A process-oriented model to measure product carbon footprint: an exploratory study based on multiple cases

Hu, Jialun; Shi, Yongjiang; Cheng, Yang; Liu, Zheng

Published in:
Production Planning & Control

DOI (link to publication from Publisher):
10.1080/09537287.2023.2266410

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Production Planning & Control
The Management of Operations

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tppc20

A process-oriented model to measure product carbon footprint: an exploratory study based on multiple cases

Jialun Hu, Yongjiang Shi, Yang Cheng & Zheng Liu

To cite this article: Jialun Hu, Yongjiang Shi, Yang Cheng & Zheng Liu (10 Oct 2023): A process-oriented model to measure product carbon footprint: an exploratory study based on multiple cases, Production Planning & Control, DOI: 10.1080/09537287.2023.2266410

To link to this article: https://doi.org/10.1080/09537287.2023.2266410

PRODUCTION PLANNING & CONTROL
https://doi.org/10.1080/09537287.2023.2266410

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

A process-oriented model to measure product carbon footprint: an exploratory study based on multiple cases

Jialun Hu[a], Yongjiang Shi[b], Yang Cheng[c] and Zheng Liu[d]

[a]School of Business and Management, Royal Holloway University of London, London, UK; [b]Department of Engineering, University of Cambridge, Cambridge, UK; [c]Department of Materials and Production, Aalborg University, Aalborg, Demark; [d]Cardiff School of Management, Cardiff Metropolitan University, Cardiff, UK

ABSTRACT

Climate change is global challenge and decarbonisation becomes top agenda for manufacturing firms. As it is generally recognized that only the measured get managed, an understanding and measuring of the Product Carbon Footprint (PCF) is now needed. International standards have provided the basic steps for carbon footprint measurement, yet, in practice, there is knowledge insufficiency and high cost. This paper aims to answer the research question: '*How can companies conduct PCF measurement projects effectively?*'. This research adopts the qualitative method with multiple case studies. Data is collected through interviews with operation managers and the sustainability specialists of nine manufacturing companies, with a focus on the motivation and details of activities relating to their PCF measurement projects. Through within-case and cross-case analysis, a process model is proposed alongside the identification of three types of PCF, trial-oriented, process-oriented, and market-oriented PCF. A series of tailored measurement process models are further developed according to the PCF scenarios. The holistic process model contributes to the understanding of a PCF measurement that is based on empirical evidence. Practically, the process model can serve as a 'cookbook' to implement PCF measurement projects.

ARTICLE HISTORY
Received 5 April 2023
Accepted 26 September 2023

KEYWORDS
Product carbon footprint; carbon footprint measurement; PAS 2050; sustainability

1. Introduction

Climate change is recognized as one of the most severe challenges globally due to the large amount of CO_2 emission from production, transportation and consumption. While traditionally companies compete in terms of cost, quality and agility, the requirement for decarbonisation and sustainability has become increasingly more important (Nuber, Velte, and Hörisch 2020). As it is generally recognized that only the measured get managed, a method to measure and report the carbon emission profile has become a priority (Rebitzer et al. 2004; Pandey, Agrawal, and Shanker 2011; Xiao et al. 2021; Velte 2021).

The measurement of carbon footprint has so far covered various levels. At an enterprise level, carbon emission is categorized into Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from the generation of purchased energy), and Scope 3 (all indirect emissions not included in scope 2 that occur in the value chain of the reporting company, including both upstream and downstream emissions) (WRI 2013, 2015), according to the Greenhouse Gas Protocol (GHG) convened in 1998 by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) (WBCSD and WRI 2004). Measurement can also focus on a product level, regarded as a product carbon footprint (PCF), (Gao, Liu, and Wang 2014; Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; He et al. 2019; Velte 2021; Wong et al. 2022), which examines the emission from the upstream raw material to the end of use phase, linking different enterprises along the supply chain (Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; Wong et al. 2022).

Current understanding of a PCF is seen in three main streams. The first steam utilizes modelling and simulation to analyze production and environmental factors (Plassmann et al. 2010; Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; Mahapatra, Schoenherr, and Jayaram 2021; Wong et al. 2022). The second stream relies on empirical data to explore activities in a specific area of PCF (Matos and Hall 2007; Aikins and Ramanathan 2020; Lee 2011; Lee and Cheong 2011), such as product design, logistics, recycling etc. The third stream concerns industry standards to guide practice (Hussain, Malik, and Taylor 2017; Liang et al. 2023). This further includes the general quantification process and communication of carbon emission results such as GHG Protocol, International Standards Organization (ISO) 14067 (ISO 2018; Liu, Wang, and Su 2016; Hussain, Malik, and Taylor 2017), as well as specific PCF guidelines with an *ad hoc* indication on GHG calculation and monitoring, such as Publicly Available

CONTACT Zheng Liu zliu@cardiffmet.ac.uk Cardiff School of Management, Cardiff Metropolitan University, Cardiff, UK

Specification (PAS) 2050 issued by the British Standards Institute (BSI) (Sinden 2009; BSI 2011; Liu, Wang, and Su 2016).

Whilst PCF measurement has received increasingly more attention in recent studies (Wong et al. 2022), the understanding, in particular regarding its process and procedure, is still insufficient (Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; Mahapatra, Schoenherr, and Jayaram 2021). Existing PCF methodologies face challenges of how they can be applied in different complex scenarios (Chau, Leung, and Ng 2015) or across various organizations in the whole supply chain (Sundarakani et al. 2010; Winter and Knemeyer 2013; Singh et al. 2015). In practice, there is lack of implementation details and consistent elements in industry guidelines such as GHG/ISO/PAS (Liang et al. 2023). Thus, a new systematic PCF measurement framework is required to advance the knowledge of PCF measurement process and support industry implementation effectively (Sundarakani et al. 2010; Jensen 2012; He et al. 2019; Velte 2021).

Based on the above-mentioned background, this study aims to identify details of activities during the PCF measurement, developing a new process-oriented model which considers factors in various industry scenarios and different areas of the supply chain. Thus, the research question is: *How can companies conduct PCF measurement projects effectively*? Through multiple case studies on companies who have practised the PCF measurement, the motivation, process, activities, and prioritized areas are explored. Findings contribute to the limited understanding of the PCF measurement with empirical observations. In addition, a new holistic PCF measurement process model is provided for practitioners to apply according to various industry scenarios.

