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SUSTAINABILITY ASSESSMENT OF PLASTIC SHEET PILING

Carbon Footprinting analysis for THE Plastic Piling Company

Abstract

Sustainability of the product is becoming a crucial factor for success in the market. Sustainability theory and methods are quite general. This research constitutes a serious attempt to assess the sustainability of plastic sheet piling, and calculate the product carbon footprint. In the case of plastic sheet piling no significant previous research has been done to address sustainability. The product lifecycle including stages such as raw material production, manufacturing, transportation, installation, and disposal/recycling, and its related supply chain have been analysed in detail to identify those factors that have impact on the product carbon footprint and the three main dimensions of sustainability: environmental, social and economic. The installation stage, which is not normally addressed in this kind of studies, has been assessed by the development of a case study. This case study could be the foundation of a future trial case that allows evaluating this stage objectively.

The methods that have been developed and customised to assess both carbon footprint and sustainability of plastic sheet piling can be used as guidelines for the evaluation of similar products within the sector.

One of the main conclusions of the study is that although the product design influences the carbon footprint, overall there is little difference between products used within the same category of applications. Therefore, installation is the deciding factor, and the hybrid solutions, which has been proven to install faster and more efficiently, have emerged as the most sustainable products. The results of the study could be used by stakeholders as key factor in decision-making.

Keywords - Carbon Footprint, PVC, Triple Bottom Line, Sustainability indicator, Lifecycle, Installation

1. Introduction

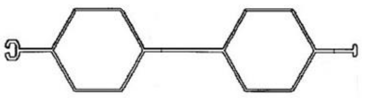
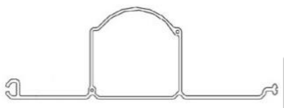
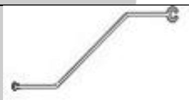
The fast pace of development of the world and the increased demands from consumers are putting pressure on the resources of the planet. This requires urgent attention by means of addressing the issue of sustainability in all aspects of life in all its three dimensions, i.e. environmental, economic and social. Therefore, the sustainability of the products and its processes has become an essential feature of successful business and wellbeing of the society. The goal of sustainability is to “meet the needs of the present generations without compromising the ability of future generations to meet their own needs” (WCED 1987 and Arena et al, 2009). However, for many businesses, product sustainability could be understood in terms of how long any particular product or service could exist in the market and fully satisfy customer requirements (expectations), before being replaced by another more up-to-date product. Furthermore, the concept of carbon footprint has been very much associated with the sustainability issue and it is considered one of its main indicators as it measures environmental impacts translated into emission of CO_2 equivalent.

A decade ago, plastic material which makes a positive contribution to the sustainability issues, started to attract the attention of the sheet piling sector. However, the authors found no comprehensive studies about carbon footprint and sustainability of the plastic sheet piling. The aim of this paper is to present the result of a sustainability assessment of plastic sheet piling based detail study and calculate the carbon footprint of the range of plastic sheet piling that are commonly used within the sector. The results will be used as part of the customised product sustainability assessment in order to address the environmental, social and economic needs of the stakeholders involved through the product’s lifecycle of the plastic sheet piling.

2. Background of plastic piling

Plastic sheet piling (PSP) is a type of sheet piling that is driven using interlocking sheets of its main material to form a wall in the ground. The applications of plastic sheet piles are soil retention, erosion control, cut-off wall, retaining wall, flood protection, temporary works, seawall, wave reduction, highway applications, ground water and/or chemical containment or diversion, water flow control, bank stabilization. The usage of sheet piling covers a broad area and its use is becoming popular not only as structural construction product, but also as an ornamental element.

1.1 The geometry of plastic sheet piling profile differs between manufacturers. Some tend to keep the same shape as steel ones. However, shape innovation is being developed by manufacturers whilst trying to utilize hybrid systems (which combine the use of plastic piles with timber or steel poles) in order to reduce material requirements. The cross section of the plastic sheet piles discussed in this paper.

P1 Multilock	
P2 Prolock	
P3 EcoZ	

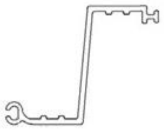
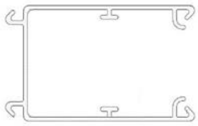
P4 Europile	
P5 UltraZ	
P6 Truline	

Figure 1 Cross section

The positive impact on sustainability could be highlighted by performing comparison between several materials that could be used in the same application as shown in Table 1. Steel, concrete and PVC can all used as raw materials for sheet piling. The resistance for environmental conditions and fire, the life, recovery, main usage, and manufacturability of the material, and the related indirect emissions and pollution are the standpoints that are considered when compared in terms of sustainability.

Material	**Steel**	**Concrete**	**PVC**
Resistant for different environmental conditions	Wide range that can be used in all kind of environmental conditions but needs special treatment	Wide range that can be used in all kind of environmental conditions but needs special treatment	Resistant that can be used in all kind of environmental conditions without the need of special treatment
Life of material	50 years	50-70 years	75 years
Material recovery	Full or partial	No	Full or partial
Main usage	Road construction Underground construction Flood protection Construction of landfills	Foundation objects Foundations of bridges Secure of excavation	Cut-off walls Ditch blocking Retaining wall Bank stabilization Erosion control Drainage channels Bank retention Flood defence
Manufacturing	No production in the UK	Available	Wide availability
Fire resistance	Decrease of bearing capacity More sensitive to heat than concrete At relatively low temperature steel starts to elongate In 500°C steel bears tensile stresses and reaches its yield	Till 500°C it is resistant to fire, above 500°C the strength is almost 0	Highly resistant
Transportation	Not difficult but neither easy	Difficult to transport, special treatment is needed to keep its properties	Easy to transport, light
CO_2 emission during manufacturing process (kg CO_2 e/m^3)	Steel – 17000 Recycled steel - 4000	400	5000
Fossil fuel energy used in the manufacturing (MJ/kg)	35	2	80
Pollution	Gases: 95% CO_2, CO, NO, SO_2 Sewage – 0.06m^2/t, Solid waste, Soil – landfill without sealed ground and sewage collection, Waste: dust – 0.9-15 kg/t, Sludge – 0.3kg/t, Noise: 95-115 dB	Gases: CO_2 Dust	Phthalate plasticizers Vinyl chloride monomer Dioxins

Table 1: Material comparison of steel, concrete and PVC

PVC contributes with some features that have positive effect on the sustainability of plastic piling products such as long lifetime, no maintenance required, possibility of recycling material, light - easy handling and transportation, does not rust, and good fire resistance.

One of the key engineering parameters used in design is the bending moment that a sheet pile can bear. It allows an easy strength comparison of the range of plastic sheet pile. Figure 2 summarises the maximum allowable bending moment for the plastic sheet piling in the range of The Hammerman PPC. (THE Plastic Piling Co 2011)

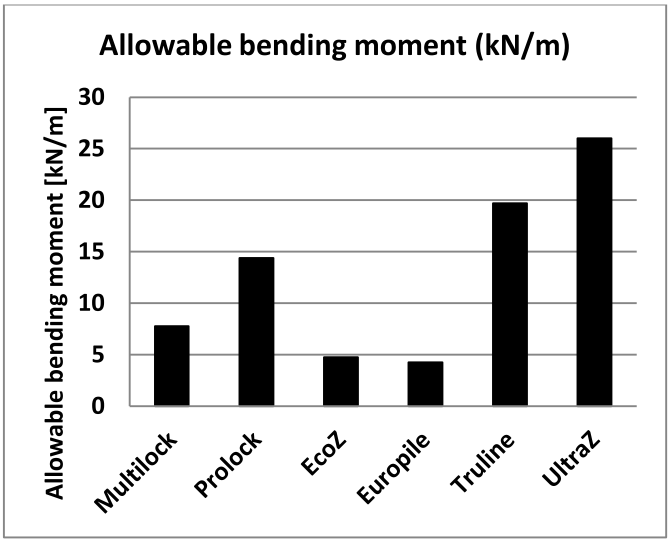


Figure 2: Strength comparison

The most common methods of installing sheet piles are determined by the type of wall piles. One is cantilever wall/sheet piling`s resistance depends on the passive resisting capacity of the soil for preventing overturning.

