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Sustainability Assessment of Plastic Sheet Piling

Carbon Footprinting study

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Abstract

Sustainability of the product is becoming a crucial factor for success in the market. Sustainability theory and methods are quite general. This research aims to calculate the product carbon footprint (PCFP[1]), and assess the sustainability of Plastic Sheet Piling (PSP[2]). In the case of PSP no significant previous research has been done to address sustainability. The product life cycle 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 PCFP 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 PSP can be used as guidelines for the evaluation of similar products within the construction sector. The evolution in sheet piling allows designs to get greener and cost effective. The main conclusion of the study is that the advanced design solutions which have been proven to be less costly and to install more efficiently has emerged as the most sustainable products. The results of the study will be used by stakeholders (manufacturers, distributors, product users, contractors, etc.) as key factor in decision-making.

Keywords - Carbon Footprint, PVC, Sustainability Indicator, Life Cycle, Installation, Plastic Sheet Piling, Vinyl sheet piling, PVC sheet piles.

[1] Product Carbon Footprint
[2] Plastic Sheet Piling

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 before being replaced by another more up-to-date product. Furthermore, the concept of carbon footprint (Laurent, 2010) is considered one of its main indicator 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 PSP. The aim of this paper is to evaluate the different design solutions of plastic sheet piles shown in Figure 1 through calculating their product carbon footprint and assessing their sustainability.

The paper is structured as follows: in Section 2 the background of Plastic Sheet Piling has been introduced, Section 3 presents the developed research methodology, Section 4 discusses the PSP Life Cycle, Section 5 presents the results of an extensive literature review of Product Carbon Footprint calculations and sustainability assessment, Section 6 presents the data collection process from which data had been used for the carbon footprint calculations in Section 7, and in the sustainability assessment in Section 8, Section 9 presents the results and limitations, and the report finishes with conclusion in Section 10.

2. Background of plastic 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 where it offers landscaping features on top of being only hidden structural element.

The products discussed in this paper and shown in Figure 1 are produced by three different companies in three countries: the Netherlands (1 and 2), Poland (3-5), and USA (6). These companies are key suppliers in the PSP market and also produce wide range of plastic sheet piles. The geometry of PSP profile differs between manufacturers; some tend to keep the same shape as steel piles but the most successful pile-designs take advantage of the advanced plastic construction methods and take the development further. As shown in Figure 1 the three groups of PSP discussed in this paper are a) Economy range meaning that this type is light gauge but using the traditional steel pile profiles – generic U and Z piles, b) Traditional range is similar expect that the sections are an exaggerated version of a steel sheet pile, thicker and deeper and so use a lot more material, and c) Advanced type of piles, are the first plastic piles worldwide to introduce new designs, than enhance rigidity and strength without reliance on excessive material. These advanced designs taking advantage of the methods available for the production of PSP, enabling more complex shapes using the minimum possible amount of materials and maximising the strength of the piles, producing a superior cost effective solution. The United Kingdom is prolific with economy Z-shaped piles, the USA with more heavy duty traditional Z and U piles, but the EU is leading the way in design.

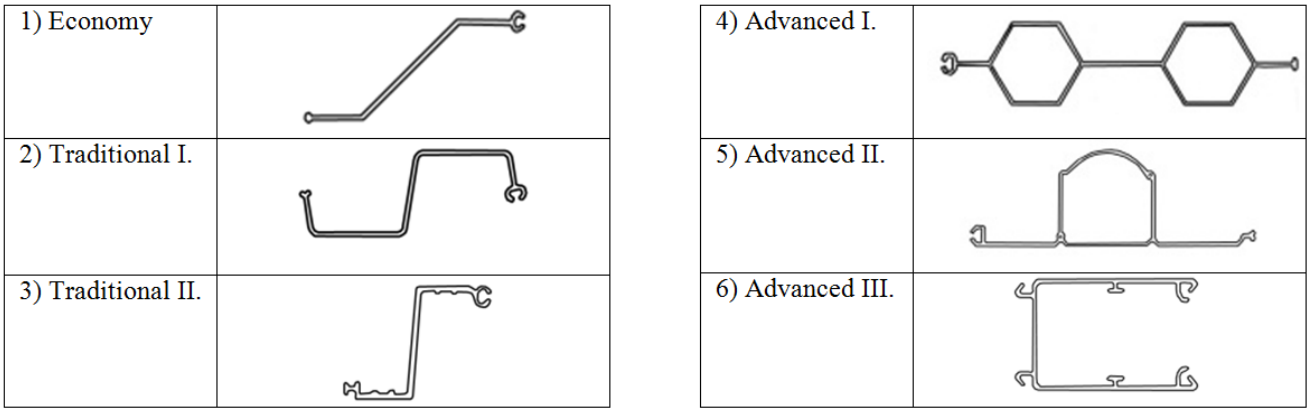

Figure 1: Categorisation and Cross section of the six plastic sheet piles

Manufacturers try to utilize hybrid systems which combine the use of plastic piles with timber or steel poles, or with concrete in order to reduce material requirements such as in the case of Advanced I, II, and III products.

2.1. Allowable bending moment

One of the key engineering parameters used in design is the bending moment that allows an easy strength comparison of the range of plastic sheet piles. Figure 2 summarises the maximum allowable bending moment for the PSP of this range, as the type of the plastic sheet pile has a major effect on it.

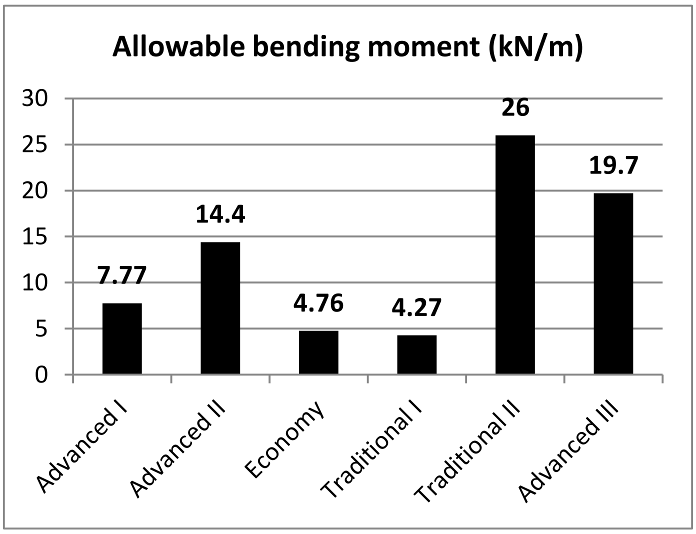

Figure 2: Strength comparison of six plastic pile product

2.2. PSP environmental resistance

The positive impact on sustainability could be highlighted by performing comparison between the two raw materials for sheet piling which are steel and PVC as shown in Table A1. 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.