The remainder of the paper is structured as follows. After this section, Section 2 reviews the PCF measurement literature. Section 3 explains the research method. Section 4 introduces the cases with a summary of the within-case analysis. Section 4 contains the cross-case analysis, which is followed by the discussion in Section 5 and the conclusion in Section 6.

2. Literature review

2.1. Product carbon footprint measurement

Recent studies have highlighted the need for a PCF measurement along with quantifying and analyzing the impact of carbon emission in global supply chains (Sundarakani et al. 2010; He et al. 2019; Nuber, Velte, and Hörisch 2020; Velte 2021; Wong et al. 2022). This can be complicated as multiple companies at multiple stages across the supply chain must be involved (Sundarakani et al. 2010; Winter and Knemeyer 2013; Singh et al. 2015). Methods are different depending on the driver (product or supply chain) and focus (internal or external) (Montoya-Torresa, Gutierrez-Franco, and Blanco 2015). Overall, there are three streams of PCF assessment in theory and practice: quantitative measurement based on modelling, empirical studies, and industry standards.

The first stream of PCF measurement uses quantitative data and metrics only, focusing on modelling, optimizing and simulation of supply chain level green issues (Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; Wong et al. 2022), which include design (Chaabane, Ramudhin, and Paquet 2012; He et al. 2019; Wang et al. 2021), manufacturing process (He, Qian, and Li 2023), logistics cost (Jaegler and Burlat 2012), warehousing activities (Cholette and Venkat 2009), facility location (Marti, Tancrez, and Seifert 2015), consumption (Wong, Chan, and So 2020), and Tier-1 supplier activities (Sundarakani et al. 2010). Depending on the characteristics of the product, namely functional product or innovative product, the carbon emission assessment priorities can be different (Marti, Tancrez, and Seifert 2015). Therefore, understanding the patterns of a carbon footprint and its linkage to product types needs further exploration in more complex settings (Marti, Tancrez, and Seifert 2015; Wong et al. 2022). However, these approaches have not yet fully considered a few of the most important parameters such as the societal elements (Jawahir et al. 2006; Montoya-Torresa, Gutierrez-Franco, and Blanco 2015). The measurement is not comprehensive or sufficient due to a lack of transparency and inaccuracy in the calculations (Gaussin et al. 2013). Other methods take the wider elements including the fuzzy qualitative parameters into consideration (Gaussin et al. 2013). Nevertheless, the product lifecycle assessment can be conceptual, focusing on a single lifecycle stage, such as the design or new product development stage, instead of the whole manufacturing process (Gaussin et al. 2013; He et al. 2019; He, Qian, and Li 2023). It is, therefore, suggested that the assessment of a carbon footprint should be holistic, considering the entire supply chain, and should be applied for every manufacturing company and product (Gaussin et al. 2013; He et al. 2019; Wong et al. 2022; He, Qian, and Li 2023).

The second stream is empirical studies. For instance, case studies of Hyundai identify three steps to address carbon footprint (Lee 2011; Lee and Cheong 2011): (1) setting up a guideline and measurement instruction to key suppliers for Scope 1 and 2, using direct measurement, (2) Hyundai and its suppliers developing the carbon process map of each component, meanwhile suppliers reporting their mapping results to Hyundai to help identify high carbon burdens, and (3) working with suppliers and calculating the product carbon footprint. The indicators include stack air emission on-site and off-site energy recovery, total energy use, total electricity use, total fuel use, source reduction activities, and raw materials modification. Empirical studies also identify that transportation and sales/distribution are the two key factors of carbon emission in the UK food supply chains, with the application of life-cycle assessment (LCA) and calculating carbon related activities in: (1) growers' field, (2) inland logistics outside the UK, (3) transportation, and (4) sales and distribution (Aikins and Ramanathan 2020). Case studies across the oil and gas and agricultural biotechnology indicate that current carbon footprint assessment techniques cannot cope with the increase in complex challenges relating to supply chain sustainability (Matos and Hall 2007). In the beef sector, it is proposed that Cloud Computing Technology during retailing stage can be used to measure carbon emission (Singh et al. 2015). Recent studies also implement various measuring approaches to case companies. For instance, an LCA method is established to analyze oil product pipeline transportation systems, which concerns emissions produced at different stages by collecting real data from a case company (Huang et al. 2021). Another research combines a process analysis of Scope 1 and Scope 2 emission with a multiregional input-output analysis for upstream Scope 3 emission to calculate PCF of a Spanish Timber company (Alvarez, Tobarra, and Zafrilla 2019). Following the steps defined by the GHG Protocol steps, another study also calculates PCF based on data from a wine making company (Karalis and Kanakoudis 2023).

