil fuels. In France, 77% of the electricity produced in 2014 was from nuclear power while 17.7% was from renewable energy sources such as hydropower, wind and solar (Le réseau de l'intelligence électrique, 2015). This explains the very low level of carbon emissions associated with grid-connected electricity in France.

5.1.1 Different country location of production facilities (different grid electricity mix)

In order to investigate the impact of different scenarios involving the source of energy used in the production of P1 and P2, electricity inputs from different European countries were considered. The countries considered for this analysis are the production locations of the five of the main producers of stone wool insulation products (similar to P2), which together accounted for 95 percent of total production in Europe (EURIMA, 2009). The distribution of these plants is shown in Table 6.

Table 6: Number of mineral wool installations per country (Ecofys, 2009)

Country	**Facilities**	**Country**	**Facilities**
Austria	1	Italy	2
Belgium	1	Lithuania	3
Czech Republic	3	Netherlands	2
Denmark	3	Poland	8
Finland	8	Romania	2
France	6	Slovakia	1
Germany	11	Slovenia	2
Greece	1	Spain	4
Hungary	3	Sweden	5
Ireland	1	United Kingdom	5

According to Table 6, the production facilities for top stone wool producers in Europe are located in 20 European countries. Each country has different electricity mix and the impact of locating production facilities in these countries will be modelled into this analysis. Although the entire production and supply chain of P1 is mainly based in France, a similar modelling approach is adopted to investigate the impacts of having different electricity inputs from power grids of different countries. The analysis was conducted with the assumption that all other factors such as power consumption, transportation types, distances, production efficiency and inputs remain constant. Only the electricity input to the production facilities of both materials would be the variable for this analysis.

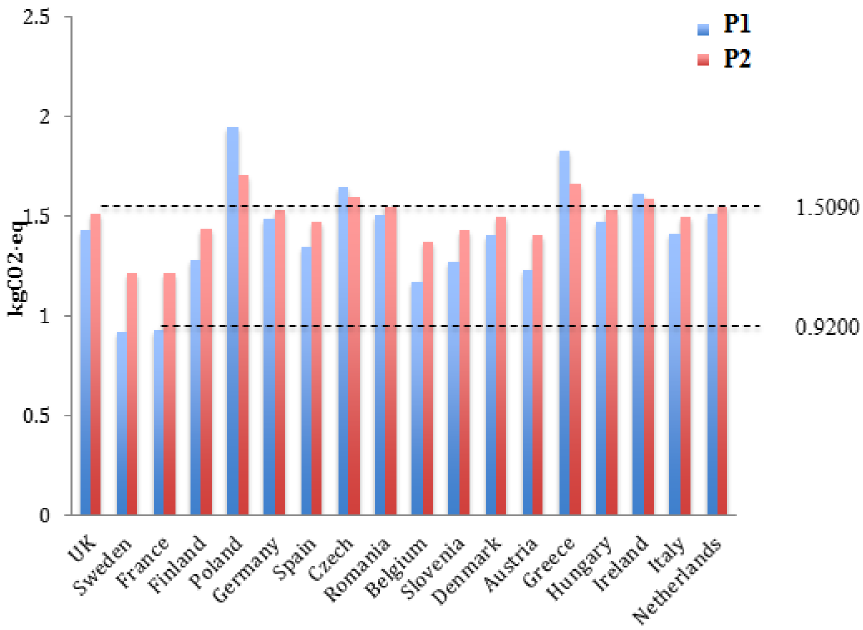

Figure 8: Total carbon emissions of insulation materials' supply chains produced in different countries

Based on the graph in Figures 8, the country with the lowest carbon emissions for the production of P2-type products (stone wool) is Sweden, followed by France and Belgium. In Sweden, 35.50% of its electricity mix is from renewable energy sources and 32.50% is from nuclear generation (International Energy Agency, 2013). This is reflected on the results shown in the graph in Figure 8 where by utilising Sweden's electricity mix, P1 will be able to reduce the total emissions from its supply chain by 0.72%. The difference is more significant for P2, as utilising Sweden's electricity mix rather than the UK's, would reduce the total emissions by 19.95%. Interestingly, the graph in Figure 8 also highlighted that the production of P1 is more electricity intensive than that of stone wool insulation.