The most common methods of installing sheet piles are determined by the type of wall. These walls are cut-off, anchored, and cantilever wall showed in Figure 3.

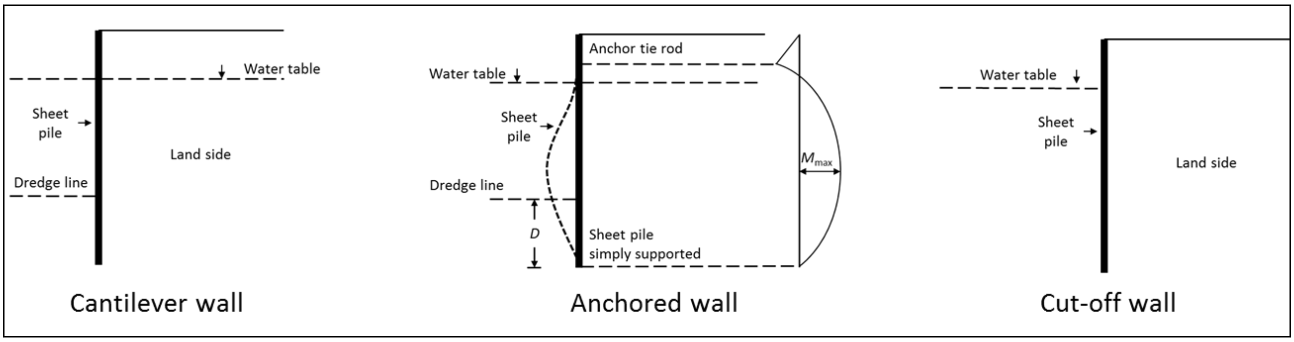

Figure 3: The three most common sheet pile installation wall types

When applying cut-off wall application the sheet piling only has to resist load when it is driven. In the case of Anchored wall additional strength is included using cables which will be anchored to the soil. The third is cantilever wall where its resistance depends on the passive resisting capacity of the soil for preventing overturning. A large number of installation methods are available, from vibrating hammer broadly extended in PSP, to manual installation. The basic driving techniques of installing plastic sheet piles is using vibrator hammers, and less often impact hammers. 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. It has been shown that dynamic soil resistance during the vibrating process is one of the 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 4 illustrates the methodology that has been developed to achieve the objectives of the project. It consists of four phases, and each includes several tasks and deliverables.

Phase		Objectives	Deliverables
1) State of the Art of Carbon Footprint and Sustainability	1.1 1.2	Literature review of Sustainability Assessment and PCFP for PSP Map the PSP lifecycle and identify key impact factors and activities on emissions	State of the Art report; Emission factors
2) Data Collection	2.1	Conduct industrial visits and face-to-face interviews with manufacturers, distributors, product users, and contractors	Data for calculations
3) PCFP Calculations	3.1 3.2	Develop PSP customised PCFP equations Calculate the PCFP of PSP using the developed equations	PCFP Equations; Calculated PCFP
4) Sustainability	4.1 4.2 4.3 4.4	Identifying the sustainability indicators in the lifecycle stages Clarifying the criteria of sustainability assessment Analysis of sustainability Delivering a weighting system in order to address the sustainability issues in the PSP business.	Identifying the most sustainable product and design

Figure 4: Research methodology

4. PSP Life Cycle

Life cycle assessment is a tool (EHSC, 2010) that aims to assess the environmental impacts of a product, service or process through its entire life cycle. The product life cycle of the PSP has been represented as shown in Figure 5 namely: raw materials production, manufacturing, transportation, installation, and disposal/recycling. This aids to identify those environmental inputs and outputs that are needed to calculate the total PCFP, and the impacts at environmental, social and economic dimensions of sustainability. The following presents in detail each of the key activity of the PSP life cycle.

- **Raw materials:** This stage includes raw material transportation, and raw material production using a mix of recycled and virgin PVC, and additives. Final products contain 88-100% recycled PVC that comes from scrap of windows and pipes.

- **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 out, and cut into the final length. The geometry of the cross section of the final plastic sheet piles (Figure 1) has a major impact on the resource consumption (e.g. energy, water) during the manufacturing process.

- **Transportation:** International and UK transport including road, train and sea. The design determines the efficiency of stocking the plastic sheet piles.

- **Installation**: Installation is a crucial stage in case of structural products such as plastic piles. Several different parameters determine the installation process such as the type of application, pile type and geometry, soil conditions, installation equipment, and site location.

- **Disposal/Recycling:** Measured data is not available about the end of life of PSP as the products entered the market only several years ago, and the lifespan of the product is around 75 years.