The third stream concerns industry standard and policy for practice purpose. Accordingly, three popularly used international standards are GHG, ISO 14067, and PAS 2050 (Hussain, Malik, and Taylor 2017). Yet due to a lack of uniformity in terminology, element, and criteria, there can be inconsistent results when companies use these standards (Wang, Wang, and Yang 2018; Scrucca et al. 2020; Liang et al. 2023). GHG Protocol provides accounting standards for companies to develop comprehensive and reliable inventories of their GHG emissions (WBCSD and WRI 2004). However, in the GHG Protocol, there are no specific product rules available (Garcia and Freire 2014). ISO 14067 concerns principles, requirements, and guidelines for the quantification and communication of the PCF, including goods and services, covering GHG emissions and removals over the life cycle of a product (ISO. 2018). Nevertheless, ISO 14067 is still a general standard, and its early version has limitations in terms of reporting the carbon storage of products (Wang, Wang, and Yang 2018). PAS 2050, known as a 'Guide to the PAS 2050:2011', represents the first attempt to offer a practical and consistent method for accounting for the GHG balance from products (Sinden 2009). It builds on the existing ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards, and further specifies the life cycle GHG emission assessment at product level (BSI 2011). Compared to GHG Protocol and ISO 14067, PAS 2050 sets directions on how to deal with common methodological issues such as system boundary definition and allocation, as well as more specific issues, such as carbon storage and delayed emissions (Garcia and Freire 2014). Thus, PAS 2050 has been widely adopted as a specific PCF guidance, and PCF assessment stages are recommended as scoping, data collection, footprint calculations, and interpreting footprint results and driving reductions (BSI 2011). PAS 2050 indicates that companies should consider the following sequentially: business priorities; judicial selection of products; intended audience for the study, which will affect the degree of accuracy and resolution needed for PCF; project timescale; internal stakeholders, gaining aids from internal function departments; and supplier engagement (BSI 2011). According to PAS 2050 (BSI 2011), for a typical footprint data calculation, and for each unit of process, three types of items – material/resources input, energy, waste (if direct GHG emissions are included as waste) – are the categories to calculate. After getting together the data of each unit of processes, the total PCF will be the summary of all these units. But alongside the summary, the following issues are all needed to be taken care of: co-product allocation; sub-process Energy, Resource Input, Waste (ERW) allocation; biogenic carbon accounting and carbon storage; energy and combined heat and power related (energy source, such as grid electricity, renewable energy, renewable electricity tariffs, on-site energy production, etc.); agriculture (mainly land use change which is complex); refrigeration; transport emission; and recycling (landfill or incineration). After the footprint result, a hotspots analysis of the carbon footprint and an uncertainty analysis should be applied, and a carbon footprint reductions plan on self-own production, product design, upstream and downstream supply chain could follow it.

2.2. Identification of the research gaps

Extant literature has provided important theoretical foundations, in terms of the carbon emission assessment. However, research gaps still exist relating to the PCF measurement.

First, most of PCF measurement studies are analytical (Mahapatra, Schoenherr, and Jayaram 2021) and are using modelling, optimizing and simulation (Montoya-Torresa, Gutierrez-Franco, and Blanco 2015; Wong et al. 2022). However, a limitation can be highlighted, as the measurement methods depend on various conditions, which lead to different results in calculating products of similar types (Dias and Arroja 2012; Montoya-Torresa, Gutierrez-Franco, and Blanco 2015) due to a lack of standardization including defining system boundaries (Suh et al. 2004) and allocation methods (Ekvall and Weidema 2004).

Second, as for the limited number of empirical studies which highlight PCF measurements (Lee 2011; Lee and Cheong 2011; Matos and Hall 2007; Mahapatra, Schoenherr, and Jayaram 2021), they either cover a very specific stage or area, such as on-site production (Lee and Cheong 2011), upstream supplier (Lee and Cheong 2011) and transportation (Aikins and Ramanathan 2020), or apply an existing calculation method to a case company (Alvarez, Tobarra, and Zafrilla 2019; Huang et al. 2021; Karalis and Kanakoudis 2023). The whole process of PCF measurement across the life cycle is still not clear (Gaussin et al. 2013).

Third, though there is general guidance from a policy aspect, current standards of GHG/ISO/PAS focus on technical issues such as system boundary definition and allocation, carbon storage, and delayed emissions, and there are different elements among the standards (Wang, Wang, and Yang 2018; Scrucca et al. 2020; Liang et al. 2023). These can confuse organizations during the application. In addition, existing standards are too broad and not sufficient to understand the details of activities and their connection with a specific industry context (Liu, Wang, and Su 2016), and hence difficult to be applied. Thus, there is a need for a PCF measurement, which can address the complex patterns of the carbon footprint and its linkage to complex industry settings (Marti, Tancrez, and Seifert 2015). In other words, practical guidance and tailored approaches are required.

Thus, in order to fill the research gaps, there is a need to explore the extensive process of conducting PCF with the details of activities, to understand the scenarios, and to provide practical solutions to cope with different settings.

3. Methodology

To answer the 'how' question given in the introduction – *How can companies conduct PCF measurement projects effectively?*, a qualitative research approach was adopted which can explore a contemporary phenomenon in its real-life context which is under-explored (Eisenhardt 1989; Yin 1981, 2018) or still unknown (Voss, Tsikriktsis, and Frohlich 2002), and can offer new theoretical insights (Siggelkow 2007). Specifically, multiple-case studies were used (Eisenhardt 1989). Theoretical sampling was applied in selecting cases (Eisenhardt 1989; Denzin 2009) which can highlight theoretical issues (Matos and Hall 2007) relating to a product carbon emission assessment. The case selection criteria were the following: (1) the case organization has developed PCF measurement projects; (2) the PCF process is conducted internally or externally through an engagement with the supply chain partners; (3) there is abundant qualitative data to form the evidential chain e.g. good access to primary data and the company's archive; and (4) cases concern the different types of manufacturing. For example, the case company can mainly perform the final assembly of the product, e.g. Information, Communication & Technology (ICT) industry. Alternatively, the company can mainly conduct the production of component, sub-systems or products e.g. steel manufacturing. This resulted in the engagement with four companies from the ICT sector and five from beverage, electronic, food and steel sectors. Specifically, it was noted that ICT companies are among the earliest to practise PCF measurement and have more matured experience. In addition, the ICT industry shows multi-tiers of suppliers. To measure PCF, companies need to collaboratively work with various supply chain partners, across many stages of manufacturing. Thus, the selection of cases provides an industry setting that can generalize the findings.

Semi-structured interviews were conducted from 2020 to 2022 (Eisenhardt 1989; Yin 2018) with the case companies. The interviewees were individuals who are in the position of operation managers, supply chain managers and sustainability specialists, and those that have a full understanding of the carbon footprint assessment process in the case company. An overview of the case companies and the interview information is shown in Table 1.

The data collection followed the research framework indicated in the four stages of PAS 2050 since: (1) PAS is the first PCF-specific guidance (Sinden 2009; BSI 2011); 2) It has clear product rules and process to follow (compared to GHG Protocol) (Garcia and Freire 2014); (3) PAS 2050 has been referenced and integrated into the updated version of ISO 14067 (ISO. 2018), which demonstrates its impact on PCF standards; and (4) It is a widely adopted PCF guidance in practice, considered by companies since 2008 (Liang et al. 2023). Specifically, the four stages/aspects for our data collection are: (1) scoping: describe the product to be assessed and the unit of analysis; draw a map of the product life cycle; agree the 'system boundary' of the study, prioritize data collection activities; (2) data collection: draw up a data collection plan; engage with suppliers to collect primary activity data; collect secondary emission factors and other secondary data to fill gaps; check data and assess data quality; (3) footprint calculations: compile activity data and balance flows according to the functional unit; multiply activity data by emission factors to generate footprint; check calculations and record all data sources and assumptions; and (4) interpreting footprint results and driving reductions: identify

Table 1. Overview of the analyzed case studies.