The analysis indicated that utilising some country's electricity mix may significantly increase the total emissions of the supply chain of P1, to the extent that it becomes higher than the total emissions of producing stone wool insulation in that particular country. These are exhibited in countries such as Poland, Czech Republic, Greece and Ireland where the proportion of renewable energy electricity generation schemes connected to the national grid are still relatively lower than other European countries (International Energy Agency, 2013).

The analysis therefore establishes that re-locating production facilities can potentially enable manufacturers of both products to reduce the carbon emissions from their supply chains. However, this will require a significant supply chain re-design with substantial capital investment. The case for changing the electricity mix is even stronger for stone wool manufacturers as the emissions reduction will be more significant. P1 production facility, on the other hand is already operating in a country where the electricity mix from the grid is exhibiting very low emissions intensity, being among the lowest in Europe. The potential emissions reduction that can be gained by switching production location from France to Sweden is not very substantial. Nevertheless, this analysis can form the basis of any future feasibility studies if the company manufacturing P1 decides to expand the production to other European countries.

If the UK are able to replicate the electricity mix of any of the countries exhibiting low carbon emissions intensity for its electricity generation such as Sweden and France, the total emissions of products manufactured in the UK can be reduced and consequentially help establish the UK as a low carbon manufacturing hub. However, from the UK government's point of view, it is a significant task to reduce the emissions intensity of the country's electricity mix from 0.6044 kgCO_2-eq to Sweden's level of 0.0880 kgCO_2-eq, which is a 85.44%. At present, only 12 percent of UK's electricity is generated by renewable energy sources (Webster, 2014). Increasing this percentage would involve the decommissioning of existing coal-powered power plant, and building new renewable generation facilities such as wind turbines and tidal barrages. In addition, some of the feasible locations for these new generation facilities are not connected with sufficient transmission network capacity (Sustainable Development Commission, 2007). Therefore, large amount of capital investments will be required from both the government and energy companies in the effort to match Sweden's carbon emission level.

On the contrary, P1 manufacturing company's decision to re-locate the manufacturing facilities from the UK to France in 2013 gives a total emissions value that is 35.47% lower than the potential emissions if the manufacturing facilities were still located in the UK. It can also be observed from the graph that if P1 is produced in the UK, its total life cycle carbon emission would be only 5.52 percent lower than that of stone wool. Therefore, locating the production facilities in France has effectively enhanced P1's cause as a sustainable and environmentally friendly insulation product. Other product manufacturers looking to reduce the environmental impact from their manufacturing activities (especially if electricity intensive) may consider re-locating their production facilities to France. Nonetheless, many other factors will have to be taken into consideration before such decisions are made.

5.1.2 Micro Renewable Generation Schemes

As insulation material manufacturers have little or no control on the country's electricity mix, another potentially feasible approach that can be considered in efforts to reduce carbon emissions from the electricity is by commissioning micro-renewable generation schemes. Based on the assumption that the micro-renewable generation scheme caters for 100 percent of the production facility's electricity demand, the total carbon emission for production of both P1 and P2 is calculated. According to the Department of Energy and Climate Change (2011), there are a range of micro generation technologies available for commercial scale applications. These include solar photovoltaic (PV) panels, wind turbines, hydroelectric and bio energy.

The scenario is modelled by using emissions intensity values from Ecoinvent (2010) database of a range of renewable electricity generation schemes. Similar to section 5.1.1, these values are incorporated in the process LCA, replacing the emissions intensity of medium voltage electricity obtained from the grid of the country where the products are produced and assuming that all other elements such as power consumption remain constant. The results of this analysis are shown in the graph in Figure 9.