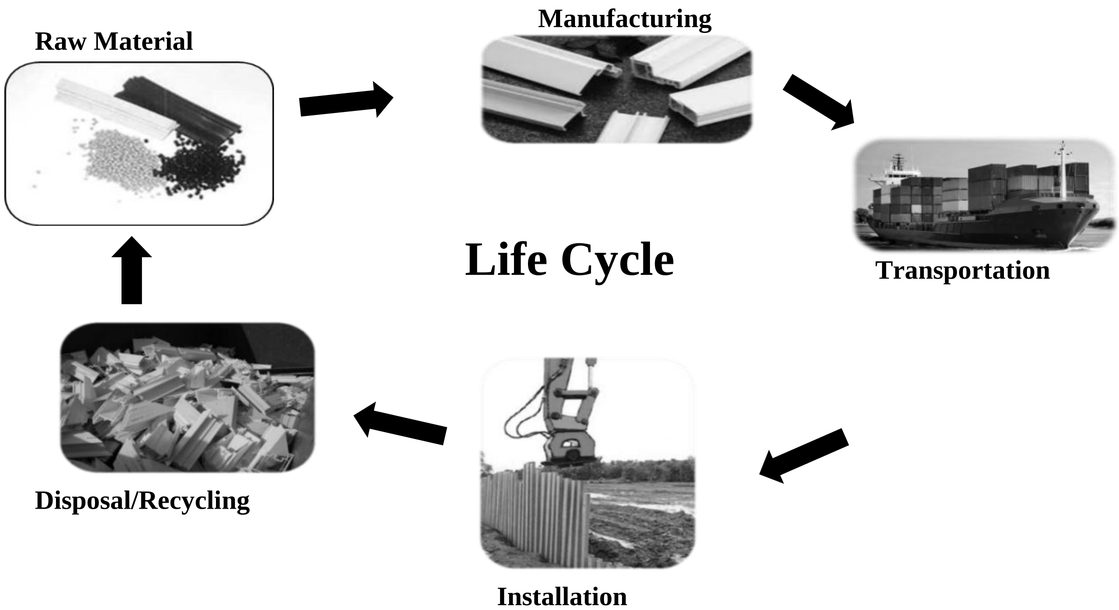

Figure 5: PSP Life Cycle

5. Related literature

5.1. A Review of PCFP Calculation

Product Carbon Footprint measures the environmental impacts of a product throughout its life cycle. It focuses on the analysis and quantification of the total product life cycle emissions that contribute to climate change (Higgs et al, 2009 and 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 life cycle of a product within established boundaries (Wiedmann et al, 2008; 2010). From the six Kyoto gases (CO_2, CH_4, N_2O, SF_6, perfluorocarbons, and hydrofluorocarbons) this research focuses only on CO_2. The emissions that should be considered in the PCFP 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. (Padney et al, 2010; Carbon Trust, 2010; BSI, 2008). The PCFP 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 (O'Connell et al, 2010; Weidema et al, 2008; Plassmann et al, 2010). This can be done 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-eq by applying conversion factors (Padney et al, 2010).

Several methodologies exist that offer guidelines to calculate the PCFP. 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 PCFP are still evolving. PAS 2050 standardises for the first time a method, and it is used as a guideline in this paper. PAS 2050 specifies rules for identifying the system boundary and data quality rules for secondary data (Plassmann et al, 2010 and Sinden, 2009).

There are several challenges to face when calculating PCFP, 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 and Finkbeiner et al, 2009). The result of the PCFP analysis can be used to manage and reduce emissions, increase environmental efficiency, reduce costs, or to promote social responsibility, etc. (Padney et al, 2010; and Carbon Trust, 2010).

5.2. 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 life cycle from three different points of view: environmental, social and economic which are called the pillars of sustainability (Heijungs et al, 2010). Life Cycle Analysis (LCA) is one of the methodologies which assess the environmental aspects during the life cycle 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 life cycle (Spillemaeckers et al, 2006). Both life cycle assessment and PCFP are unsuitable for assessing social and economic dimensions, which are more related to companies involved across the product life cycle rather than to a product itself. Social dimension of sustainability is usually related to employment, work conditions, community, health and safety, while the economic dimension is directly associated with 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 life cycle (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. It is necessary to establish the right boundaries to the system due to complexity (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).

Table A2 illustrates the main affecting factors and the affected parameters within PCFP calculations and the factors that have impact on the life cycle from a sustainability point of view. Those factors have been identified based on the understanding of the literature and the analysis of the piling life cycle. The affecting factors determine the basis for the PCFP calculations. The affected parameters have different units which are comparable when converted into kg of CO_2 equivalents.

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.

6. Field Study Data Collection Process

6.1. Collected Data Type

An industrial field study was carried out to collect the relevant data. The types of data are as follow:-

a. **Secondary Data :**

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. These are:

- **Activity data** refers to all the material and energy amounts involved in the plastic sheet piles life cycle with regards to the factors listed in Table A2 that determines the type of data related the environmental impact.
- **Emission/conversion factors** provide the link that converts from activity data into the amount of GHGs emitted per ‘unit’ of activity, e.g. kg GHG per kWh energy used. These factors can be found in databases provided by organisations such as DEFRA or the Centre for Environmental Assessment of Product and Material Systems (CPM).

b. **Primary data**

Data that is collected from the pile manufacturer companies and this data is specific to the PSP life cycle, and also from some constructors that have been already using piles. Quantitative data had been used for the PCFP calculations, and the quantitative data for the Sustainability Assessment.

6.2. Plastic sheet piling PCFP Data

The primary data collected is related to the affecting factors in Table A2. The primary data collection process included the development of semi-structured questionnaires, and face-to-face interviews, also observations and collection of 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. However, despite using the same questionnaire for all the manufacturing companies in this study, the type and quality of the gathered information varied greatly among them. This was mainly caused by the different importance each supplier gives to the internal management of performance data. The followings are descriptions of the data collected for PCFP calculations related to the life cycle stages which had been used in Section 7:-

Raw material: The affecting factor data of material production as well as the emission factors which is obtained from databases available online (EC, 2004). Data about raw material transportation was gathered from the manufacturers.

Manufacturing: The three PSP manufacturers were visited and assessed. The parts of the questionnaire are shown in Table 1. Information about the total energy, water and gas consumption of the facilities are available in the case of Advanced I and II where product related percentage in relation to the whole production is available. The consumption can be assumed for the production of all the products manufactured in the facility. In case of the other products (Economy, Traditional I and II, and Advanced III) the total information about consumption during production is not available, therefore the detailed information about machines' specifications and operating conditions are required.

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 1: The main sections of the questionnaire for the manufacturing life cycle stage

Figure **6** is an example of a question which is related to machine power specifications of all the equipment used to produce the piles. However, the field study showed that the water consumptions neglectable for the PCFP calculation as it is in closed system where the water is re-used.