Case company	Industry sector	Number of employees (2022)	Turnover (Billion USD)	Interviewee position	Number of the interview
Lenovo (Case 1)	ICT	75,000	$71.62	Executive Director of Manufacturing	2
				Chief Standard Expert	2
				Global Low Carbon Tech & Product Carbon Footprint Leader	2
				Public Relationship Manager	1
Tsingtao Brewery (Case 2)	Beverage	31,700	$4.47	Executive Director of Manufacturing	2
				Carbon Specialist 1	2
				Carbon Specialist 2	2
ZTE (Case 3)	ICT	75,000	$17.68	Product Quality Manager	4
				Corporate Environmental Specialist	2
Acer (Case 4)	ICT	7,713	$8.68	Director of Corporate Sustainability Office	3
				Vice Director of Environmental Affairs	3
AUO (Case 5)	Electronic	38,000	$7.77	Head of Risk, Environment, Safety Management	3
				Product Quality Manager	2
Tungho Steel (Case 6)	Steel	2,946	$1.89	Director of Production	2
				Senior Manager of Environmental Affairs	2
				Project External Consultant	2
BenQ (Case 7)	Electronic	1,300	$0.5	Vice Director of Strategic Procurement	2
				Senior Manager in Product Quality	2
				Product Environmental Specialist	2
Dell (Case 8)	ICT	133,000	$101.2	Supply Chain Sustainability Manager 1 (China)	2
				Supply Chain Sustainability Manager 2 (China)	2
				Sustainability Manager (UK)	4
British Sugar (Case 9)	Food	132,000	$21.67	Carbon Manager	4

hotspots; test sensitivity; identify reduction opportunities; ensure transparency where communicating (BSI 2011). Accordingly, interview questions were designed to capture the PCF process and stages, alongside open questions tailored to each case company (Appendix 1). In addition, secondary data were collected including the case companies' website and news releases, for the purpose of data triangulation and external validity (Eisenhardt 1989; Miles and Huberman 1994; Voss, Tsikriktsis, and Frohlich 2002; Yin 2018).

The unit of analysis was the PCF measurement project. Data analysis followed a within-case analysis and a cross-case analysis (Voss, Tsikriktsis, and Frohlich 2002). For the within-case analysis, transcripts were first developed from the interview recordings. Second, the transcripts were read by each author independently and developed open coding for each case. Third, the initial codes were generated after the discussion and comparison. These codes resulted in generating the key steps of PCF for each case study, which were then compared to the dimensions/stages stated in the PAS 2050 guidance, namely scoping, data collection, footprint calculation, and interpreting footprint results and driving reductions (BSI 2011). Across the cases, the new dimensions/stages were actively searched with the support of the codes/steps, and findings were integrated into a holistic process model. This iterative process was continually repeated until theoretical saturation (Eisenhardt 1989; Voss, Tsikriktsis, and Frohlich 2002).

Moreover, findings were compared in relation to the motivation, goal, data requirement and industry settings of the PCF, with a focus on explanation and causality (Voss, Tsikriktsis, and Frohlich 2002), as well as patterns across the cases (Voss, Tsikriktsis, and Frohlich 2002). Case scenarios were then categorized according to their patterns, similarity and differences (Grodal, Anteby, and Holm 2021). This resulted in the further identification of three types of PCF, as shown in the discussion section.

4. Within-case analysis

4.1. Overview of the cases

4.1.1. Case 1: Lenovo

Lenovo started carbon footprint measurements internally from 2008. Later, the company moved on to getting third-party certificates. In 2022, it worked with TUV Rheinland (China) and was certified for its laptop carbon footprint calculation and carbon neutrality. For the measurement process, Lenovo applied a national database from the bureau of the ICT industry in China, and the footprint result contained phases from suppliers, production (ODM data), distributors, usage and recycle. It used primary data partially collected by its internal Product Certification Team. Material, production and distribution were the focused categories during Lenovo's PCF measurement. Starting from material and raw components, Lenovo traced the parts' carbon emissions from its first-tier suppliers. With the BOM (Bill of Materials), emissions were calculated with the data from the National Basic Component Database. The basic data collection process for raw components was implemented by its suppliers. For suppliers who were not certificated with ISO 14064 or did not have the data collection capability, Lenovo sent them information collection forms. To all the suppliers and OEMs, the Lenovo product certification team performed site-visits to check the data accuracy. Lenovo then conducted the calculation. Distribution and logistics, user phase, and recycling statistics were obtained from the internal logistics and product design departments of Lenovo.

4.1.2. Case 2: Tsingtao Brewery

The carbon footprint measurement project of the Tsingtao Brewery began in 2010 from the plant, which produced beer for the UK market. From 2021, Tsingtao started to invite a third-party institute for measuring the GHG footprint in its plants. With its senior management support, policies were issued to ensure the higher priority of carbon management projects; for instance, priority in job orders and funding. The involved staff were promised a promotion to become a 'Carbon Specialist'. The measurement project focused on the supply of material, production, and distribution. The material emission data came from the suppliers, who received training from Tsingtao. The data collection was an iterative process as the Tsingtao team strictly controlled the data quality from suppliers. The production part of data gathering was executed by Tsingtao's internal team. A key task was the allocation of emissions, involving the yield, number of bottles, and the economic outcome. As for the distribution part, detailed data were gathered from the wheat suppliers and distributors in the UK. This included sales data for each sales point as much as the second-tier distributors. The final data of distribution was a weighted average result for all the bottles sold in the UK. The recycle of packaging, was not included in the calculation.