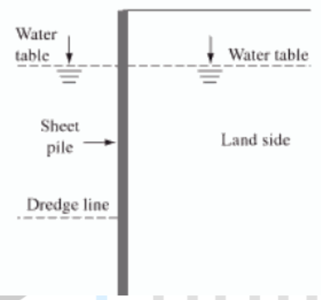


Figure 3 Example of waterfront sheet-pile wall

The second is anchored wall additional strength is included using cables which will be anchored to the soil. Therefore, there are new components in the system such as wales and tie-road.

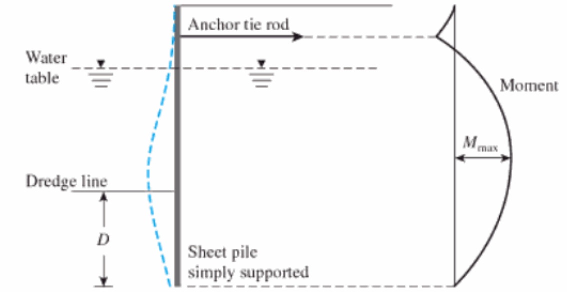


Figure 4 Exampled of anchored wall

The third is a cut-off wall application the sheet piling only has to resist load when it is driven. The intention of the construction reduces water seepage.

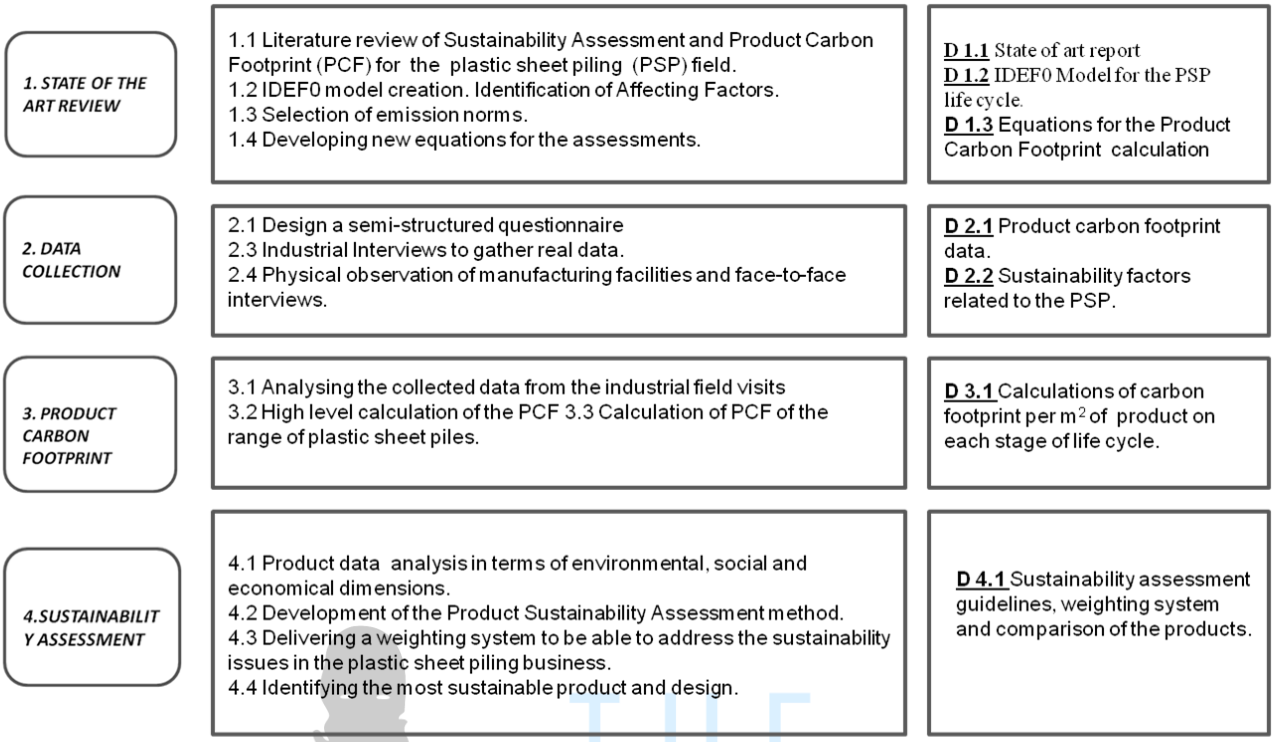
A large number of installation methods are available, from vibrating hammer broadly extended in plastic sheet piling, to manual installation. Three basic driving techniques can be used to install sheet piles (whether is steel or plastic) such as impact driving, vibratory driving, and jacking. Driving sheet piles using vibration hammers is possible due to the reduction of the static soil resistance around the pile however other authors consider that piles are not installed because of the vibrating force, but because of the sinking of the pile into the soil under gravity forces (Huybrechts et al, 2002).

It has been shown that dynamic soil resistance during the vibrating process is one of important parameters in the determination of the driveability of a sheet pile. Therefore, further research should be performed to analyse it (Huybrechts et al, 2002).

Industry related initiative regarding to CO_2 emissions shows that sustainability within construction sector is becoming more important, for instance there are some industry-related initiatives so as to reduce the carbon footprint of construction projects. This fact can justify why companies have to assess the sustainability for all of its products.

3. Research methodology

Figure 5 illustrates the methodology that has been developed to achieve the objectives of the project. It consists of five phases, and each includes several tasks and deliverables.



1. STATE OF THE ART REVIEW	1.1 Literature review of Sustainability Assessment and Product Carbon Footprint (PCF) for the plastic sheet piling (PSP) field. 1.2 IDEF0 model creation. Identification of Affecting Factors. 1.3 Selection of emission norms. 1.4 Developing new equations for the assessments.	D 1.1 State of art report D 1.2 IDEF0 Model for the PSP life cycle. D 1.3 Equations for the Product Carbon Footprint calculation
2. DATA COLLECTION	2.1 Design a semi-structured questionnaire 2.3 Industrial Interviews to gather real data. 2.4 Physical observation of manufacturing facilities and face-to-face interviews.	D 2.1 Product carbon footprint data. D 2.2 Sustainability factors related to the PSP.
3. PRODUCT CARBON FOOTPRINT	3.1 Analysing the collected data from the industrial field visits 3.2 High level calculation of the PCF 3.3 Calculation of PCF of the range of plastic sheet piles.	D 3.1 Calculations of carbon footprint per m^2 of product on each stage of life cycle.
4.SUSTAINABILITY ASSESSMENT	4.1 Product data analysis in terms of environmental, social and economical dimensions. 4.2 Development of the Product Sustainability Assessment method. 4.3 Delivering a weighting system to be able to address the sustainability issues in the plastic sheet piling business. 4.4 Identifying the most sustainable product and design.	D 4.1 Sustainability assessment guidelines, weighting system and comparison of the products.

Figure 5: Research methodology

1. **PHASE: State of the Art of Carbon Footprint and Sustainability**

1.1 Performing an extensive literature review of the carbon footprint theory and sustainability applications within the piling sector in order to develop the framework theory of the subject and to synthesise the best practices.

1.2 Mapping the plastic sheet piling lifecycle to identify the key activities and factors that have major impact on sustainability and carbon footprint emissions.

1.3 Developing new product carbon footprint equations customised for the plastic sheet piling.

2. **PHASE: Industrial Field Study Data Collection**

2.1. Arranging industrial visits and face-to-face interviews with stakeholders using semi-structured questionnaire

3. PHASE: Product Carbon Footprint calculations

3.1. Performing the product carbon footprint calculations using the collected data from the industrial field study.

4. PHASE: Sustainability Assessment Method

4.1. Identifying the sustainability indicators in the lifecycle stages

4.2. Clarifying the criteria of sustainability assessment (Relevance, Analytical Soundness, and Measurability).

4.3. Analysis of sustainability understanding and crucial affecting factors relevant for different stakeholders. Summarising different opinions and creating common understanding of sustainable products.

4.4. Delivering a weighting system in order to address the sustainability issues in the plastic sheet piling business. Identifying the most sustainable product and design.