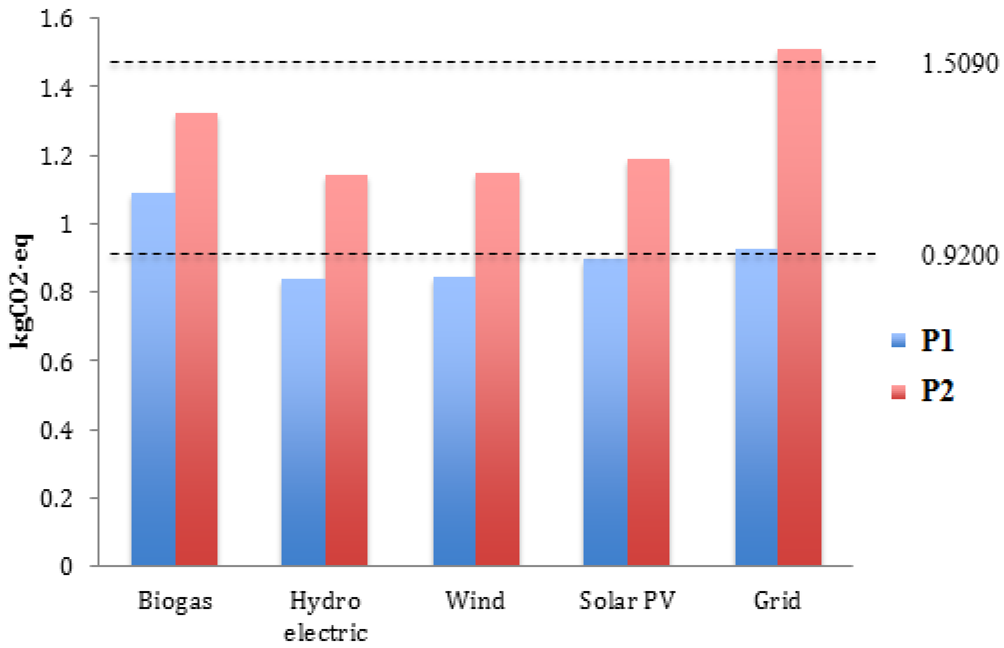

Figure 9: Total carbon emissions of supply chains of insulation materials produced with renewable electricity source

The result of the analysis indicates that switching to renewable energy sources in the production of both P1 and P2 generally reduces the total carbon emissions from the supply chain. The only exception is switching to electricity generated using biogas for P1, where the total emissions will actually increase by 16.08%. This is opposed to P2 case, where switching to biogas will reduce the total emissions by 18.57% to 1.3233 kg CO_2-eq. This is mainly attributed to the UK grid in which stone wool production facilities are connected to, which exhibits high emissions intensity level.

The renewable energy scheme that gives the highest amount of reduction in emissions for both P1 and P2 supply chains is hydro electricity with reductions of 9.02% and 36.72% respectively. Although the findings imply that hydro electricity generation may help to significantly reduce the supply chain carbon emissions of both products, the feasibility of commissioning such scheme at a micro-level needs to be investigated further. Running a hydroelectric generation scheme involves harnessing the energy from flowing water to generate electricity, which may only be feasible if the production facilities are located near flowing water sources such as river streams. Consequently, the impact to the local environment, particularly fish and the river ecosystem need to be carefully assessed prior to any construction of such schemes.

The next type of renewable generation scheme that can help reduce the lifecycle emissions of both types of insulation products is wind energy, with potential reductions of 8.27% for P1 and 36.09% for P2, resulting in total emissions of 0.8373 kg CO_2-eq and 1.1481 kg CO_2-eq respectively. Micro wind generation schemes are growing in Europe with good progress being seen in the development of standards for such schemes (Department of Energy and Climate Change, 2011). The Committee on Climate Change (2011) had identified that wind energy is a feasible replacement solution to non-reliable energy sources, as a great percentage of geographical locations in Europe have access to stable and reliable wind sources. Just like any other renewable generation schemes, the energy generated from wind turbines are intermittent and might not be able to match peak or off peak demand. Therefore, reliable electricity storage system should also be put in place. Alternatively, the manufacturing facility may also utilise a mix of both wind generation scheme and grid connected electricity to address this problem.

The use of solar photovoltaic (PV) schemes is also another example of how the total emissions from the supply chain can be reduced by utilisation of the renewable sources rather than depending on grid connected electricity. However, similar issues to both hydroelectric and wind power generation schemes need to be addressed in order to adopt solar PV as a feasible alternative to grid connected electricity. Nevertheless, continuous research and development have now resulted in more efficient and reliable solar PV technology being available commercially (Department of Energy and Climate Change, 2011).

In the UK, there are also economic benefits that can be gained by connecting the micro generation schemes to the grid through the introduction of Feed-in Tariff (FIT) scheme by the government. Through this scheme, Licenced Electricity Suppliers will pay generation tariffs to small or medium scale electricity generators for the electricity generated (Ofgem, 2013). Therefore, the implementation of renewable generation schemes, although may require a substantial capital investment, can potentially generate additional profit in addition to lower carbon emissions and reduced electricity bills.