4.1.3. Case 3: ZTE

For ZTE, the carbon footprint measurement was triggered by a telecom carrier customer request from Europe in 2006 due to the concern of the EU's recycle and hazardous material control. ZTE adopted the LCA software EIME to complete the carbon footprint measurement, relying more on the secondary data. The measurement process was implemented by the product quality department. The best seller products and those with clear customer requirements were chosen for the measurement. The process map was embedded in the company's software, following the fundamental steps of manufacturing (raw materials, design, procurement, and production), distribution, usage, and recycle. For most raw materials (referred to the semi-finished parts from suppliers), the ZTE's special team decomposed the parts and analyzed the manufacturing process. Accordingly, the raw material, mainly metals, and the possible manufacturing processes were traced in the internal database of EIME. With regard to the provided product specifications, structures, product markets, distribution methods, distribution journeys, and usage, the team imported the data to the software. ZTE's product quality department also built up the common database such as battery modules. The distribution part was a related fixed variable, and this variance usually came from the production phase and user phase. ZTE arbitrated the distance, transportation methods and the vehicle of recycle transportation.

4.1.4. Case 4: Acer

Acer has formed a focus group called Acer Product GHG Working Group that is aligning with most of the first-tier suppliers. The company has implemented the Scope 3 Accounting & Reporting and Product Carbon Footprinting & Reporting as in 2008. The PCF measurement started in 2009. From 2022, Acer has extended its footprint data collection to third-tier suppliers. Acer outsourced its manufacturing to OEMs, so the carbon footprint measurement was mainly conducted through collecting data from suppliers, OEMs and distributors. It followed the PAS 2050 product life cycle: raw material acquisition, production, distribution & retail, use and end of life. Acer positioned the product in the supply chain and it determined the timetable and scale before the data collection. Data were recorded and processed through carbon footprint accounting tools and forms, which was TEEMALCI001. The calculation included R&D/manufacturing, transportation, user phase, and disposal part, as well as the emission factor database. In fact, for Acer's electronic products, the usage phase and manufacturing contribute nearly 80% of the carbon footprint. According to Acer, accreditation was strategically important, which can continuously motivate the company in its periodical and yearly carbon reduction action planning that is considering both internal practices and the external supply chain.

4.1.5. Case 5: AUO

AUO began auditing the GHG emissions of its global manufacturing sites in the early 2000s, and the ISO 14064 standard was introduced to disclose emissions-related information through external verification. It was the first Taiwan company to attend the UK accreditation system and to get products labelled with a carbon footprint declaration. From then on, AUO also generated its own product carbon footprint calculation e-system (PCF System), which could provide the longitudinal data of the same product and compare between products in different sizes. In 2020, AUO obtained the first ISO 14067:2018 Carbon Footprint certificate among the LCD panel manufacturers. For the PCF measurement, the LCD TV was a representative product, which had a significant number of sub-parts and involved more than 500 suppliers. AUO organized the suppliers briefing and training meeting to gather data. The PCF started from the extracting of resources from suppliers, then the transportation stage towards the manufacturing site. The calculation considered emissions at the manufacturing, assembling, packaging, and transportation of products to the next tier customers. From then, the PCF mapping further included the phases of usage, transportation to the recycling site, and recycling, before the recycled materials go back to manufacturing. Emissions during transportation from customers to disposal were also calculated in AUO's practice.

4.1.6. Case 6: Tungho Steel

Tungho Steel was the first steel manufacturer that participated in the product carbon footprint measurement tutorial project from the Taiwan Industrial Development Bureau together with its suppliers since 2010. After 2019, Tungho focused more on the carbon emission reduction practices within its plants. Tungho Steel described its PCF measurement process in terms of plotting the processes map, determining the boundaries and priorities, collecting data, allocating the emission according to the weight, and a calculation and uncertainty analysis. It was noted that the PCF involved over 10 suppliers who were initially reluctant to reveal the data on electricity/gas usage linking to their operating cost. Tungho gave two points to their suppliers to persuade them. First, the verification of the PCF would be limited to Tungho, so the suppliers would only need to provide the data without verification files. Second, suppliers could take advantage of the government support for a free tutorial and carbon reduction advice. The Tungho team conducted the site-visit to the supplier plants to coach the data collection procedure. The product carbon footprint accreditation enforces a strict verification requirement on the data sources, which are the paper sheets and tables, as the proof of data credibility.

4.1.7. Case 7: BenQ

BenQ started the journey of PCF measurement from 2009. In 2010, it obtained the BSI PAS 2050 label for many of its LCD TVs and LCD Monitors products. BenQ was active in the carbon emission reduction agenda. In 2022, the company announced its plan for Carbon Neutrality by 2050, for its collaboration fleet vendor and 400 partner suppliers, in which the total market capitalization exceeds US$1 trillion, to put in efforts towards carbon emissions reduction goals. A representative project was BenQ's LCD TV measurement. Multiple business functions were involved, including product certification, product R&D management, logistics and supplier management departments. The process was supported by 7–8 consultants from the Taiwan Industrial Development Bureau and the Institute of Industrial Research. BenQ organized a conference attended by selected suppliers to introduce the PCF measurement tools & process. Afterwards, suppliers collected data according to the forms designed by the consultant. A second conference was held to communicate the data collection progress. BenQ's special team also visited key suppliers. Other issues such as the emission allocation criteria were also considered. Instead of focusing on product amounts, bulk and price, the emission was allocated according to length of working hours.

4.1.8. Case 8: Dell

Dell's carbon footprint measurement was implemented at the headquarters in Texas, US from 2010. In the global scope, Dell took part in the CDP Supply Chain Project to help manage the carbon emission along its supply chain. Until 2022, Dell had published most of its mainstream products' carbon footprint in a whitepaper including desktops, laptops, monitors, and servers. Dell calculated the carbon footprint of its laptops using PAIA (Product Attribute to Impact Algorithm), which was a stream-lined LCA method developed by MIT's Materials System Laboratory. The footprint measurement included raw material consumption, manufacturing, logistics, and product use and end-of-life management. The detail measurement process was conducted by the Dell Environmental Affairs Department. Dell chose one of its representative typical high-volume, mainstream business laptop E-series. The measurement boundaries included the following: material (components, parts) and product manufacturing in Asia; transportation to final assembly; final assembly in Asia and Europe; transport to customers in the USA, Germany, and China respectively; use in the US, Europe, and China for four years; transport to recycling; and end of life disposal and recycling. Using secondary data, the results showed that the manufacturing and user phase took up the two largest portions of the total carbon footprint of Dell's laptop.