4. Related Literature

4.1 Plastic Sheet Piling Lifecycle

Lifecycle assessment is a tool (EHSC, 2010) that aims to assess the environmental impacts of a product, service or process through its entire lifecycle. The product lifecycle of the plastic sheet piling has been represented as shown in Figure 6 namely: raw materials production, manufacturing, transportation, installation, and disposal/recycling. This aids to identify the impacts at environmental, social and economic dimensions of sustainability, and those environmental inputs and outputs that are needed to work out the total product carbon footprint. The following presents in detail each of the key activity of the plastic sheet piling lifecycle.

- **Raw materials:** The contribution to the total product carbon footprint of the raw materials is by raw material production and transportation. Regarding to the production of raw material all the products covered in this study are made of a mix of recycled and virgin PVC, and additives. The authors found out through the interactions with the different stakeholders that plastic piling products are made of approximately 93% recycled PVC that comes from scrap of windows and pipes. The composition also includes small amounts of additives that improve properties of the product (e.g. UV protection) and the manufacturability. All plastic sheet pile will have a small percentage of virgin PVC in the outer layer.

- **Manufacturing:** The core of the manufacturing stage is an extrusion process, in which raw materials are continuously fed in pellet form into a heated chamber and carried along by a feed screw (Razavi Alavi et al, 2009). During the process, the material is compressed, melted and forced out from the chamber through a final die that determines the final cross section of the profile at a fixed output rate. Finally, the continuous product is cooled down, pulled and cut into the final length. The geometry of the cross section of the final plastic sheet piles (Figure 1**Figure 6**) has a major impact on the resource consumption (e.g. energy, water) during the manufacturing process.
- **Transportation:** Delivering plastic sheet piles involves international transport. The geometry and dimensions are key features that determine the design of the stocking of plastic sheet piles, and also the mean of transportation that could be done by a combination of road, train and sea. These have major impacts on the carbon footprint calculation. The transportation step also covers the retailing which involves those activities from when the product is received in the country of destiny until it reaches the final customers at the construction site. It may include handling, storage, and local transportation.
- **Installation**: Installation is a crucial stage in case of structural products. Several different parameters determine the installation process such as the type of application, pile type and geometry, soil conditions, installation equipment, and site location. These parameters also have impact on the product carbon footprint.

- **Disposal/Recycling:** Information is not available about the end of life of plastic sheet piling as the lifespan of the product is around 75 years. As the product itself entered to the market only several years ago none of the products have yet reached the end of the lifecycle.

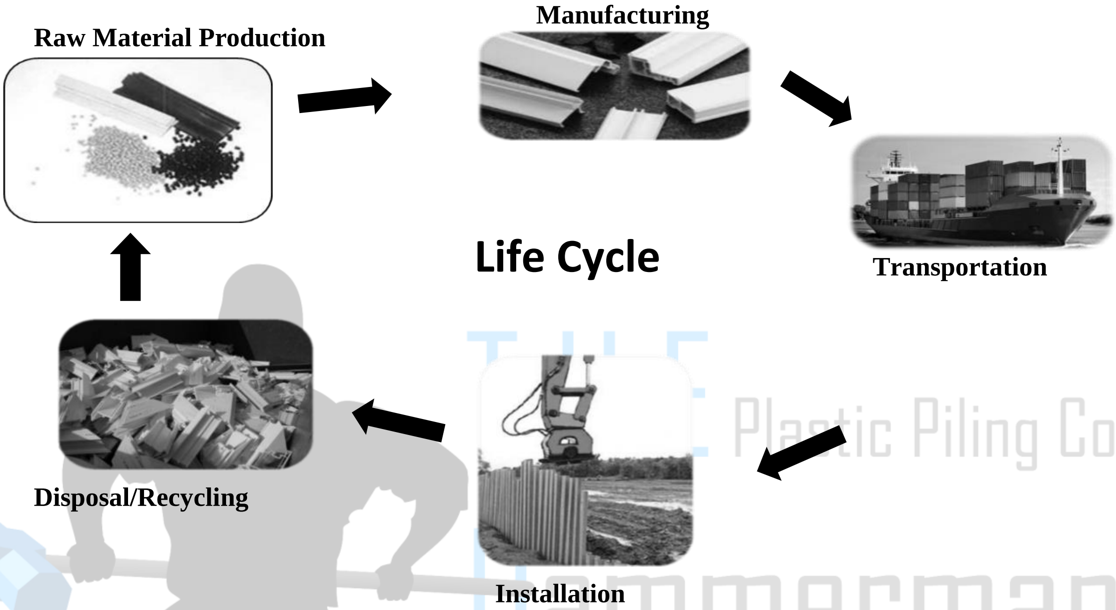


Figure 6: Plastic Sheet Piling Lifecycle

Table 2 illustrates the main affecting factors and the affected parameters within product carbon footprint calculations and the factors that have impact on the lifecycle from a sustainability point of view. Those factors have been identified based on the understanding of the literature and the analysis of the piling lifecycle as well as detail mapping of the lifecycle using IDEF0. However, the IDEF0 models are not presented in this paper due to space limitation.

Affecting Factors for Product Carbon Footprint Calculations			
Stage	**Sub-Activities**	**Affecting Factors**	**Affected Parameters**
Raw material (RM) Production **(Estimation)**	RM extraction	Material type, technology used	Resources Usage (Electricity (kWh), Fuel (m^3), Water (m^3)), Direct greenhouse gas emissions (m^3), Waste (kg)
	RM production	Material type and VCM[1] purity, moisture content and additives technology used, reaction parameters	Resources Usage (Electricity (kWh), Fuel (m^3), Water (m^3)), Direct greenhouse gas emissions (m^3), Waste (kg)

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[1] **VCM=Vinyl Chloride Monomer**

	RM transportation	Way, load, quantity, geometry of the piles, distance, handling operations	Fuel consumption (m^3), Electricity consumption (kWh)
Plastic Pile (PP) Manufacturing (Extrusion)	RM preparation	Type of pile	Raw materials (kg) and Additives (kg)
	RM preconditioning and feeding	Type of raw material and pile, and raw material flow rate	Electricity consumption (kWh)
	Extrusion	Raw material viscosity and thermal conductivity Quantity of raw material in a pile, and the geometry of a die Extrusion parameters	Electricity consumption (kWh), Water consumption (m^3), Waste (kg), Direct greenhouse gas emissions (m^3)
	Cooling Process	Geometry and thickness of a product, cooling parameters, temperature, flow rate	Electricity consumption (kWh), Water consumption (m^3)
	Cutting Process	Technology used, and product geometry and length	Electricity consumption (kWh), Waste (kg)
	Stacking Process	Technology used, and product geometry and length	Electricity consumption (kWh),
International Transportation	PP Packaging	Material type, packaging requirements	Raw materials (kg), Waste (kg), Direct greenhouse gas emissions (m^3)
	Cargo-Handling	Cargo-handling plan, weight of a pile	Electricity consumption (kWh), Fuel consumption (m^3)
	Truck transport	Distance, load, vehicle dimensions, weight and geometry of a pile	Fuel consumption (m^3)
	Rail Transportation	Distance, load, coach dimensions, weight and geometry of a pile	Electricity consumption (kWh)
	Maritime Shipping	Distance, load, coach dimensions, weight and geometry of a pile	Fuel consumption (m^3)
	Retailing Cargo-handling	Cargo-handling plan, weight of a pile	Electricity consumption (m^3), Fuel consumption (m^3)
	Retailing Domestic transport	Way of transportation, load, quantity, geometry of a pile, distance	Fuel consumption (m^3)
Installation	Installation	Installation method, geotechnical and structural circumstances, geometry of a pile	Fuel consumption (m^3)
Disposal and Recycling	Disposal/Recycling	Material type, technical factors, disposal technique, distance to recycling place	Electric consumption (kWh), Direct greenhouse gas emissions (m^3), Waste (kg)

Table 2: Affecting factors for product carbon footprint calculations of the plastic sheeting piling

The affecting factors determine the basis for the product carbon footprint calculations. The affected parameters have different units which are comparable when converted into kg of CO_2 equivalents. The detailed explanation about the comparability of the different units for the product carbon footprint calculations is presented in Section 6.1 that discusses the high level carbon footprint calculations.