Please fill in the below table with the appropriate data

Machine Power Specifications		
Electricity	Pile Product	
Equipment	*kW*	*%Used*
Preconditioning Mixer		
Feeding Blower		
Feeding Screw		
Additives Unit		
…		
Coextrusion Motor		
Heaters		
Other		
Total electricity consumption (kW)		
Water	*m^3/h*	
Extruder Cooling System		
Sheets Cooling Process		
Other		
Total water consumption		

Figure 6: Example of a table for collecting data about the manufacturing step from the life cycle

Transportation: the distance was calculated from the manufacturing site to the London port in UK, and then to the installation site (assuming Birmingham). The secondary data about emission factors related to the calculated distances had been taken from DEFRA (2010). In addition, vehicle type and pile geometry have impact on the vehicle capacity which secondary data has been taken from the manufacturers.

Installation: There is no data available regarding the installation of the PSP from the literature or trade organisation as it is relatively new market. Effort has been made in this research to collect data to help the study, and a set of questions were developed for constructors to capture data in subjective manner in connection with construction work and the use of the piles. Using this data, a general case study of cantilever retaining wall has been designed as shown in Figure A1 in Appendix C.

Disposal: This is secondary data that has been obtained from standardized data from DEFRA (2011).

The following sections present in detail the PSP carbon footprint calculation and the sustainability assessment.

6.3. PSP Sustainability data

Figure 7 shows an open question which is used to gather data from the pile manufacturers.

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 7 Example of open question about health and safety which is part of the sustainability section in the manufacturing life cycle stage

The contractors were met separately and interviews were conducted about the installation of piles they have experienced.

How long did it take to install all the linear footage of the wall: (hours)

Figure 8: Example of a question asked from PSP contractors

7. Carbon Footprint Calculations For Plastic Sheet Piles

Studies related to carbon footprint calculation can be found 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. As discussed in Section 5.1 PAS 2050 was used. The main steps of performing the carbon footprint calculation based on PAS 2050 are the following:-

- Process Map: key activities of the product life cycle as presented in Figure 5
- System Boundaries: defining the boundaries for the calculations, for where the effort of gathering data is going to be concentrated, also clarifies inputs (resources) and outputs (emissions)

- Data Collection: this is explained in Section 5
- PCFP Calculations: The calculations involve multiplying the activity data by the appropriate emission factors using the equations discussed in Section 6.1
- Uncertainty: is a measure of precision of the data and calculations

Assessment of the GHG emissions is carried out in a manner that allows the mass of CO_2 emission to be determined per functional unit in which the PCFP results are going to be expressed. This functional unit is related to the final use of the plastic sheet piles which are 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 meter 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 follows:-

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. This units takes the allowable bending moment into account, as follows:-

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

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. The equation used to calculate total PCFP in case of PSP is the following:

$$PCFP = \sum Activity\ Carbon\ Emission =$$

$$Raw\ Material + Manufacturing + Transportation + Installation + Disposal$$

Equation 1: PCFP calculation equation

This means the kg of CO_2 emission of each stage of the pile life cycle is calculated separately, and then their aggregates give the total PCFP result.

7.1 Raw Materials Production

Equation 2 is designed to calculate the CO_2 emission of the PVC plastic that has got both virgin and recycle materials. Table 2 lists data and emission factors used in equations 2 and 3 to calculate the PCFP for the raw material production and transportation. The data is in kg CO_2 per kg however it had to be translated into the functional unit which is kg CO_2 per effective m^2.

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

Equation 2: Production of PVC

Equation 3 has been designed to calculate the CO_2 emissions during the production of PVC.

- F_v (Kg CO_2/ton PVC) is a emission factor that provides the information about how many kg of CO_2 are emitted for producing a ton of virgin PVC
- F_r is the same for recycled PVC
- (%Virgin mat/100*F_v + % Recycled mat *F_r) (Kg CO_2/ton material) is the emission factor of the PVC used (composed by both, virgin and recycled PVC)
- Kg/m: is how much is the weight of one meter pile
- 1/Effective width is used to have the result in effective $m_{2.}$

Equation 3 is used to calculate the emission of transporting raw materials to manufacturing facilities. It takes into account the type of vehicle, distance and geometry parameters in order to express results in effective m^2.

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

Equation 3: Transportation of raw materials

Table 2 contains the data and emission factors used in the calculation of PCFP for the raw material production and transportation life cycle stage.

Data type	Data Source	Adv I	Adv II	Eco	Trad I	Trad II	Adv III
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 2: Data and emission factors used in the calculation of PCFP for the raw material production and transportation life cycle stage

7.2 Manufacturing Process

Equation 4 is design to calculate the CO_2 emission of the plastic extrusion manufacturing process used to produce the piling sheets. It consists of annual electricity consumption times the weight of plastic pile per one meter by total annual PVC used in production. To calculate the carbon footprint of the manufacturing stage, the energy consumption per effective square meter needs to be estimated. In Company 1, the total energy consumption of the whole manufacturing facilities of one year is available. Therefore, the percentage of energy consumption to produce the Advanced I and II piles was easy to calculate.

$$Manufacturing\left(\frac{kg\,CO_2}{eff\ m^2}\right) = \frac{Annual\ electricity\ consumption * Weight\ per\ m}{Total\ annual\ PVC\ used * Effective\ width}$$

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

The data used is represented in **Table 3**.

Data Type/Product	Data Source	Adv I	Adv II
Primary	**Annual electricity consumption (kWh/year)**	2,738,586	
	Total annual PVC consumption (Kg PVC/ year)	5,680,000	
	Effective width (m)	0.5	0.5
	Weight per m (Kg/m)	6.2	8.4
Secondary	**Electricity Emission Factor (kg CO2/kW·h)**	0.64	0.64

Table 3: The data used in the manufacturing life cycle stage in case of Advanced I and II

Second method is related to the products of Company2 and 3. Based on the specifications and working conditions of all the machines of the production lines 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 to make the estimation of the energy consumption possible. Equation 5 was developed 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)

The data used is represented in Table 4.

Data Type	Data Source	Eco	Trad I	Trad II	Adv III
Primary	**SGR**[3]	1.05	1.05	1.05	1.081
	Energy Consumption	4.58	4.77	11.2	10.2
Secondary	**Electricity Emission Factor (kg CO2/kW·h)**	0.699	0.699	0.699	0.709

Table 4: The data used in the manufacturing life cycle stage in case of Economy, Traditional I and II, and Advanced III

7.3 International Transportation

The Equation 6 was developed for calculations.

$$Transportation_{\ m^2\ of\ product} = \frac{Norm * Distance}{VC * GF}$$

Equation 6: International transportation of piles

The geometry factor (GF) for transportation of different products has been created by using the maximum capacity of the vehicle and estimated maximum number of plastic piles per vehicle. In

[3] Scrap Generation Ratio

the case of different vehicles being used it is necessary to sum up the emissions from every vehicle types. The summary of the data used for PCFP calculations for the international transportation is shown in Table 4.