5.2 Scenario 2: Configuration of clothing collection methods

This analysis will focus solely on P1, as the process involved, which is the collection of clothings, is only applicable to this circular supply chain. The supply chain map shown in Section 4 implies that transport, which forms the main element in the clothing collection process, is also a major carbon hotspot in the supply chain and categorised as a high impact element, which contributes to 6.31% of the total emissions. A significant proportion of this is attributed to the transport during clothing collection phase, with 5.69% of the overall emissions, where 3.98% of the total emission is from collection of clothes in containers. Collections from containers also form 70% of the total clothing collection. Therefore, this analysis will model different scenarios of clothing collection in containers to identify the configuration that will be able to reduce the existing carbon emissions. At present, clothes are collected from containers twice a week using 3 tonne lorries with a fill rate of 70 percent. This configuration results in 0.0369 kgCO_2-eq of emissions per functional unit. The analysis is conducted by changing the frequency of collection from the containers from twice a week, to a number of different frequencies. The types of vehicles used are also adjusted according to the frequency of collection, based on the assumption that the fill rate for each collection remains at an average of 70 percent.

Table 7: Scenario analysis of different clothing collection configuration

Frequency	Type of Vehicle	Total Emissions (kg CO_2-eq)
Twice a week (Base)	3.5T – 7.5T lorry	0.9200
Twice a week	7.5T – 16T lorry	0.9005
Once a week	7.5T – 16T lorry	0.8918
Once in 2 weeks	7.5T – 16T lorry	0.8875

The result of the analysis is shown in Table 7. The analysis shows that changing the type of collection vehicle from 3.5T to 7.5T lorry to a bigger 7.5T to 16T lorry without changing the frequency of collection reduces the total emissions by 2.12 percent. However, noting that the current average fill rate is 70 percent, switching to a bigger vehicle without changing the frequency of collection means that the fill rate will be significantly reduced. Although the bigger capacity lorries exhibits less carbon emission, the economics of using a bigger collection vehicle needs to be investigated further in terms of its fuel consumption and maintenance.

The analysis also shows that reducing the frequency of collection from containers will reduce the total emissions from the life cycle of P1. The result of the analysis shows that reducing the frequency of collection to once in a week reduces the total emissions by 3.07% compared to the base scenario and reducing the collection frequency to once in two weeks reduces the total emissions by 3.53% from the base scenario. This is achieved through reduced total transport distance, as well as the utilisation of lorries with bigger capacity, which evidently exhibits lower emissions intensity. Reducing the frequency of collection from containers located all over the country means that the manufacturer of P1 will need to allocate bigger storage facilities to store a bigger amount of clothes for a longer period. This will ensure a steady supply of material input for the next stages of manufacturing of P1.

5.3 Further Opportunities

The potential of adopting a more closed-loop supply chain through the recycling of end-of-life P1 insulation materials can also be explored. This can initially complement the existing input of waste cotton material before potentially being developed further to become another major source of input material. As regards P2 supply chain, some major stone wool insulation manufacturers are already exploring the potential of adopting a closed-loop circular supply chain by utilising their own waste insulation material as production inputs for new materials (Rockwool, 2013; Paroc, 2014). Some of these companies have even developed reverse logistics mechanisms to propel the concept forward within their organisations.

6. Conclusions

In the last decades, green and sustainable supply chain management practices have been developed, trying to reduce negative consequences of production and consumption processes on the environment. In parallel to this, the circular economy discourse has been propagated in the industrial ecology literature and practice. Circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth.

In this paper, through a case study from the construction industry, the performances of traditional and circular production systems have been compared.

Specifically, the research has compared the environmental impacts of the supply chains of two different types of insulation materials. The study aimed to identify whether the circular supply chain of the insulation material P1, which is made from recycled materials, exhibits lower carbon emissions than P2, which is produced through a traditional linear supply chain from virgin raw materials. The analysis was conducted using traditional process LCA methodology, utilising a combination of data provided by the industry and a reliable database, which is utilised by worldwide practitioners of LCA methodology. This has allowed the calculation and analysis of the total lifecycle emissions of the products being studied. In addition, supply chain carbon maps were derived, hence providing a greater visibility of the supply chain. The modelling of different scenarios enables the identification of potential strategies to reduce the environmental impacts of the two products.