4.2 A Review of Product Carbon Footprint Calculation

During recent years, several tools have been developed to measure the environmental impacts of a product throughout its lifecycle, from which the Product Carbon Footprint stands out. It focuses on the analysis and quantification of the total product lifecycle emissions that contribute to climate change (Higgs et al, 2009; O'Connell et al, 2010; Hauschild, 2005 ;), and it can be generally defined as a measure of the greenhouse gases (GHG) emissions that are directly and indirectly generated during the lifecycle of a product within established boundaries (Weidema et al, 2008; Finkbeiner, 2009; Wiedmann et al, 2008; 2010; Plassmann et al, 2010). The typical product carbon footprint considers the six Kyoto gases (CO_2, CH_4, N_2O, SF_6, perfluorocarbons, and hydrofluorocarbons). The choice of the included gases will depend on the type of product, the relative importance of each gas, and the purpose of the calculations (Padney et al, 2010 and Laurent et al, 2010), although this research focuses only on CO_2. The emissions that should be considered in the product carbon footprint can be classified in three main groups, such as direct emissions (directly generated during a process), emissions associated with the purchased energy, and indirect emissions. In many cases, depending on the product, this group of emissions may represent the major contribution to the total product carbon footprint (Padney et al, 2010; Carbon Trust, 2007; BSI, 2008).

The product carbon footprint is normally expressed in kilograms of CO_2 equivalents (CO_2-eq) per functional unit, which represents the unit in which the end user consumes the product (2010; O'Connell et al, 2010; Weidema et al, 2008; Plassmann et al, 2010). To calculate the product carbon footprint, the greenhouse gas impacts are transformed into CO_2-eq by applying the emissions factor entitled by Global Warming Potential which expresses the relative impact with respect to CO_2. On the other hand, the purchased energy and indirect emissions are usually transformed into $CO_2$2-eq by applying conversion factors that may come from standards or cross-industry emission factors (Padney et al, 2010; Higgs et al, 2009).

Several methodologies exist that offer guidelines to calculate the product carbon footprint. Some of the most used are the greenhouse gas protocol, ISO 14064, Publicly Available Specifications (PAS) 2050, 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (Finkbeiner, 2009). The methodologies for calculating product carbon footprint are still evolving. There is not a broadly accepted method mainly because there is no agreement on selecting gases, establishing supply chain boundaries and the scope of the calculations. In addition, there are several challenges to face when calculating product carbon footprint, such as availability and reliability of data, multiple databases, etc. It is necessary to be aware that the combination of these leads to uncertainty and establishes some limits in the use of the results (Higgs et al, 2009; Padney et al, 2010; Weidema et al, 2008; Finkbeiner et al, 2009; Plassmann et al, 2010).

The result of the product carbon footprint analysis can be used to manage and reduce emissions, increase environmental efficiency, reduce costs, manage the supply chain, comply with legislative requirements, to promote social responsibility, etc. (Padney et al, 2010; Plassmann et al, 2010; Carbon Trust, 2007).

The following subsection presents the justification of the use of PAS 2050 for the reason to be used to calculate carbon footprint of plastic sheet piling.

4.2.1 The PAS 2050 Guideline for Product Carbon Footprint Calculation

PAS 2050 standardises for the first time a method for assessing a product’s carbon footprint. This allows organisations a comprehensive approach to evaluate the lifecycle greenhouse gas emissions. It is based on existing lifecycle analysis approaches (among them the existing ISO 14040/44 standards), but simplifies and adapts these approaches in order to calculate the carbon footprint of products across their lifecycle. PAS 2050 is designed to support a third-party organisation, but where organisations do not want to disclose the information, compliance with any given standard is not compulsory. This methodology accounts for emissions of all greenhouse gas and each gas is converted into a CO_2 equivalent value. PAS 2050 specifies rules for identifying the system boundary and data quality rules for secondary data, and it does not support comparative assertions, but recognises that individual stakeholders could compare results (Plassmann et al, 2010 and Sinden, 2009).

4.3 Sustainability Dimensions

Achieving sustainability has become a major issue in industrial activities, especially in the manufacturing sector as the core of the industrial economies, due to several causes such as shortage of non-renewable resources, global warming, customers' trends in favour of environmentally friendly products, etc. In the manufacturing sector sustainability can be addressed at three main levels: product, technological processes and supply chain system (Jayal et al, 2010). The sustainability of a product, as a result of the manufacturing operations, can be assessed by evaluating the impacts throughout the whole lifecycle from three different points of view: environmental, social and economic. Those three dimensions are called the pillars of sustainability (Heijungs et al, 2010 and Spillemaeckers et al, 2006). In order to assess product sustainability, environmental impacts and also social and economic impacts across its lifecycle (from cradle to crave) must be considered. Lifecycle Analysis (LCA) is one of the methodologies which assess the environmental aspects during the lifecycle of the product and analyses the inputs such as raw materials, energy, water, and outputs such as emissions, waste, sub-products that are used during its lifecycle (Spillemaeckers et al, 2006). Both lifecycle assessment and product carbon footprint are unsuitable for assessing social and economic dimensions, which are more related to companies involved across the product lifecycle rather than to a product itself. In general, social dimension of sustainability is usually related to employment, work conditions, community, health and safet. While the economic dimension is directly associated to the profitability of the product (Spangenberg et al, 2010). There is a clear lack of metrics to measure social or economic impact of a product across the lifecycle (Jayal et al, 2010).

To analyse product sustainability from social and economic dimensions the supply chain needs to be identified, including participants such as manufacturers, suppliers, contractors, transporters. However, sometimes the supply chain associated to the product is so complex that a thorough analysis may be expensive and may require excessive time and resources. Therefore, it is necessary to establish the right boundaries to the system that can be done by researchers (Spillemaeckers et al, 2006). As sustainability performance is becoming one of the decision-making factors, companies which take any initiative to reduce the impact, will not only reduce environmental impact, but will also increase business efficiency and consequently save money (EGP, 2009). The different industrial sectors could enhance their sustainability practices by addressing the 6R approach (reduce, reuse, recover, redesign, remanufacture, recycle) at the product level, technical development and process planning in order to reduce social and environmental impacts of the products at the process level, and lifecycle thinking at the system level (Jayal et al, 2010).

The review of the related literature helped to define the foundation for the research presented in this paper. The following section describes the data collection.

5. Data Collection Process

In order to perform the product carbon footprint calculations and product sustainability assessment, an industrial field study was carried out to collect the relevant data. Two types of data are necessary to calculate the carbon footprint: activity data and emission factors.

- **Activity data** refers to all the material and energy amounts involved in the plastic sheet piles lifecycle (e.g. material inputs outputs, resources consumed during extruding and installation, transport) . The factors listed in Table 2 determine the type of data related the environmental impact that needed to be collected from the field study to perform the product carbon footprint calculations and the sustainability assessment.

- **Emission factors** provide the link that converts these quantities (from activity data) into the resulting GHG emissions: the amount of greenhouse gases emitted per ‘unit’ of activity e.g. kg GHGs per kg input or per kWh energy used. Conversion or emission factors can be found in databases provided by organisations such as DEFRA or the Centre for Environmental Assessment of Product and Material Systems (CPM).

Activity data and emissions factors can come from either primary or secondary sources:

- **Primary data** refers to direct data collected from companies participated in this study and it is specific to the plastic sheet piles lifecycle. In this study this data is related to the piles manufacturers in Poland, the Netherlands and USA and constructors (piles installation) in UK and Poland.
- **Secondary data** refers to data that is not specific to the plastic sheet piles, but rather represent an average or general measurement of similar processes or materials obtained from industrial reports and trade associations. In this study this data is related to the raw material production and transportation.

The type of data were collected are related to the affecting factors for product carbon footprint calculation of the plastic sheet piling as identified from the literature and captured in Table 2. The primary data collection process included the development of semi-structured questionnaires, face-to-face interviews, observations and collecting other data such as material and machine specifications. Therefore, the authors developed two sets of semi-structured questionnaire related to the manufacturing and installation stages. The following are description of the data collected related to the lifecycle stages:-

Raw material: The CO_2 emissions from the plastic raw material are related to the material production and transportation. The affecting factor data of material production is the percentage of virgin and recycled PVC (which is the main plastic material for piles) as well as the emission factors which is obtained from databases available online (EC, 2011). Data about raw material transportation was gathered from the manufacturers.