Data Type	Data Source	Adv I	Adv II	Eco	Trad I	Trad II	Adv III
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
	$kgCO_2$ per vehicle km	0.9306	0.9306	0.9306	0.9306	0.9306	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 PCFP calculation for the international transportation

7.4 Installation

Equation 7 below was used to calculate the emissions of CO_2 during the installation stage. For the carbon footprint calculations conversion factor and activity data is necessary to calculate the CO_2 equivalent emission. The conversion factor comes from DEFRA, and the activity data comes from the calculation of the equipment consumption in liter per hour divided by the performance rate in meter per hour. In order to get the results in m^2 a division by the length of pile is necessary.

$$\textit{Emission}\left[\frac{kg\,CO_2}{m^2}\right] = \textit{(Conversion factor*Activity data)/length of pile}$$

Equation 7: Emission factor for the installation

	Activity data (L/m)	Conversion Factor ($kgCO_2$/L)	Length of pile
Advanced I	3,7	2,672	Figure A1**Error! Reference source not found.**
Advanced II	3,7	2,672	
Economy	3,2	2,672	
Traditional I and II	3,2	2,672	
Advanced III	5,68	2,672	

Table 6: Data for the Installation Stage

7.5 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 (Equation 8).

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

Equation 8: Emission factor for the disposal

Table 7 summarises all the required data, the value of the specific emission factor used and the result for the PCFP in the disposal stage.

Data type	Data Source	Adv I	Adv II	Eco	Trad I	Trad II	Adv III
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 7: Data necessary of PCFP for PSP in the disposal stage

The results of the PCFP calculations are discussed in Section 7.6.

7.6 Results of the PCFP Calculations

This section is presenting a detail calculation the PCFP of Advanced I plastic piling sheet using a set of Equations 2, 3, 4, 5, 6, and 8 presented in previous sections.

Equation 2: Raw material production $\mathrm{RM} = \left(\frac{\left(\left(\frac{7}{100}*1.944\right)+\left(\frac{93}{100}*0.1543\right)\right)*6.2}{0.5}\right) = 3.47$

The parameters of Equation 2 are obtained from Table 2.

Equation 3: Raw material transportation $= 6.11*0.00001*500*\frac{6.2}{0.5} = 0.38$

The parameters of Equation 3 are obtained from Table 2.

The value of the raw material of the PCFP calculation is the addition of Equation 2 and 3: 3.47+0.38= 3.85 kg of CO_2 per eff m^2 as show in Table 8.

Equation 4: Manufacturing $= \frac{2{,}738{,}586 * 6.2}{5{,}680{,}000 * 0.5} * 0.64$ =3.83 kg of CO_2 per eff m^2

The parameters of Equation 4 are obtained from Table 3.

Equation 5: Manufacturing (Economy pile) $= 4.58 * 1.05 * 0.699$ =3.36 kg of CO_2 per eff m^2

The parameters of Equation 5 are obtained from Table 4.

Equation 6: Transportation $= \frac{0.9306 * 830}{95 * 17.5}$ =0.46 kg of CO_2 per eff m^2

The parameters of Equation 6 are obtained from Table 5.

Equation 8: Disposal = 0.04 * $\frac{6.2}{0.5}$ =0.50 kg of CO_2 per eff m^2

The parameters of Equation 8 are obtained from Table 7.

As Advanced I is part of a hybrid solution additional material is required such as timber pole or reinforced concrete. In this case it`s consumption is 1.48 kg of CO_2 per eff m^2 as show in Table 8-F. The PCFP value is 12.8 kg of CO_2 per eff m^2 (Table 11-G) which is addition of the above as explained in Equation 1.

	A	B	C	D	E	F	G	H
PLC Stages / Product	Raw Material	Manufacturing	Transportation	Installation	Disposal	Subcomponent	PCFP (kg of CO_2 per eff m^2)	Total PCFP (kg of CO_2 per eff m^2/kNm/m)
Advanced I	3.85	3.83	0.46	2.68	0.50	1.48	12.8	**1.65**
Advanced II	5.21	5.18	0.68	2.68	0.67	2.14	16.56	**1.15**
Economy	3.73	3.36	0.63	2.44	0.42		10.58	**2.22**
Traditional I	1.93	3.50	2.02	2.44	0.57		10.46	**2.45**
Traditional II	11.42	8.22	1.78	2.44	1.34		25.2	**0.97**
Advanced III	11.35	7.82	6.10	3.20	1.39	1.75	31.61	**1.6**

*hybrid solution including the contribution of the plastic pile and the subcomponent also (timber pole or reinforced concrete)

Table 8: PSP PCFP in kg CO_2 per effective m^2

Following the same calculation method, the rest of the PCFP calculation of the other PSP products have been made and illustrated in Table 8. This is without the installation as it could not be calculated using effective square meter. Table 8-G shows that Traditional I and Economy products have the lowest carbon emission of 8.02 and 8.14 respectively without the consideration of the allowable bending moment which must be considered as it is related to the forces that pile will bear while it is driven into the soil as has been explained in Section 2.1. Hence, the Total Advanced I PCFP value is 1.3 kg of CO_2 per eff m^2*kNm/m which is the results of dividing the PCFP value of 12.8 kg of CO_2 per eff m^2 (Table 11-G) by the corresponding allowable bending moment shown in Figure 2 which 7.77 kNm/m for the Advanced I. Therefore the results show that Traditional II and Advanced II have the lowest carbon emission. This is important finding that the simplicity of product geometry is not necessarily the solution for obtaining lower carbon emission. The installation carbon emission calculation is obtained by using Equation 7. Therefore the Advanced I installation calculation is as follow:

Equation 7: Installation = (2,672 * 3.7=9.89 kg of CO_2 per eff linear meter)/3.7=2.68

The parameters of Equation 7 are obtained from Table 6.