The results from this research indicated that P1, which is the insulation material produced within a circular supply chain exhibits lower total carbon emissions within its production life cycle compared to stone wool insulation material which typically follows a linear supply chain route in its production life cycle. Supply chain carbon mapping showed that the use of chemicals in the treatment of both types of insulation products contributed to significant proportions of the total life cycle carbon emissions of both products. The results also show that transport elements dominate a larger proportion of the total emissions of the circular supply chain compared to the linear one This is mainly due to the clothing collection phase further upstream of P1 supply chain, which is transport intensive. Qualitative discussion resulting from an interview with industry stakeholders however questioned the economic viability of the circular supply chain.

One of the limitations of the research is the reliance on secondary data for the undertaking of the process LCA exercise. Another limitation in this study lies in the traditional process LCA methodology itself. As discussed in the literature review, its restricted system boundary is an issue that needs to be addressed in order to increase the accuracy of the environmental impact assessment.

In terms of future researches, more environmental indicators should be considered in order to perform a much more robust comparison between a linear and circular supply chain system. Apart from the Global Warming Potential (GWP), the measurement of other categories such as land and water usage and ozone depletion may provide more holistic overviews of the environmental impact associated with the supply chains. In addition, the bottom-up process LCA methodology used in this research could be integrated together with the top-down environmental input-output methodology to develop a hybrid LCA framework (Genovese et al., 2015). This will effectively resolve the complexity issue associated with LCA as discussed in the literature review of this research.

Also, attention will be devoted to the cited economic implications, in many cases representing the main challenge for the implementation of circular economy initiatives.

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Appendix A. Supply chain emissions breakdown for P1