Manufacturing: Three plastic sheet piling manufacturers were visited and assessed (refer to as company1, 2 and 3) from the Netherlands, Poland, and USA as they are key suppliers in the market also produce wide range of plastic sheet piles. The questionnaires for the manufacturers were divided into nine parts as shown in Table 3.

1. General - pile production	e.g. production rate, percentage from the total production
2. Raw material	e.g. type, chemical consumption, transportation
3. Raw material preconditioning	e.g. power consumption related to machine use
4. Extrusion process	e.g. resource consumption per product, main focus on electricity and water
5. Pile production post-treatment	e.g. resource consumption
6. Waste and wastewater treatment	e.g. facilities, energy consumption
7. Gas emissions	e.g. released gases
8. Sustainability	e.g. product design, environment, community, health and safety
9. Transportation	e.g. vehicle details for international transport, effect on sustainability

Table 3: Parts of the questionnaire for manufacturing

Figure 7 shows example of the questionnaire where it has been designed to guide the interviewee to provide data in structure manner and related to the affecting factors identified in Table 2. The question of Figure 7 is related to machine power specifications of all the equipments used to produces the piles to the electricity and water consumptions. However, the field study showed that the water consumptions neglectable for the product carbon footprint calculation as it is in closed system where the water is re-used.

Machine Power Specifications		
Electricity	P1	
Equipment	*kW*	*%Used*
Preconditioning Mixer		
Feeding Blower		
Feeding Screw		
Additives Unit		
Main Extruder Motor		
Oil Pump Main Motor		
Cooling Main Motor		
Barrel Heaters		
Vacuum Pump		
Barrel Cooling		
Die Heaters		
Calibrator		
Cooling Process (Shared)		
Take-off Rollers		
Cutting Process		
Co-extrusion: Motor		
Heaters		
Other		
Total electricity consumption (kW)		
Water	*m³/h*	
Extruder Cooling System		
Sheets Cooling Process		
Other		
Total water consumption		

Figure 7: Example of a question for collecting data about the manufacturing step from the lifecycle

To gather very specific information, which cannot be standardised, open questions were used. These types of questions were used mainly to cover the topic of transportation and sustainability.

Does the production of plastic sheet piles require any particular health and safety measures? If yes, please specify which products and what kind of measurement?

____

Figure 8: Example of open question about health and safety

Transportation:

The main factors which have impact on carbon footprint emission during the transportation are the vehicle type, fuel, distance and the geometry of the product. For the carbon footprint emission calculations the officially established emission factors and norms were provided by DEFRA

(DEFRA, 2010), emission factors for direct emissions related to fuel consumption were provided by the Department for Transport (DfT, 2011).

<u>Installation</u>:

The assessment of the installation stage is possible after understanding its complexity caused by the parameters type of application, pile type and geometry, soil conditions, installation equipment, and site location. In order to do this, the constructors a set of questions was developed in order to capture subjective data in connection with construction/piling work. Consequently a case study was developed for the installation stage in order to address the relevant aspects of sustainability, because the authors found that the impact of this stage on product carbon footprint is not significant comparing to the rest of the stages. Although from the overall sustainability point of view when comparing the different products significant differences were found. This was addressed to experts who used one of the plastic piles that are assessed in this research.

<u>Disposal</u>: This is secondary data that has been replaced by standardized data from DEFRA (2011).

The following sections present in detail the plastic sheet piling carbon footprint calculation and the sustainability assessment.

6. Carbon footprint calculations for plastic sheet piles

Studies related to carbon footprint calculation can be found for many products such as sea food or agricultural products, and even for many PVC products such as PVC sheets or pipes (Baldasano, 2005), but there were no studies found in connection with plastic sheet piles. In this way this study contributes to cover a gap in the knowledge.

Publicly Available Specifications (PAS 2050) has been used as a method to carry out the calculations of the product carbon footprint of plastic sheet piling. This is because PAS 2050 offers a method to deliver improve understanding of the Green House Gas emissions arising from their supply chains as well as provides common basis for quantifying these emissions. Figure XX illustrates the main steps of performing the carbon footprint calculation based on PAS 2050. These are the following:

- Process Map: This represents the key activities of the product life cycle which is presented in Figure 6 for the case of plastic sheet piling.
- System Boundaries: is defining the boundaries for the calculations and defining where the effort of gathering data is going to be concentrated within the plastic sheet piles lifecycle. It also clarifies inputs (e.g. resource consumption) and output (GHG emission) that should be included in the assessment for each activity and sub-activities of the life cycle and it is represented Table 2 for the case of this research.
- Data Collection: The data recorded in relation to a plastic sheet piles include all GHG emissions and occurring within the system boundary of the plastic sheet piling lifecycle. This is explained in Section 5.
- Product Carbon Footprint Calculations: The equation for calculating the plastic sheet piles carbon footprint is the sum of all materials and energy across all activities in lifecycle multiplied by their emission factors. The calculation itself simply involves multiplying the

activity data by the appropriate emission factors. The calculations and developed equations are discussed in Section 6.1.

- Uncertainty: is a measure of precision of the data and calculations.

Assessment of the GHG emissions arising from the lifecycle of plastic sheet piles is carried out in a manner that allows the mass of CO2 emission to be determined per functional unit for the piles where product carbon footprint results are going to be expressed. This functional unit was related to the final use of the plastic sheet piles. Regardless to the specific use of the plastic sheet piling it is always installed as a wall formed by a series of piles driven in the ground. This could suggest the use of kg CO_2 per m of linear wall as a functional unit. However, piles may have different lengths therefore using effective square metres of plastic sheet pile wall is more convenient as follow

Functional unit 1: kg CO_2/effective. m^2

The product selection and application specifications are affected by many parameters. A second functional unit was also used considering that the applications are related to the soil that piles must retain. Hence, the results of product carbon footprint are going to be displayed in a second functional unit that takes mechanical properties required from the wall into account, in this case is the allowable bending moment. Therefore the second functional unit is the following:

Functional unit 2: kg CO_2/effective m^2 * kNm

6.1 Total product carbon footprint equation for plastic sheet piling

A set of equations for calculating the product carbon footprint of the plastic sheet piles through their lifecycle has been developed for every stage.

$$\text{Product Carbon Footprint (PCFP)} = \sum \text{Activity Carbon Emission} = RM+MAN+T+I+D$$ [2]

---

[2] *RM: PCFP for Raw Material Production*
MAN: PCFP for Manufacturing Process
T: PCFP for International Transportation Emissions
I: PCFP for Installation

Equation 1: Product carbon footprint calculation

For every stage of the lifecycle product carbon footprint is calculated aggregating the kg of CO_2 equivalent emission for every activity associated with the stage. The emission for every activity is calculated by multiplying the activity data associated with that activity per the correspondent emission factor. As data is normally expressed in kg of CO_2/kg of material some conversions are necessary taking into account geometry data available from product's specifications in order to express results per m^2.

6.1.1 RM: Raw Materials Production

The equation used to calculate the production of PVC is:

$$RM = \left(\frac{\left(\left(\left(\frac{\%\,of\ Virgin\ material}{100} * F_V \right) + \left(\frac{\%\,of\ Recycled\ material}{100} * F_R \right) \right) \right) * \frac{1\,ton\ material}{1000} * \frac{kg}{m}}{Effective\ pile\ width\,(m)} \right) =$$

Equation 2: Production of PVC

The quantity of the additives is approximately 1%, the percentage of PVC. Emission factors for recycled material have been calculated in the cases of Company2 and Company3 where this process is managed inside the company, and taken from literature in case of Company1 where recycled material is bought by the supplier e.g. in a form of pellets. The results obtained are shown summarized in Section 6.3.

The calculation for transportation of raw materials to manufacturing facilities (Equation 3) takes into account the type of vehicle, distance and geometry parameters in order to express results per eff m^2.