The final result of the PCFP calculations shows that Economy and Traditional I are the ones with the best results in terms of PCFP emission. However, it does not mean they are best option from sustainability point of view as will be explained in Section 8. Here is the argument that low PCFP does not necessarily indicate a sustainable activity.

8. Product sustainability assessment

Assessing sustainability involves moving beyond the analysis of the PCFP and it entails evaluating the impacts of the product during its life cycle in the three dimensions of sustainability such as environmental, social and economic. Currently there is a lack of metrics how to define and measure sustainability in the social and economic dimensions (Fan, 2010 and Jayal et al, 2010). Therefore a sustainability assessment method had been developed for PSP Sustainability Assessment in order to address these qualitative dimensions using a scoring and a weighting system based on a previous investigation work on sustainable manufacturing (Fan, 2010).

8.1. Sustainability Indicators

The sustainability assessment aims to transform the qualitative information and opinions collected into quantitative data. In order to do so sustainability indicators were used as shown in Figure 10 to categorise the information. The whole table is show in Table A4. These indicators had been identified from literature (UNEP, 2009; and Calkins, 2009) and been identified through group discussions between the authors.

		1. RAW MATERIAL	2. MANUFACTURING	3. TRANSPORTATION	4. INSTALLATION	5. DISPOSAL
		Factor	Factor	Factor	Factor	Factor
1. ENVIRONMENTAL	Resources Management and Efficiency	Recycled raw material	Reuse of resources	Possibility of using alternative transport	Scrap Generation	Recyclability after use*
		Use of alternative raw material	Scrap generation	Packaging	Need of previous works (i.e. Diging)	Recycling/Disposal method*
		N. of times can be recycled	Waste recycling	Cargo handling	Handling*	Ease of recovery*
		Need of raw material preconditioning	Use of renewable energy	Usage of free space	Assembly*	Possible alternatives (i.e. reuse)*
		Diversity of raw materials sources	Plastic Piling impact on Sust. Resources Manag.	-	Driveability*	-
	Biodiversity	Impact on local biodiversity*	Impact on local biodiversity	Impact on biodiversity*	Impact on local biodiversity	Impact on biodiversity*
	Pollution	Use of hazardous products*	Hazardous products/waste	Emission, Dust & Waste*	Waste generation*	Emission*

Figure 9: Example of sustainability indicators

The sustainability indicators have been represented in a bi-dimensional indicators classification according to two main criteria, namely sustainability dimensions (UNEP, 2009) and life cycle stages. *Sustainability dimensions* include 1) environmental indicators such as resources management and efficiency, biodiversity, and pollution, 2) social indicators such as employment, health and safety, and community, 3) economic indicators that may have simultaneous impact, and 4) other indicators that are mainly related to the design of the products. The sustainability indicators have also been arranged according to the main life cycle stages (Figure 5).

Environment-related indicators are determined by the products (e.g. % of raw material, scrap generation, assembly, etc.), whereas economic and social aspects can be determined mainly by the environment (e.g. benefits for community, impact on environment, etc.).In the following the quantification of the qualitative data is discussed through giving scores and then weighting the indicators based on the work of Fan et al (2010).

8.2. Scoring System

A scoring system has been created to be able to rate the plastic sheet pile products according to the different sustainability indicators. The quantification of the qualitative data was possible through rating by giving scores to the indicators. The scores were given by authors based on the results of the interviews with the manufacturer companies and the contractors as shown in Figure 10. The system is based on scores in a range from 1 to 5 where 1 means the best case scenario. In case an indicator is not relevant or not applicable 0 had been used. In those cases when there is no data available or simply the indicator is not applicable to the company no score was given. As a result, in this research the higher the number the lower the impact it has on sustainability.

Life Cycle Stages / Sustainability Dimensions		1. RAW MATERIAL	Scores
		Factor	
1. ENVIRONMENTAL	Resources Management and Efficiency	Recycled raw material	4
		Use of alternative raw material	4
		N. of times can be recycled	5
		Need of raw material preconditioning	5
		Diversity of raw materials sources	5
	Biodiversity	Impact on local biodiversity*	-
	Pollution	Use of hazardous products*	-
		Emissions and dust*	-

Figure 10: Example of scores given to the indicators for Advanced I in the Raw Material stage for the Environmental dimension

Not all of the indicators have the same importance with regards to sustainability therefore they were weighted in a certain way as discussed in Section 8.3.

8.3. Weighting System

A bi-dimensional weighting system was developed in order to allocate more importance to those sustainability indicators that are considered more relevant in this study.

As the plastic piling business belongs to the manufacturing and construction sector, environmental indicators have been considered the most relevant. Social and economic factors are also important, but measuring them is difficult and 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%. With regards to the product life cycle stages both raw material and manufacturing stages have more frequent, more severe and longer impacts when compared in general to transportation and installation stages, therefore receiving higher percentages. Moreover, as plastic piling is a fairly recent area, information is not available concerning the disposal stage due to the lifespan of the product that is around 75 years and therefore at the time of this research it had no impact on sustainability. The following weightings have been allocated to the different stages: Raw Materials 30%, Manufacturing 40%, Transportation 10%, Installation 20% and Disposal 0%. In Section 8.4 the developed PSP sustainability assessment method is discussed using these percentages as shown in Figure 11.

Life Cycle Stages / Sustainability Dimensions		1. RAW MATERIAL 0.3 — Factor	Scores
1. ENVIRONMENTAL 0.5	Resources Management and Efficiency	Recycled raw material	4
		Use of alternative raw material	4
		N. of times can be recycled	5
		Need of raw material preconditioning	5
		Diversity of raw materials sources	5
	Biodiversity	Impact on local biodiversity*	-
	Pollution	Use of hazardous products*	-
		Emissions and dust*	-

Figure 11: Example of weights associated with the indicators for Advanced I in the Raw Material stage for the Environmental dimension

8.4. Plastic Sheet Piling Sustainability Assessment method

The PSP sustainability assessment method involves a bi-dimensional indicators classification (sustainability dimensions/life cycle stages), and a bi-dimensional weighting system (weighting/life cycle stages) as discussed in Section 8.1 and 8.3. In order to calculate the final PSP Sustainability

Assessment score several steps needed to be taken. The scores given were normalised to get the Normalised Subtotal Score (NSS) therefore getting a number – in the example 92 as shown in Equation 9 - where all the result can be related to a common base (100%), then weighted by the sustainability dimensions as described in Section 8.3 to get the Weighted Subtotal Score (WSS) of each products in each life cycle stage, and then the WSS numbers were weighted by the weights of the life cycle stages and summed up to get the Total Sustainability Score (TSS) of each pile.