Category	Input	Process	Quantity	Unit	Emissions Intensity (kgCO2-eq/unit)	Emissions (kgCO2-eq)	Emissions %
Chemicals	fungicides, at regional storehouse, RER (treatment process)	Treatment (Deinze)	0.0037	kg	10.5890	0.0394	4.28%
	diammonium phosphate, as N, at regional storehouse, RER (treatment process- fire retardant)	Treatment (Deinze)	0.0745	kg	2.8011	0.2087	22.68%
	diammonium phosphate, as P205, at regional storehouse, RER (treatment process- fire retardant)	Treatment (Deinze)	0.0745	kg	1.5745	0.1173	12.75%
Gas	natural gas, burned in boiler modulating <100kW, RER (treatment process)	Treatment (Deinze)	1.5584	MJ	0.0733	0.1143	12.42%
	natural gas, burned in boiler modulating <100kW, RER (manufacture of treatment products)	Treatment (Deinze)	1.5584	MJ	0.0733	0.1143	12.42%
	natural gas, burned in boiler modulating <100kW, RER (polyester)	Polyester	0.8424	MJ	0.0733	0.0618	6.71%
Transport	transport, lorry 16-32T, EURO4 (Delivery of collection sacks to Relaise)	Collection	0.0014	tkm	0.1656	0.0002	0.03%
	transport, van <3.5T, RER (Delivery of collection sacks to individuals)	Collection	0.0003	tkm	1.9154	0.0005	0.06%
	transport, lorry 3.5-7.5T, EURO4, RER (collecting bundles)	Collection	0.0338	tkm	0.4689	0.0158	1.72%
	transport, lorry 3.5-7.5T, EURO4, RER (in containers)	Collection	0.0786	tkm	0.4689	0.0369	4.01%
	transport, lorry 16-32T, EURO4, RER (phase association 1)	Collection	0.0066	tkm	0.1656	0.0011	0.12%
	transport, lorry 16-32T, EURO4, RER (phase association 2)	Collection	0.0033	tkm	0.1656	0.0005	0.06%
	transport, lorry 16-32T, EURO4 (Transport Bruary-Billy)	Sorting (Bruay)	0.0202	tkm	0.1656	0.0034	0.36%
	transport, lorry 16-32T, EURO4 (Transport Billy-Deinze)	Fraying (Billy)	0.0000	tkm	0.1656	0.0000	0.00%
	transport, lorry 7.5-16T, EURO4 RER (manufacture of treatment products)	Treatment (Deinze)	0.0000	tkm	0.2216	0.0000	0.00%
	operation, freight train, RER (manufacture of treatment products)	Treatment (Deinze)	0.0000	tkm	0.0292	0.0000	0.00%
	transport, lorry 7.5-16T, EURO4 RER (transport of the treatment chemicals)	Treatment (Deinze)	0.0000	tkm	0.2216	0.0000	0.00%
	transport, lorry 16-32T, EURO4 (Transport Deinze-Billy) (treatment process)	Treatment (Deinze)	0.0000	tkm	0.1656	0.0000	0.00%
	transport, transoceanic freight ship, OCE (Polyester) (Busan-Havre)	Polyester	0.0000	tkm	0.0108	0.0000	0.00%
	transport, lorry 16-32T, EURO4 (Polyester) (Jeonju-Busan-Le Havre-Billy)	Polyester	0.0000	tkm	0.1656	0.0000	0.00%
Electricity	electricity, medium voltage, production FR, at grid	Sorting (Bruay)	0.0018	kWh	0.0946	0.0002	0.02%
	electricity, medium voltage, production FR, at grid (shredding phase)	Fraying (Billy)	0.3787	kWh	0.0946	0.0358	3.89%
	electricity, medium voltage, production FR, at grid (treatment process)	Treatment (Deinze)	0.1303	kWh	0.0946	0.0123	1.34%
	electricity, medium voltage, production FR, at grid (manufacture of treatment products)	Treatment (Deinze)	0.1303	kWh	0.0946	0.0123	1.34%
	electricity, medium voltage, production FR, at grid (polyester)	Polyester	0.3510	kWh	0.0946	0.0332	3.61%
Plastics	polyethylene, HDPE, granulate, at plant, RER (collection sacks)	Collection	0.0016	kg	1.9485	0.0031	0.33%
	polyethylene, HDPE, granulate, at plant, RER (treatment process)	Treatment (Deinze)	0.0002	kg	1.9485	0.0003	0.03%
	injection moulding, RER (treatment process)	Treatment (Deinze)	0.0037	kg	1.3342	0.0050	0.54%
	packaging film LDPE, at plant RER (roll PEBD (treatment process)	Treatment (Deinze)	0.0010	kg	2.7004	0.0026	0.29%
Binder	extrusion, plastic pipes, RER (polyester)	Polyester	0.1232	kg	0.3776	0.0465	5.06%
	packaging film LDPE, at plant RER (polyester)	Polyester	0.0181	kg	2.7004	0.0488	5.30%
Metals	cast iron, at plant, RER (Iron wire 1)	Sorting (Bruay)	0.0001	kg	1.5166	0.0002	0.02%
	cold impact extrusion, steel, 5 strokes, RER (Iron wire 1)	Sorting (Bruay)	0.0001	kg	1.2888	0.0002	0.02%
	cast iron, at plant, RER (Iron wire 2) (shredding phase)	Fraying (Billy)	0.0003	kg	1.5166	0.0005	0.05%
	cold impact extrusion, steel, 5 strokes, RER (Iron wire 2) (shredding phase)	Fraying (Billy)	0.0003	kg	1.2888	0.0004	0.04%
	cast iron, at plant, RER (Iron wire 3) (treatment process)	Treatment (Deinze)	0.0003	kg	1.5166	0.0005	0.06%
	cold impact extrusion, steel, 5 strokes, RER (Iron wire 3) (treatment process)	Treatment (Deinze)	0.0003	kg	1.2888	0.0004	0.05%
Wooden Materials	EUR-flat pallet, RER (treatment process)	Treatment (Deinze)	0.0000	Unit	6.1595	0.0000	0.00%
	EUR-flat pallet, RER (polyester)	Polyester	0.0006	kg	6.1595	0.0035	0.38%
Water	tap water, at user, RER (treatment process)	Treatment (Deinze)	0.2231	kg	0.0003	0.0001	0.01%
					Total Emissions (kgCO2-eq/kg)	**0.9200**	**100.00%**