U: PCFP for Use of plastic sheet piling
D: PCFP for Disposal

$$RM\ Tranportation\left(\frac{kg\,CO_2}{eff\ m^2}\right)=FT\left(\frac{kg\,CO_2}{kg\,km}\right)*\ Distance\,(km)*\ \frac{Linear\,Weight\left(\frac{kg}{m}\right)}{Effective\ Width\,(m)}$$

Equation 3: Transportation of raw materials

A summary of data used in this stage is shown in Table 4 below.

Data type	???	Product (P)1	P2	P3	P4	P5	P6
Primary data	**Supplier (Country)**	Netherlands	Netherlands	Poland	Poland	Poland	USA
	% Virgin PVC	7	7	12	0	12	5
	% Recycled PVC	93	93	88	100	88	95
	Linear Weight (kg/m)	6.2	8.4	2.86	4.3	9.4	10.6
	Effective Width (m)	0.5	0.5	0.27	0.3	0.29	0.305
	Transportation mean	<33 tons	<33 tons	>33 tons	>33 tons	>33 tons	>33 tons
Secondary data	**Average distance to RM suppliers (km)**	500	500	80	80	80	1020.9
	F_T: Transp. Emission Factor (kg CO_2/km·kg)	$6.11 \cdot 10^{-5}$	$6.11 \cdot 10^{-5}$	$4.15 \cdot 10^{-5}$	$4.15 \cdot 10^{-5}$	$4.15 \cdot 10^{-5}$	$4.15 \cdot 10^{-5}$
	F_V: Emission Factor Virgin PVC (kg CO_2/kg)	1.944	1.944	1.944	1.944	1.944	1.944
	F_R: Emission Factor Virgin PVC (kg CO_2/kg)	0.1543	0.1543	0.1314	0.1314	0.1314	0.1970

Table 4: Data and emission factors used in the calculation of product carbon footprint for the raw material production and transportation

6.1.2 MAN: Manufacturing Process

Product carbon footprint calculations for activities at the manufacturing stage differ depending on the type of data available for every product. Information about the total energy, water and gas consumption of the facilities is available where product related percentage in relation to the whole production is required. In case of Company1 the same resources consumption can be assumed for the production of all the products manufactured in the facility. In case of Company2 and 3 the information is not available, the assumptions cannot be made therefore the information about machines` specifications and operating conditions is required. The carbon footprint of the manufacturing stage involves the processes from raw materials preconditioning before feeding the machines until the final product ready to be transported.

To calculate the contribution to the carbon it is necessary to take into account some circumstances related to water, scrap, liquid waste, and gas. The water consumption is not significant in the manufacturing of plastic piling sheets due to the application of a close loop where water is used in a sub-process for cooling. The scrap that results from start ups, shut downs, color changes or unusable pieces are mechanically recycled into raw materials ready to use in the same process. For this reason, only the energy consumption associated with this scrap should be taken into account. There is no liquid waste associated with the extrusion process of plastic piling products. Some gases are released during the extrusion process, however the amount of them are so small that do not require measures to control them. Consequently, those gases can be removed from the carbon footprint calculations without causing a significant error. As a result only the energy involved in the manufacturing process will be considered.

To calculate the carbon footprint of the manufacturing stage, the energy consumption per effective square meter needs to be estimated. There are two main methods to estimate it. For one hand based on the total energy consumption of the whole manufacturing facilities of one year the percentage of the total production that each product represents and the total yearly production of each product. This method can be used when it is possible to assume that all manufacturing processes within the company have similar energy consumption and then it is possible to allocate the energy consumption to one product based on the percentage of the total production. *Equation 4: Manufacturing (assumed similar energy consumption between processes)*Equation 4 was used for these calculations.

$$Manufacturing = \frac{Annual\ electricity\ consumption * Weight\ \ per\ m}{Total\ annual\ PVC\ consumption * Effective\ width}$$

Equation 4: Manufacturing (assumed similar energy consumption between processes)

For another hand based on the specifications and working conditions of all the machines that form the production line of each product. This second method should be used when there are substantial differences in the energy requirements among the different processes and then it is not possible to allocate the energy consumption to each product based on the percentage of the total production. The method was selected in collaboration with the engineers of each of the suppliers involved in the project. However, in both of the cases, it has been necessary to make some approximations in collaboration with the engineers during the industrial visits to make the estimation of the energy consumption possible. Equation 5 was used for these calculations.

$$Manufacturing\left(\frac{kg\,CO_2}{eff\;m^2}\right) = Energy\,Consumption\left(\frac{kW*h}{eff\;m^2}\right) * SGR * Electricity\;Emission\;Factor\left(\frac{kg\,CO_2}{kW*h}\right)$$

Equation 5: Manufacturing (differences in energy consumption between processes)

A study about composites was developed by Creative Pultrusion Inc. regarding the CO_2emissions during manufacturing stage where they state that 1.65 lbs of CO_2 is emitted per every pound of pultruded product manufactured. *I don`t think composites are mentioned elsewhere.*

6.1.3 T: International Transportation

. The Equation 6 was used for calculations.

$$Transportation_{\,m2\;of\,product}\;\frac{Norm*Distance}{VC*GF}$$

Equation 6: International transportation of piles

The geometry factors for transportation of different products have been created by using the maximum capacity of the vehicle and estimated maximum number of plastic piles per vehicle. In the case of different vehicles being used it is necessary to sum up the emission from every vehicle type.

The summary of the data used for product carbon footprint calculations for the international transportation is shown in Table 4.

Data Type	Product	P1	P2	P3	P4	P5	P6
Primary	**Supplier**	Netherlands	Netherlands	Poland	Poland	Poland	USA
	Vehicle capacity (VC) m^3	95	95	95	95	95	60
Secondary	**Geometry Factor (GF) eff m^2 per m^3**	17.5	11.875	27.675	8.625	9.79	6.2181
	Distance	830	830	1780	1780	1780	7747
	gCO_2 per vehicle km	930.6	930.6	930.6	930.6	930.6	573.5 lorry, 28.5 train, 15.9 vessel
	(gross vehicle weight)	(>33t)	(>33t)	(>33t)	(>33t)	(>33t)	(7.5-17t)

Table 5: Data emission factors used for the product carbon footprint calculation for the international transportation

6.1.4 I: Installation

During the assessment of the product sustainability, the impacts during the use and installation of the products must be taken into consideration.

As has been noted in the literature review, the installation stage during LCA has not been assessed so far in any study, since the impact during its use is normally substantially greater than the impact of its installation. In most construction materials, as the product is static, the impact during use is not significant in terms of carbon footprint, thus the installation stage should be considered as it could be one of the stages with emissions.

The consumption of the equipment when driving a plastic sheet pile is different depending on the dimensions of the piles (geometry and length), the soil conditions and the equipment used. There were three approaches considered for assessing the installation stage. An *analytical approach* was tried, however this resulted in a very complex task due to non-linear interaction between soil, plastic sheet piles, the equipment, and the way of decision-making of stakeholders. Limitations of the approach are lack of geo-engineering understanding and complexity. The information/knowledge acquired is general understanding of the installation process, equipment involved and engineering parameters used for design. However, throughout the interviews with the suppliers and some contractors it was found out that the assessment of the installation process is only possible to conduct through carrying out empirical tests, and it also pointed out the necessity of the development of a case study. Another way to assess the carbon footprint was trying to gather *data from previous projects* conducted by stakeholders. The intention was to discover any trend in the fuel consumption of the equipment that could be linked with some parameters such as soil parameters or method of installation for the product range. Because of the privacy policy, not many contractors and customers disclosed the information. The limitations of the approach are difficulties to engage companies, time limitations, and the subjectivity of data. The information/knowledge acquired is answers about product sustainability and contractors/customers understanding of sustainability. Keeping these approaches in mind it is important to discuss the most effective way to assess the carbon footprint for every application. It is an *empirical approach* to carry out a case study measuring the consumption taking into consideration all the parameters involved. Limitation is that this is a time-consuming activity, many cases are needed to be conducted, and the data is subjective. Information/knowledge acquired is the result of the case study and comparability of parameters involved through installation.