Life Cycle Stages / Sustainability Dimensions		1. RAW MATERIAL 0.3	Scores
		Factor	
1. ENVIRONMENTAL 0.5	Resources Management and Efficiency	Recycled raw material	4
		Use of alternative raw material	4
		N. of times can be recycled	5
		Need of raw material preconditioning	5
		Diversity of raw materials sources	5
	Biodiversity	Impact on local biodiversity*	-
	Pollution	Use of hazardous products*	-
		Emissions and dust*	-
	NSS		92

Figure 12: Example of the Normalised Subtotal Score for Advanced I in the Raw Material stage for the Environmental dimension

In order to perform the steps discussed above two indexes were used (index *i* and *j*). Index *i* means the 5 different life cycle stages, and index *j* means the 4 different sustainability dimensions discussed in Section 8.1. The steps followed during calculations are described below.

NSS for any stages and dimensions was calculated using Equation 9.One of the results for example in the case of Advanced I in the Raw Material stage considering the Environmental indicators is 92 (=(4+4+5+5+5)/(5*5))*100) as shown below.

$$NSS(i,j)(\%) = \frac{\sum Scores\ (i,j)}{Number\ of\ indicators\ (i,j) * 5} * 100$$

Equation 9: Normalised Subtotal Score

Secondly, WSS (i) was calculated by using the NSS numbers shown in Equation 10, and including the weightings of the Sustainability dimensions (index j substituted by numbers) as shown in Table A4. Therefore in case of Advanced I WSS in the Raw Material stage is 92.7 (=(50*92+5*100)/55), WSS in the Manufacturing stage is 76.4 (=(50*85.71+25*65+20*64+5*90)/100). The results are shown in Table 9.

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

Equation 10: Weighted subtotal score calculation

Finally, the Total Score of a product was calculated using Equation 11 including the weightings of the life cycle stages at mentioned before from Table A4.

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

Equation 11: Total sustainability score

8.5. The PSP Sustainability Assessment Results

In the sustainability assessment for each product the results of the WSS and the TSS are summarised in Table 9. In the Raw Material, Manufacturing, and Installation stages Advanced I and II are the most sustainable products with regards to our data and calculations. In the Transportation stage Economy and Traditional I and II have high score. Advanced III is good in the Raw Material stage, but in terms of Manufacturing, Transportation, and Installation shows a lower performance.

	WSS: Raw Material stage	**WSS: Manufacturing stage**	**WSS: Transportation stage**	**WSS: Installation stage**	**TOTAL (TSS)**
Advanced I (NL)	92.7	76.4	84	80.5	**82.9**
Advanced II (NL)	92.7	76.4	84	84	**83.6**
Economy (PL)	60	74	85.2	72.5	**70.6**
Traditional I (PL)	60	74	85.2	76.6	**71.4**
Traditional II (PL)	60	74	85.2	67	**69.5**
Advanced III (USA)	72.7	68.2	68.5	65.7	**69.1**

Table 9: Results of the sustainability assessment method for PSP

9. Discussion of the results and the limitations

In this research the calculation of Product Carbon Footprint of Plastic Sheet Piling has been achieved. The results clearly illustrate that whilst the design of products have influence on PCFP, overall there is little difference in terms of carbon footprint between the products within the same category of applications. The PCFP for a m^2 of pile taking into consideration the strength of the piles is between 0.97 and 2.45 kg of CO_2. The highest CO_2 consumption is related to the Raw Material and Manufacturing stages. Filling some of the products with concrete or reinforced concrete improves the strength of those products but also increases the CO_2 emission by 5-13%. In terms of sustainability the results fluctuate between the range of 69.1 and 83.6 respectively referring to Advanced III and Advanced II which shows that although there is impact on the social and economic environment not a big difference was found when comparing the results of the products among each other. The products from the same country have similar results because there are very few and small viewpoints where differences could be found – Advanced I with Advanced II, Economy with Traditional I and II, and also Advanced III. The exception is the installation stage where it can be seen that the results differ from each other in case of all the products. This depends on the type of application, pile geometry, soil conditions, installation equipment, and the site location, etc. as discussed in Section 4. There is some suggestion by the researchers to improve the installation stage by designing a more sustainable geometry (e.g. by using a hollow sheet piling profile while reducing material). In total Advanced II came out as the best product in this assessment.

Limitations of this study are related to the accuracy of the results due to the fact in the difference between the data availability at each company. The results of the PCFP study are valid as long as the adopted simplifications are considered when comparing the different cases. The developed and customised product sustainability assessment method is novel, and uses qualitative, subjective, and confidential data where subjectivity and confidentiality had to be considered. Real-case product comparison is another limitation. The PSP industry is quite a recent area therefore experiences regarding to the range of products included in this study are limited and vary significantly. This study has been conducted assuming the installation of the products in the United Kingdom.

10. Conclusion

This paper presented the first ever research carried out in the topic of Product Carbon Footprint and Sustainability Assessment in the sector of Plastic Sheet Piling (PSP). The paper evaluated the different design solutions of plastic sheet piles through calculating their product carbon footprint and assessing their sustainability.

The project identifies the steps of the life cycle for PSP for improvement. Transportation and manufacturing produces most of the CO_2 during the PSP life cycle though when using and installing the products improvements might be considered in order to enhance the sustainability of them. This paper introduces new equations for the carbon footprint calculations of plastic sheet piles and delivers a scoring and weighting system for the plastic piling sustainability assessment. This can be used as a base for further design of new products. In this paper it had been found that the simplicity of product geometry is not necessarily the solution for obtaining lower carbon emission. It is recommended that during the design of a product the entire product life cycle is considered to be able to improve the overall product carbon footprint and sustainability.