Appendix B. Supply chain emissions breakdown for P2

Category	Input	Process	Quantity	Unit	Emissions Intensity (kgCO2-eq/unit)	Emissions (kgCO2-eq)	Emissions %
Chemicals/ Organics	1-butanol, propylene hydroformylation, at plant	Acrylic	0.0000	kg	2.6104	0.0001	0.01%
	chemical plant, organics	Acrylic	0.0000	unit	123660000.0000	0.0004	0.03%
	ethylene glycol, at plant	Acrylic	0.0003	kg	1.5726	0.0005	0.03%
	butyl acrylate, at plant	Acrylic	0.0001	kg	4.3408	0.0003	0.02%
	chemicals organic, at plant	Acrylic	0.0000	kg	1.8984	0.0001	0.00%
	phenol, at plant	Rock wool	0.0289	kg	3.8691	0.1800	11.93%
	urea, as N, at regional storehouse	Rock wool	0.0178	kg	3.3102	0.0951	6.30%
	lubricating oil, at plant	Rock wool	0.0038	kg	1.0506	0.0064	0.42%
	formaldehyde, production mix, at plant	Rock wool	0.0804	kg	1.1074	0.1436	9.51%
	hexamethyldisilazane, at plant	Rock wool	0.0003	kg	3.0550	0.0014	0.09%
	ammonia, liquid, at regional storehouse	Rock wool	0.0045	kg	2.0974	0.0153	1.02%
	oxygen, liquid, at plant	Rock wool	0.0001	kg	0.4091	0.0001	0.00%
	ammonium bicarbonate, at plant	Rock wool	0.0017	kg	1.1753	0.0033	0.22%
Electricity	electricity, medium voltage, production UCTE, at grid	Acrylic	0.0023	kWh	0.5314	0.0012	0.08%
	electricity, medium voltage, at grid	Rock wool	0.3798	kWh	0.6044	0.3702	24.53%
	electricity, medium voltage, production NORDEL, at grid	Board	0.0000	kWh	0.1707	0.0000	0.00%
	electricity, medium voltage, production UCTE, at grid	Board	0.0000	kWh	0.5314	0.0000	0.00%
	electricity, medium voltage, at grid	Board	0.0000	kWh	0.6044	0.0000	0.00%
	electricity, high voltage, at grid	Electricity	0.0042	kWh	0.5929	0.0025	0.16%
	transmission network, electricity, medium voltage	Electricity	0.0000	km	18444.0000	0.0000	0.00%
	electricity, low voltage, production UCTE, at grid	Gas	0.0002	kWh	0.5946	0.0036	0.24%
Binder	portland cement, strength class Z 42.5, at plant	Rock wool	0.1929	kg	0.8220	0.2556	16.94%
	lime, hydrated, packed, at plant	Rock wool	0.0015	kg	0.7638	0.0019	0.12%
Transport	transport, lorry>16t, fleet average	Acrylic	0.0007	tkm	0.1336	0.0001	0.01%
	transport, freight, rail	Acrylic	0.0039	tkm	0.0396	0.0002	0.01%
	transport, freight, rail	Rock wool	0.2094	tkm	0.0396	0.0134	0.89%
	transport, lorry >28t, fleet average	Rock wool	0.1089	tkm	0.1372	0.0241	1.60%
	transport, van <3.5t	Board	0.0000	tkm	1.9154	0.0000	0.00%
	transport, lorry >16t, fleet average	Board	0.0001	tkm	0.1336	0.0000	0.00%
	transport, freight, rail	Board	0.0004	tkm	0.0396	0.0000	0.00%
	transport, lorry >16t, fleet average	Machine	0.0000	tkm	0.1336	0.0000	0.00%
	transport, lorry >16t, fleet average	Packaging	0.0009	tkm	0.1336	0.0001	0.01%
	transport, freight, rail	Packaging	0.0017	tkm	0.0396	0.0001	0.00%
Fuels	hard coal coke, at plant	Rock wool	6.9762	MJ	0.0189	0.2126	14.09%
	heavy fuel oil, at regional storage	Board	0.0000	kg	0.4525	0.0000	0.00%
	light fuel oil, at regional storage	Board	0.0000	kg	0.5092	0.0000	0.00%
Gas	natural gas, high pressure, at consumer	Rock wool	1.1223	MJ	0.0020	0.0036	0.24%
	natural gas, high pressure, at consumer	Board	0.0007	MJ	0.0020	0.0000	0.00%
	natural gas, high pressure, at consumer	Gas	0.2133	MJ	0.0020	0.0108	0.72%
	industrial furnace, natural gas	Gas	0.0000	unit	10379.0000	0.0002	0.01%
Machinery	diesel, burned in building machine	Rock wool	0.0661	MJ	0.0920	0.0098	0.65%