Case study developed for the installation stage

The aim of the case study is to gather consumption data and equipment for a tailored project in order to calculate the CO_2 during the driving of the plastic piles. Due to the complexity of the installation stage and the lack of a broad range of previous project data, a case study was developed in order to assess the carbon footprint during the installation stage. The case is the application of a retaining wall, precisely a cantilever wall into a generic soil condition. This type of soil is common in several countries and also in UK. When the geometry and the soil parameters were selected the supplier`s software was used to define the length of a pile. Product 1, 2 and 6 have been involved in the case study using it as part of a hybrid system, and product 1 and 2 with timber pole, and 6 with reinforced concrete. Products 3-5 was involved in the case study as one product using a defined common thickness.

For the carbon footprint calculations having the consumption of the equipment per m_2 (activity data) and the conversion factor is necessary to calculate the CO_2 equivalent emission. Equation 7 below was used to calculate the emissions of CO_2 during the installation stage where:

C: equipment consumption [L/h]

Pr: performance rate (time) [m/h]

$$Emission\left[\frac{kg\ of\ CO_2}{m}\right] = Conversion\ factor * \left[\frac{C}{P_r}\right]$$

Equation 7: Emission factor for the installation

When a project is designed, the stakeholders are interested in the emissions per linear meter of wall therefore the comparison will take into consideration the length. Each emission measured per square meter can be transformed into emission per linear meter by multiplying it with a defined length of a pile. Therefore this case analysis sets a common comparison for a specific project.

6.1.5 U: Use of plastic sheet piling

Emissions have not been identified for this step of the lifecycle as once installed, plastic sheet piles do not require any maintenance.

6.1.6 D: Disposal

The estimation of the CO_2 emission for disposal has been calculated using an emission factor for the disposal of plastic found in DEFRA (2011) Guidelines. The same procedure has been followed to develop the calculations for all products in this disposal stage.

$$D\left(\frac{kg\ of\ CO_2}{eff\ m^2}\right) = F_D * \frac{Weight\ per\ m\left(\frac{kg}{m}\right)}{Effective\ width\,(m)}$$

Equation 8: Emission factor for the disposal

Table 6 summarises all the required data, the value of the specific emission factor used and the result for the product carbon footprint in the disposal stage.

Data type		**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
Primary	**Weight per m (kg/m)**	6.2	8.4	2.86	4.3	9.4	10.6
	Effective width (m)	0.5	0.5	0.27	0.3	0.29	0.305
Secondary	**FD: Emission factor for disposal of plastic (kg CO_2 per kg PVC)**	0.04	0.04	0.04	0.04	0.04	0.04

Table 6: Data necessary and results of the calculation of product carbon footprint for plastic sheet piling in the disposal stage

6.2 Results

Table 7 is a compilation of the results of the product carbon footprint for all the stages in the plastic sheet piling lifecycle. Results are included in the two functional units defined previously.

						Product Carbon Footprint		
PRODUCT	**RM**	**MAN**	**T**	**I**	**D**	**Total PCFP (kg CO_2 per eff m^2 of pile)**	**Allowable bending moment (kNm/m)**	**Total PCFP (kg CO_2 per eff m^2 of pile * kNm)**
P1	3.85	3.83	0.47	-	0.50	10.11 (1)	7.77	1.30
P2	5.21	5.18	0.69	-	0.67	13.89 (2)	14.4	0.97
P3	3.73	3.36	0.63	-	0.42	8.15	4.76	1.71
P4	1.93	3.50	2.02	-	0.57	8.03	4.27	1.88
P5	11.42	8.21	1.78	-	1.30	22.71	26	0.87
P6	11.35	7.85	6.10	-	1.39	28.44 (3)	19.7	1.44

Table 7: Summary of results of product carbon footprint expressed in both functional units

(1) The most common way to use this product is in combination with another element as a hybrid solution. The most common is to combine Product 1 with a timber pole. This total result for the carbon footprint includes 8.632 kg CO_2 per m^2 contributed by the plastic pile and 1.48 kg CO_2 per m^2 contributed by the timber pole.

(2) The most common way to use this product is in combination with another element as a hybrid solution. The most common is to combine Product 2 with a timber pole. This total result for the carbon footprint includes 11.75 kg CO_2 per m^2 contributed by the plastic pile and 2.14 kg CO_2 per m^2 contributed by the timber pole.

(3) Product 6 is also a product normally used in hybrid solutions. It has been considered its use in combination with gravel. The total product carbon footprint is 26.687 kg CO_2 per m^2 from the plastic pile and 1.75 kg CO_2 per m^2 from the gravel.

Results of the case study, allowing the installation stage to be included in the Product Carbon Footprint assessment, are shown in Table 8.

			Emission (kg CO_2/linear meter)				
Product	**Raw Material**	**Manufacturing**	**Transportation**	**Installation**	**Disposal**	**Total**	**% of Subcomponent**
P1	14.23	14.16	1.72	9.92	1.84	52.56	0.2
P2	19.27	19.18	2.53	9.92	2.49	64.09	0.17
P3-5	54.24	39.01	8.46	8.55	6.16	116.42	0
P6	39.73	27.48	21.34	15.18	4.87	183.57	0.41

Table 8: Table of the results – CO_2 emission of Plastic Sheet Piling

7. Product sustainability assessment

The analysis and calculation of the product carbon footprint through the whole lifecycle can be used as a quantitative environmental indicator. However, assessing sustainability involves moving beyond the analysis of the product carbon footprint. A product sustainability assessment entails evaluating the impacts of the product during its lifecycle in the three dimensions of sustainability: environmental, social and economic. A product sustainability assessment method has been developed for the case of plastic sheet piling. The method, which is explained in detail below, includes the indicators that have been used to assess the sustainability of plastic sheet piling products and the scoring and weighting system that has been created to transform qualitative data and opinions into a quantitative assessment.

7.1 Sustainability Indicators

The indicators that are used in a product sustainability assessment depend highly on the particular product that has to be evaluated. In addition, indicators that are related to both economic and social dimensions are usually subjective and more related to the company rather than only to the product. For these reasons a list of the sustainability indicators for the assessment of plastic sheet piling products was created. These indicators have been identified based on the analysis of the data collected. The sustainability indicators have been matrix-arranged according to two main criteria, namely sustainability dimensions and lifecycle stages. *Sustainability dimensions* include environmental indicators such as the product carbon footprint, resources management and efficiency, biodiversity, and pollution, social such as employment, health and safety, and community, economic and other indicators that may have simultaneous impact and are mainly related to the design of the products. The sustainability indicators have also been arranged according to the main *lifecycle stages*.

Scoring System

Most of the information that is used to assess product sustainability usually comes from qualitative data and opinions. Hence, a scoring system has been created to use the qualitative data for rating the products according to the different sustainability indicators. The system is based on scores from 1 to 5, where 5 is the highest rate and 1 is the lowest. In case an indicator is not relevant or not applicable 0 was be used. In those cases when there is no data available or simply the sustainable indicator is out of the boundaries of this study, no score is given. As the sustainability indicators are formulated in both positive and negative ways than the higher the rate the lower the impact on sustainability.

7.2 Weighting System

As part of this product sustainability assessment method, a bi-dimensional weighting system has been developed in order to allocate more importance to those sustainability indicators that are considered more relevant. As the plastic piling business belongs to the manufacturing and construction sector environmental indicators have been considered more relevant. In addition, social and economic factors are less accurate and normally more subjective to evaluate. Therefore, the following weightings have been allocated to the different sustainability dimensions: Environmental 50%, Social 25%, Economic 20% and others 5%. The second dimension of the weighting system aims to differentiate between the stages of the product lifecycle. In order to allocate weightings to each stage, the product's impacts at environmental, social and economic levels have been generically analysed according to a triple criteria: frequency, severity and time span of the impacts. In the case of plastic piling products, both raw materials and manufacturing stages may have more frequent, more severe and longer impacts when compared in general to transportation and installation stages. On the other hand, as plastic piling is a fairly recent area, information is not available concerning the disposal stage. Then, according to the reasoning, the following weightings have been allocated to the different stages: Raw Materials 30%, Manufacturing 40%, Transportation 10%, Installation 20% and Disposal 0%.