4.1.9. Case 9: British Sugar

British Sugar with its branding arm Silver Spoon was the first sugar manufacturer to calculate, certify and publish the carbon footprint of its sugar, partnering with the Carbon Trust (Carbon Trust 2006) on the PAS 2050 method from 2008. Recently, British Sugar focused on improving its carbon emission related activities, such as the CHP (Combined Heat and Power) plants, and pledged in 2018 to reduce their carbon footprint by 30% by 2030. It developed a detailed PCF assessment. Specifically, a working group was formed by the British Sugar internal energy expert and the UK consultancy firm, North Energy. It analyzed the process flow to establish the data requirement and allocated the GHG Emission between products (granulated sugar, Topsoil and LimeX) based on the separated values. The full life cycle of the product was assessed including the following: cultivation and harvesting of pelletized seeds into the harvested sugar beet and sugar beet tops co-product; transportation of all inputs from field to plant; process stages including combined heat and power plant, washing, slicing and diffusion, purification/filtration/crystallization, water treatment, and animal feed processing. The measurement was conducted across all four British Sugar plants located in Wissington, Bury St Edmunds, Cantley, and Newark. The final GHG emission of products was calculated with the weighted average of all plants.

4.2. Summary of within-case analysis

From the case studies, the PCF steps of each company were analyzed and grouped according to the four dimensions/stages highlighted in the PAS 2050 guidelines, namely scoping, data collection, footprint calculation, and interpreting footprint results and driving reductions (BSI 2011). A summary of the case findings is shown in Table 2.

Table 2. Summary of the case studies.

	Product carbon footprint measurement processes (PAS 2050 guideline dimensions/stages)			
Case	Scoping	Data Collection	Footprint calculation	Interpreting footprint results and driving reductions
Case 1	• Determine the product for PCF • Allocate PCF task according to BOM • Select Involved Suppliers	• Design Data Collection Forms for Internal & External user • Engaging Suppliers to Complete Data Form • Engaging Internal Department to Complete Data Form • Obtain Data from Suppliers • Obtain Data from Internal Departments • Site-visit to Check Data Validity	• Calculate the footprint	• Setting Reduction Action Plan
Case 2	• Select PCF product • Internal workshop on PCF Action Plan • Draw Process Map and Task Allocation • Select Involved Suppliers	• 1st Training Workshop for Suppliers • Obtain Data from Less Capable Suppliers • Obtain Data From capable suppliers • Site-Visit Consulting to support data collection • Obtain data from internal departments	• Calculate the footprint	• N/a
Case 3	• Determine the product for PCF • Obtain product specification & bill of material • Design data collection forms for internal departments • Analyzed the components of raw material	• Obtain data from internal departments	• Input data to software and calculate the footprint	• N/a
Case 4	• Project kick-off, support from Senior Management • Position company in the supply chain • Determine standards & guidelines	• Design/Choose carbon footprint accounting tools & forms • Drawing Input/output Process • Emission allocation principle	• Calculate R&D/Manufacturing Part • Transportation part • User phrase part • Disposal part	• Setting reduction amount target • Set carbon reduction action planning

(continued)

Table 2. Continued.

Case	Product carbon footprint measurement processes (PAS 2050 guideline dimensions/stages)			
	Scoping	Data Collection	Footprint calculation	Interpreting footprint results and driving reductions
	• Aims & scope of carbon footprint measurement—to response to customer and NGO requirement, and gain certification • Determine product category rules & function unit • Set timetable & scale	• Conduct data quality analysis • Balance between data quality & efficiency	• Emission factor database	• Accreditation of PCF result • Determine carbon disclosure types
Case 5	• Organize the project team • Determine system boundary, bill of material, list of suppliers	• Design data collection forms • Distribute forms and retrieve filled forms	• Integrate data and calculate the carbon footprint • Validate the files and site-visit to factories (including suppliers)	• Generating the carbon footprint report • Setting the carbon reduction strategy • Certify carbon footprint result
Case 6	• Plotting the processes map • Determine the boundaries and priorities	• Collecting data	• Allocating the emission according to the weight • Calculating the footprint • Uncertainty analysis	• Certified by third-party organization
Case 7	• Project Kick-off, support from Senior management, and goal—to gain certification in order to compete with rival products • Determine the product for PCF • Setting product category rules (PCR) and system boundary • PCF Training Workshop (Internal) • Draw process map and determine key components & processes • PCF training workshop (suppliers) and generate forms	• Obtain data from suppliers • Obtain data from internal departments • Validate data with forms & supporting documents	• Calculate the footprint	• Third-party accreditation
Case 8	• Determine the product and scope of the study • Determine the system boundaries • Use bill of materials	• Extract data from Database Gabi	• Calculate the life cycle carbon footprint	• Conduct life cycle impact analysis to the result
Case 9	• Analysis of process flow • Draw the process flow map of British Sugar's procedures • Established detailed data collection requirement	• Produced a series of MS Excel workbooks for each plant to collect data • Calculated the weighting of GHGs to electricity exported to the grid from CHP	• Allocated GHG emission between products based on their market value • Produced a cradle-to-factory gate assessment of all products produced, including processes of cultivation, transportation of inputs and inside-plant processing	• N/a

5. Cross-case analysis and findings

5.1. A Similar process framework across cases

Through cross-case analysis, a process framework reflecting the basic stages of the PAS 2050 guidelines with the combination of the new theme/stage identified through the case studies is proposed as Figure 1. Detailed steps for each stage mentioned in the PAS 2050, as well as new stages and steps beyond the PAS 2050 guidance e.g. preparation are identified (Details will be elaborated in Section 6.1). Accordingly, this process framework consists of five main stages of PCF measurement: preparation, scoping, data collection, footprint calculation, and interpretation and accreditation. Detailed steps are also shown in Figure 1.