The different plastic sheet pile designs discussed in this research encourage further innovation in design improvement of these products, and being lighter and cheaper than steel piles enhanced with many possible product designs validates the fact of being better and greener than traditional piles. Advanced plastic pile design solutions applied in a combined way with other materials such as wood multiplies the benefits of using plastic sheet piles, and these, so called hybrid solutions are the most sustainable among the ones discussed in this paper.

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APPENDIX A

Material	**Steel**	**PVC**
Resistant for different environmental conditions	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	75 years
Material recovery	Full or partial	Full or partial
Main usage	Road construction Underground construction Flood protection Construction of landfills	Cut-off walls Ditch blocking Retaining wall Bank stabilization Erosion control Drainage channels Bank retention Flood defence
Manufacturing	No production in the UK	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	Highly resistant
Transportation	Not difficult but neither easy	Easy to transport, light
CO_2 emission during manufacturing process (kg CO_2 e/m^3)	Steel – 17000 Recycled steel – 4000	5000
Fossil fuel energy used in the manufacturing (MJ/kg)	35	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	Phthalate plasticizers Vinyl chloride monomer Dioxins

Table A1: Material comparison of steel, concrete and PVC

APPENDIX B

Affecting Factors for PCFP 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[4] 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)
	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 A2: Affecting factors for PCFP calculations of the plastic sheeting piling

[4] VCM=Vinyl Chloride Monomer

APPENDIX C

A cantilever retaining wall is in generic soil conditions which is characterised by the parameters shown in Table A3 according to EN 1997 Eurocode7. The sheet piling is to retain a 2 meter wall in height. The length of the wall is not considered as the carbon footprint is calculated per linear meter of bend.

The steps of the case study were the following:-

1. Selection of the variables of the installation project, e.g. height of the pile
2. Wall type (i.e. cut-off, cantilever, and anchored) for each product considered in the study as listed in Section 2.2. The wall design and dimensions for the case study is illustrated in Figure A1.
3. Gather equipment resource consumption data from constructors
4. Calculate the PCFP of the case study
5. In the case of Advanced I and II a timber pole should be used because of being a hybrid system. The Economy and Traditional piles have very similar geometry therefore the optimal thickness was selected for them. Advanced III is also part of a hybrid system using a filling; the design contains reinforced concrete.

Pile type	Case 1 (retaining wall dimension)
Advanced I	3.7 m long pile, and 5 m hard wood with 120mm diameter
Advanced II	3.7 m long pile, and 5 m long timber pole with 120mm diameter
Economy	length 4,75 m
Traditional I and II	length 4,75 m
Truline800	3.5 m pile with reinforced concrete (2 corrugated bars of ¾" at 4 in from the bottom

Figure A1: The different wall design and dimension for the case study

soil bulk density (ρ)	—
density of soil (I_L)	
soil internal friction angle (ϕ_u)	
material factor for soil (γ_m)	9,
Secondary and primary compressibility modulus ($M^{(n)}$)	

Table A3: Soil parameters of a cantilever wall geotechnical design in generic soil conditions

APPENDIX D

						Product						
		Life Cycle Stages / Sustainab. dimensions	1. RAW MATERIALS	0.3	2. MANUFACTURING	0.4	3. TRANSPORTATION	0.1	4. INSTALLATION	0.2	5. DISPOSAL	0
			Factor	Score	Factor	Score	Factor	Score	Factor	Score	Factor	Score
1. ENVIRONMENTAL	0.5	Resources Mangament and Efficiency	Recycled raw material	4	Reuse of resoruces	5	Possibility of using alternative transport	1	Scrap Generation		Recyclability after use	-
			Use of alternative raw material	4	Scrap generation	2	Packaging	5	Need of previous works (i.e. Diging)		Recycling/Disposal method	-
			N. of times can be recycled	5	Waste recycling	5	Cargohandling operations	5	Handling	-	Ease of recovery	-
			Need of raw material preconditioning	5	Use of renewable energy	5	Usage of free space	5	Assembly	-	Possible alternatives (i.e. reuse)	-
			Diversity of raw materials sources	5	Plastic Piling impact on Sust. Resources Manag.	3			Driveability	-		
		Biodiversity	Impact on local biodiversity	-	Impact on local biodiversity	5	Impact on biodiversity	-	Impact on local biodiversity		Impact on biodiversity	-
		Pollution	Use of hazardous products	-	Hazardous products/waste	0	Emission, Dust & Waste	-	Waste generation	-	Emission	-
			Emissions and dust	-	Emission and dust	5			Emission and dust		Hazardous releases	-
			NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL	
2. SOCIAL	0.25	Employment	Employees involved in raw materials preparation	-	Employees involved ratio	3	Employees involved	2	Employees involved		Employees involved in end on life disposal	-
					Employees increase due to Plastic Piling Business	1						
		Health & Safety	H&S: raw materials production	-	H&S: Manufacturing	4	H&S: Handling	5	H&S: Handling		H&S: Disposal	-
			Accidents and Diseases	-	Accidents and Diseases	4	Accidents	-			Accidents and Diseases	-
					Working Hours	5						
		Community	Impact on community	-	Impact on community	5	Impact on community	5	Impact on community		Impact on community	-
			Benefits on community	-	Benefits on community	4					Benefits on community	-
			NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		TOTAL	
3. ECONOMIC	0.2		Raw materials cost	-	Reuse of resources	5	Delivery time	5	Installation costs		Disposal costs	-
			Cost reduction by using more recycled raw material	-	Relevance of plastic piling business in the company	5	Transportation	5	Installation time			
			Cost reduction by using alternative raw material	-	Machine usage for Manufacturin piles							
					Electricity costs	1						
					Impact on indirect economy	1						
			NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL	
4. OTHER	0.05				Design Importance: Ease of Manufacturing		Design Importance: Ease of Stacking	3	Design Importance: Ease of Driving		Design Importance: Disposal	
					Company's Sustainable Initiatives	4	Sustainable Transportation Design	5	Design Importance: Ease of Handling			
									Design Importance: Ease of Assembly			
			NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL		NORMALISED SUBTOTAL	
			WEIGHED TOTAL		WEIGHED TOTAL		WEIGHED TOTAL		WEIGHED TOTAL		WEIGHED TOTAL	
											TOTAL	

* the indicator with "-" sign have not been used

Table A4: Sustainability indicators