Materials	refractory, fireclay, packed at plant	Rock wool	0.0011	kg	1.1896	0.0020	0.13%
	glass wool mat, at plant	Rock wool	0.0004	kg	1.4958	0.0011	0.07%
Metals	bauxite, at mine	Rock wool	0.0828	kg	0.0080	0.0011	0.07%
	aluminium, production mix, wrought alloy, at plant	Rock wool	0.0008	kg	10.8810	0.0134	0.89%
	sheet rolling, aluminium	Rock wool	0.0008	kg	0.6025	0.0007	0.05%
	brass, at plant	Machine	0.0000	kg	2.4599	0.0000	0.00%
	bronze, at plant	Machine	0.0000	kg	2.7792	0.0000	0.00%
	cast iron, at plant	Machine	0.0000	kg	1.5166	0.0000	0.00%
	steel, low-alloyed, at plant	Machine	0.0000	kg	1.7555	0.0000	0.00%
	aluminium, production mix, at plant	Machine	0.0000	kg	8.4236	0.0000	0.00%
	section bar rolling, steel	Machine	0.0000	kg	0.1985	0.0000	0.00%
	steel, low alloyed, at plant	Pallet	0.0003	kg	1.7555	0.0006	0.04%
Production	acrylic binder, 34% in H2O, at plant	Acrylic	0.0039	kg	1.4621	0.0057	0.38%
Chemicals/ Inorganics	titanium dioxide, chloride process, at plant	Acrylic	0.0020	kg	4.1315	0.0081	0.53%
	biocides, for paper production, unspecified, at plant	Board	0.0000	kg	5.6482	0.0000	0.00%
	sulphur hexafluoride, liquid, at plant	Electricity	0.0000	kg	122.9400	0.0000	0.00%
Additives	basalt, at mine	Rock wool	0.9373	kg	0.0075	0.0113	0.75%
Facilities	rock wool plant	Rock wool	0.0000	unit	60156000.0000	0.0571	3.79%
Papers	kraft paper, unbleached, at plant	Rock wool	0.0041	kg	0.8486	0.0056	0.37%
	corrugated board base paper, kraftliner, at plant	Board	0.0004	kg	0.6600	0.0003	0.02%
	corrugated board base paper, wellenstoff, at plant	Board	0.0006	kg	0.8180	0.0005	0.03%
	corrugated board base paper, testliner, at plant	Board	0.0004	kg	0.8209	0.0003	0.02%
	paper mill, non-integrated	Board	0.0000	unit	117830000.0000	0.0000	0.00%
Agricultural	potato starch, at plant	Board	0.0000	kg	0.7174	0.0000	0.00%
Others	limestone, milled, packed, at plant	Rock wool	0.1242	kg	0.0193	0.0039	0.26%
	dolomite, at plant	Rock wool	0.1090	kg	0.0281	0.0049	0.33%
Water Supply	Water, unspecified natural origin (tap water, at user)	Acrylic	0.0000	m3	0.0003	0.0000	0.00%
	tap water, at user	Rock wool	0.1688	kg	0.0003	0.0001	0.01%
	tap water, at user	Board	0.0005	kg	0.0003	0.0000	0.00%
Wooden Materials	particle board, outdoor use, at plant	Pallet	0.0000	m3	329.7500	0.0064	0.42%
	sawn timber, softwood, raw, air dried, u=20%, at plant	Pallet	0.0001	m3	58.4810	0.0032	0.21%
Waste Management	disposal, emulsion paint remains, 0% water, to hazardous w	Acrylic	0.0000	kg	2.5327	0.0000	0.00%
	disposal, municipal solid waste, 22.9% water, to municipal i	Rock wool	0.0022	kg	0.5049	0.0018	0.12%
	treatment, sewage, to wastewater treatment, class 3	Rock wool	0.0010	m3	0.3884	0.0006	0.04%
	disposal, used mineral oil, 10% water, to hazardous waste in	Rock wool	0.0001	kg	2.8526	0.0004	0.03%
	disposal, solvents mixture, 16.5% water, to hazardous waste	Rock wool	0.0000	kg	1.9839	0.0001	0.00%
	disposal, zeolite, 5% water, to inert material landfill	Board	0.0000	kg	0.0071	0.0000	0.00%
Plastics	epoxy resin, liquid, at plant	Machine	0.0000	kg	6.7304	0.0000	0.00%
	polyethylene, LDPE, granule, at plant	Packaging	0.0088	kg	2.1026	0.0186	1.23%
	extrusion, plastic film	Packaging	0.0088	kg	0.5240	0.0046	0.31%
					Total Emissions (kgCO2-eq/kg)	**1.5090**	**100.00%**