5.1.1. Stage one: Preparation

The preparation is the setting of the overall planning of the PCF measurement. This stage includes the identification of PCF goals and targets (Case 1, 2, 3, 5, 8), as well as the priority (Case 2), prior to the measurement project. Also, the function unit of footprint measurement, which is the targeted product or service, is determined at this stage. Details of the Preparation stage are shown in Appendix 2 and will be discussed in Section 6.1.

5.1.2. Stage two: Scoping

Stage Two shows the engagement with relevant stakeholders to scope the measurement project. Synthesizing from the case studies, there are four steps of Scoping: (1) Step One: Describe the product to be assessed and the unit of analysis (Case 1, 2, 3, 4, 7, 8); (2) Step Two: Draw the map of the product life cycle (Case 2, 6, 9) – the process-mapping stage is an initial brainstorming exercise to map all of the 'flows' of materials and energy in and out of the product system as they are used to make and distribute the product, and, in this step, there are sub-steps to do as well to provide a description of the activity to aid with the data collection (Case 3, identify the geographic location of each distinct step where possible, and include all the transport and storage steps between stages); (3) Step Three: Determine the system boundary (Case 1, 3, 4, 5, 6, 7, 8) and the boundary is documented with a list of all the included activities and processes within each life cycle stage, and a list of all excluded activities and processes, and the steps taken to determine their exclusion - system boundary and BOM can help to generate the list, and, furthermore, the following elements are considered: production materials, energy, production processes and service provision, operation of premises, transport, storage, use phase, end-of-life (Case 4); and (4) Step Four: prioritize data collection activities (Case 2, 3, 5, 7, 8, 9) and this is to identify the hotspots of the emissions and skip collecting data with little impact.

It is noted that the Scoping stage includes a scoping task internally (all cases) and externally with supply chain partners (Case 1, 4, 5, 7). The same four steps are also observed in terms of external scoping, where the target is external partners and suppliers. Please refer to Appendices 3 and 4 for details of the Scoping.

5.1.3. Stage three: Data collection

Data collection is the next stage observed from all cases. Footprint measurement standards require that the company should collect primary activity data for its own operations and the operations under its control (for example product distribution). And there is a minimum percentage of the total cradle-to-gate emissions (10% in the PAS 2050) which must be calculated from primary data. Specifically, for manufacturing companies, this 10% threshold will probably be reached with the companies' emission alone. Thus, the data collection is divided into two parallel stages: internal data collection

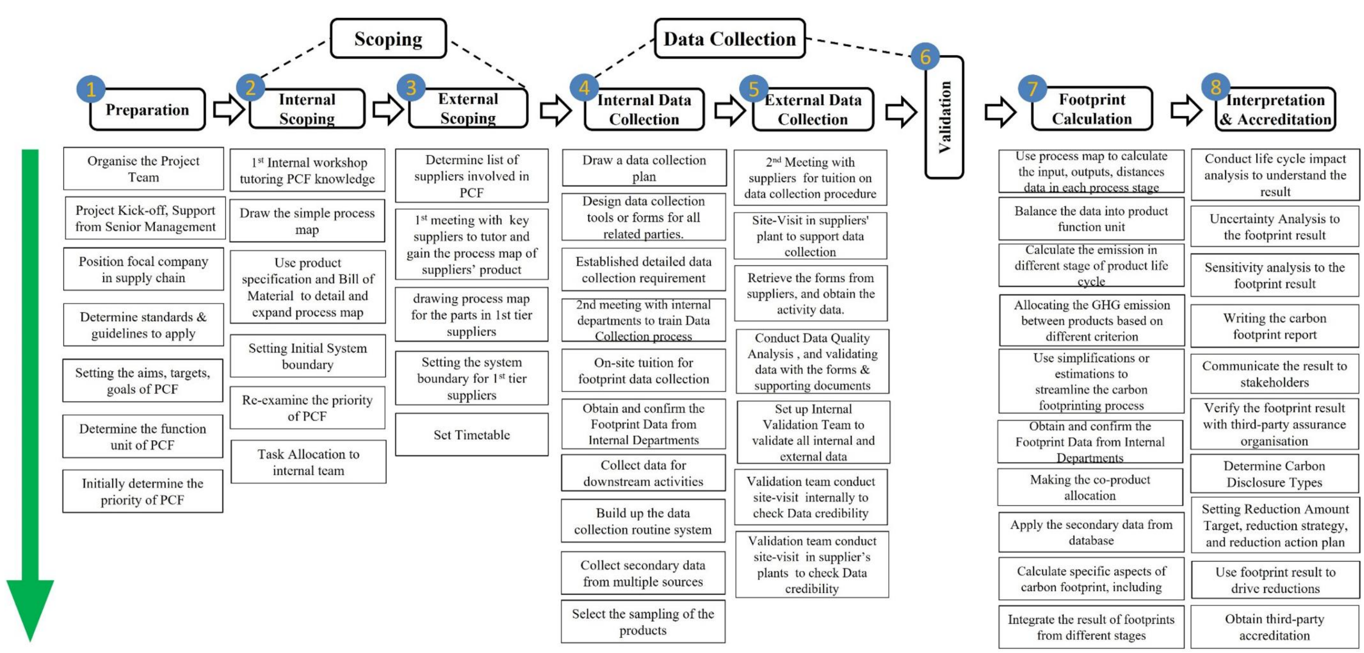


Figure 1. Product carbon footprint measurement process framework.

which focuses on the primary data collected within the focal firm's own operation (all cases) and the external data collection working with supply chain partners (Case 1, 2, 4, 5, 7). It is also noted the data collection is accompanied with validation (all cases). Please refer to Appendices 5–7 for details of this stage.

5.1.4. Stage four: Footprint calculation

The footprint calculation stage is to integrate the emission data in different stages of a product's life cycle (all cases). The emission result can be simplified as the equation according to PAS 2050 and is seen in the practice (all cases):

$$Emission = \frac{Activity * Emission\ Factor}{Allocation\ Factor}$$

In Case 2, taking the distribution of a bottle of Tsingtao beer from the plant to the Tsingtao Port as an example, the carbon emission of this single process is equal to: '100km'—the distance, times '0.03 kg/km'—the emission amount per kilometres of fuel usage that a truck consumes in transporting goods, and it is divided by '5,000'—the number of bottles in each haul.