7.3 Use of the developed sustainability assessment method

As the product sustainability assessment method involves bi-dimensional indicators classification and a bi-dimensional weighting system, several steps are necessary for calculation of the final rating for each product. To simplify the explanation, two indexes have been used:

Index i from 1 to 5 was used to name the different stages of the lifecycle. Index j from 1 to 4 was used to name the different dimensions of sustainability. Firstly, the Normalised Subtotal Score for a particular stage and dimension, NSS (i,j), was developed and calculated (Equation 9). SIS (i,j) and NSI (i,j) stand for Sustainability Indicator Score and Number of Sustainability Indicators that was within a particular stage and dimension respectively. The NSS (i,j) is calculated with Equation 9.

$$NSS(i,j)(\%) = \frac{\sum SIS(i,j)}{NSI(i,j) * 5} * 100$$

Equation 9: Normalised subtotal score

Secondly, the Weighted Subtotal Score for a particular stage, WSS (i) was developed and calculated by using the following equation (Equation 10):

$$WSS(i)(\%) = \frac{50 * NSS(i,1) + 25 * NSS(i,2) + 20 * NSS(i,3) + 5 * NSS(i,4)}{100}$$

Equation 10: Weighted subtotal score calculation

Finally, the Total Score of a product was calculated by using a weighted sum of the WSS (i) of the different stages. The following equation represents the required operation (Equation 11):

$$Score_{Total}(\%) = \frac{30 * WSS(1) + 40 * WSS(2) + 10 * WSS(3) + 20 * WSS(4) + 0 * WSS(5)}{100}$$

Equation 11: Total sustainability score

Ideally, each product within this study is to be assessed separately. However, the industrial visits to the plastic sheet pile suppliers has shown that it is hardly possible to find differences between products from the same company regarding to the sustainability indicators. The exception is the stage of installation where the difference can be found. Therefore products from the same suppliers have been rated together for all steps of the lifecycle except for the installation stage. The following Table 9 show a summary of the results were product2 got the highest score therefore being the more sustainable product among the six assessed.

(%)	**Raw Materials**	**Manufacturing**	**Transportation**	**Installation**	**TOTAL**
P1	92.7	76.4	84	80.5	82.9
P2	92.7	76.4	84	84	83.6
P3	60	74	85.2	72.5	70.6
P4	60	74	85.2	76.6	71.4
P5	60	74	85.2	67	69.5
P6	72.7	68.2	68.5	65.7	69.1

Table 9: Results of the sustainability assessment method for plastic sheet piling

8. Discussion of the results

Analysis and calculations of plastic sheet piling *carbon footprint* has been conducted based on the PAS 2050 methodology. However, there are some rules or advanced guidelines that help the users of the methodology to have high quality results when calculating the carbon footprint of some common products, in the case of plastic piling products were no previous advanced instructions found. The product carbon footprint study had to be conducted based on generic guidelines. In addition, the detailed calculation of the product carbon footprint always requires making some assumptions and establishing some boundaries in the system to simplify the framework of the study. When analysing the results the accuracy of the data used within the study has to be assessed. A semi-structured questionnaire was developed and designed to gather all the necessary activity data from the different stakeholders involved in the supply chain. However, despite using the same questionnaire for all the product suppliers in the study, the type and quality of the gathered information varied greatly from one case to another. This was mainly caused by the different importance each suppliers give to the internal recording of the performance data. The gathered data was doubly checked with the suppliers but it was not possible to find an external way to validate the truthfulness and accuracy of the information. The accuracy of the results is inevitably affected. However, the results of the product carbon footprint study are valid as long as the adopted simplifications are considered when comparing different the cases.

In terms of *sustainability* there were no previous specific studies regarding plastic sheet piling products and for this reason a product sustainability assessment method had to be developed and customised. The possible data collected was subjective, especially at social and economic dimensions. It has also been detected that confidentiality issues have to be considered. Most of the data required in the product sustainability assessment is qualitative, and therefore the transformation into quantitative rates is based on subjective interpretation. Plastic sheet piling is quite a recent area and the related market is not big. The majority of the users have used only one product from the range hence there is little experience in using the piling sheets. Therefore it was not possible to obtain information in terms of product comparison. In addition, there are products that have been used more times and consequently the number of opinions about each product varies significantly.

The interpretation of the results *without taking into account the installation stage* is shown in Table 10. It is necessary to focus on the results expressed in kg of CO_2 per effective square meter and kilo-newton meter because , most of the applications require the consideration of the strength of the products, which is represented by the allowable bending moment.

	Product Carbon Footprint							
PROD	**RM**	**MAN**	**T**	**I**	**D**	**Total PCFP (kg CO_2 per eff m^2 of pile)**	**Allowable bending moment (kNm/m)**	**Total PCFP (kg CO_2 per eff m^2 of pile * kNm)**
P1	3.85	3.83	0.47	-	0.50	10.11	10.72	1.17
P2	5.21	5.18	0.69	-	0.67	13.89	14.72	0.86
P3	3.73	3.36	0.63	-	0.42	8.15	11.08	1.71
P4	1.93	3.50	2.02	-	0.57	8.03	10.92	1.88
P5	11.42	8.21	1.78	-	1.30	22.71	30.89	0.87
P6	11.35	7.85	6.10	-	1.39	28.44	28.44	1.35

Table 10: summary of carbon footprint

According to the allowable bending moment the range of products are divided into groups. The first group consists of Products1-4 which can be used where the application does not require strong products. The second group is formed by Product5 and6 which are used for applications when high strength is demanded.

This research shows that the installation stage may mean the main difference between the products in terms of the total carbon footprint; therefore installation stage must be evaluated more in the future. The carbon footprint of this stage depends on the soil and water conditions, and the installation application. Consequently, every case is different and the product carbon footprint should be assessed considering several applications. The difference between the lengths required from products when used in the same conditions will determine significant differences between them in terms of sustainability therefore a factor that generalises the different requirements in terms of length for the different products has been calculated. This study has been conducted assuming the installation of the products in the United Kingdom.

9. Future recommendation - Towards new geometry

Sustainability throughout the lifecycle should be taken into consideration by aiming towards a more sustainable geometry. Throughout the project initial attempts were made to analyse how geometry affects the installation. As a result of such analysis the impact of geometry during driving the piles in the installation stage could be reduced. These attempts failed due to the complexity of the interactions between several elements of the system. Fortunately, few recommendations can be made for future designs such as the use of a hollow sheet piling profile in order to reduce the material requirements but without compromising the structural behaviour (Dagher et al, 2004). Also the use of hybrid systems maximize the moment of inertia of the pole, therefore the geometry of the profile should be designed according to the geometry of the pole (i.e. use rectangular section instead circular section). Larger moment of inertia of the profile increases the driveability (Huybrechts et al, 2002.).

10. Conclusions

Extensive work that has been carried out in the Plastic Sheet Piling Sector and Sustainability assessment topic gave the contribution to the area of interests. However, this is not a mere overview but a starting point for further analysis. The methodology to calculate carbon footprint was developed. Work done previously provides an extensive literature review of the best practices in terms of sustainability assessment and carbon footprint estimation.

The project identifies the steps of the Lifecycle for Plastic Sheet Piling for improvement. Though most of the steps delivered similar results when comparing the products, the installation phase can be redeveloped in many different ways. Empirical trial versions for the installation step should be conducted as the next step of the research in order to verify the analysis using the same tools and environmental conditions. The case study was utilised for the installation as an initial step for further trials.

Calculation showed that reinforcing hybrid range of product by timber or gravel increases slightly the strength of the product without affecting the carbon footprint emission. However, filling product with concrete or reinforced concrete improves the strength of the product but increase also significantly the CO_2 emission during installation stage.

Work that has been developed in this report builds new equations for the carbon footprint calculations and delivers weighting systems for the plastic piling sustainability evaluation. This can be used as a base for further design of the new product. It was also noticed that during the design of the product all steps of the lifecycle should be considered to improve the overall sustainability.

The results clearly illustrate that whilst the design of products influences the carbon footprint overall there is little difference between products used within the same category of applications. Therefore, installation is the deciding factor and product1 and 2 which has been proven to install faster and more efficiently are clearly the best plastic piles to use.


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