The general steps of calculation are summarized as the following: firstly, the emission is calculated according to the above-mentioned general equation, and balances the data into a product function unit (all cases); secondly, simplifying assumptions can be made (Case 4, 5, 6, 9); and thirdly, it is to make the allocation of the co-products which is produced together with the main product, such as the Topsoil when making sugar in the case of British Sugar (Case 9). Please see details of the Footprint Calculation in Appendix 8.

5.1.5. Stage five: Interpretation and accreditation

The interpretation stage represents the firm's reflection on their product carbon profile. The result sets the baseline of the firm's current carbon performance and, therefore, the targets and action plan for improvement can be generated (Case 1, 4, 5, 8). Third-party accreditation can be obtained during this stage (Case 5, 7). Details of this stage are shown in Appendix 9.

Compared to existing industry standards especially PAS 2050, this framework (Figure 1) adds two new stages, preparation as the starting stage of PCF measurement and accreditation as the ending stage. The preparation stage which is not commonly discussed in existing PCF standards is particularly important for practical use. It can align the organizations' resources with their purpose for PCF. In addition, the steps and activities shown in Figure 1 have more detailed mini-steps than PAS 2050/ISO 14067/GHG protocol, which focus on the actual actions (to-do list) for companies, making them more operational and actionable. Details of the new stages will be elaborated in the discussion Section 6.1.

5.2. Process differences across cases

Apart from similarities observed across the cases, there are also differences among cases when they had various goals and targets for PCF. If firms newly start their PCF journeys and are aiming to conduct a simple PCF practice, as in Case 3 and 8, the PCF processes usually require less support from senior management, and in general shorter as some stages (e.g. external scoping) are not needed, and more rely on calculation software.

While for the firms that target to conduct a thorough PCF to identify emission hot-spots in product life cycle, as in Case 1 and 2, their PCFs will require significantly more effort. These efforts include more intense engagement from senior management, setting up a special team for the PCF task, extensive internal and external scoping, and most importantly, the collection of primary data from the firms' processes.

If the firms decide to gain external third-party recognition and accreditation to PCF result, as in Case 4, 5, 6, 7 and 9, they need to perform strict procedures of all PCF steps complying with the PCF guideline requirements. For example, in the preparation stage these firms will set up both PCF team and an internal validation team. During the scoping stage, firms should ensure the scoped activities include over 95% of product's life cycle carbon emission. In terms of data collection, majority of firms' suppliers (related to the selected product) need to be covered while in other cases only some supplier data are needed. When moving to footprint calculation stage, firms are required to strictly follow the footprinting guidelines (e.g. ISO14067), while in other cases that it allows making assumptions on less-impactful emission activities. The most important difference is that the PCF result should be verified by third-party PCF auditing organization and then the PCF result is certified and disclosed to the public. The action of disclosing to public is making a commitment to firms' decarbonisation journey, which gives pressure to themselves for continuous improvement.

Details relating to these differences in PCF process across cases are also elaborated in the Appendices 2–9 in the right-hand three columns. These differences are further analyzed as three PCF scenarios in the discussion Section 6.2.

6. Discussion

6.1. New dimensions/stages to enrich PAS 2050 framework

In comparison to PAS 2050, the findings reveal that prior to scoping, companies conduct activities in preparation for the PCF projects.

For example, in Case 1, the company set the goal of PCF, which was not to be disclosed to the public, but was to be used for internal information sharing and continuous improvement. This is also seen in Case 2, where, before the scoping, the company first determined the goal and priority of PCF. It integrated carbon issues into strategic decisions and for operations improvement, as stated by Case 2's Executive Director of Manufacturing, 'Carbon emission could be [the] asset or debt of [a] corporation, depending on how it is managed. The carbon emission management is part of our corporate strategy … The earlier to consider carbon issues into [a] strategy and take action, the more benefits we can make'.

In Case 3, the goals of the PCF were set first focusing on the response to the customer's requests. In fact, its PCF was triggered by a Europe-based telecom carrier customer that was asking the company, specifically, to consider the EU's recycle regulations and hazardous material control. The Corporate Environmental Specialist in Case 3 mentioned 'We invited our clients in Europe and US to join our carbon footprinting training workshop … with 640 senior managers from 422 suppliers … to demonstrate our commitment for product carbon footprinting … '. Similarly, the goal of a carbon footprint study was set by Case 8, as the company had customers inquiring about carbon information. A Sustainability Manager of Case 8 stated, 'Dell customers are asking for PCF information and retailers such as Tesco in the UK, FNAC in France and Walmart in the US … are requiring PCF for products they are selling … ', so the company had to make a pilot for it.

In Case 5, the goal determination, before the PCF project was defined, was to gain the first PCF certification of its kind for the purpose of having a competitive advantage. The Head of Risk, Environment, Safety Management of Case 5 explained the reason of the company's proactive PCF action: '… the EU environmental requirements for electronic products are commonly regarded as industry trend … if we could prepare us for the frontiers of carbon footprinting standard, it benefits to our cost control … '. In Case 6, the goal of the PCF was highlighted as the company would like to get involved in the Taiwan IDB programme and to be certified by the Taiwan standard. In Case 9, the company set the goal as wanting to assist in the PAS 2050 pilot in order to develop the methodology.

Preparation, as the starting point of PCF measurement projects, is sometimes neglected but in fact very important. The aims and objectives of PCF need to be made clear at the beginning as it determines the resources and effort devoted to the project. Also, the PCF special team needs to be set up to better coordinate the scoping and data collection activities. Without the proper knowledge and skills from this PCF team, the efficiency and credibility of PCF process would be considerably impacted. Thus, Preparation is added as a separate stage, which refers to:

> Preparation stage is the overall planning, setting up aims, targets and priorities which have significant impact on the company's PCF before conducting the footprint measurement project.

In addition, in the final stage, Case 4, 5, 7 all highlighted getting a PCF certificate or accreditation, such as the Carbon Trust certification. This is not specified in the PAS 2050 guidance. In fact, in Case 4, accreditation was clearly emphasised at the end of its PCF project after the company issued a periodical target and yearly target-based Carbon Reduction Target Action Planning.

Some companies conduct the PCF and would like to use PCF result as a marketing tool demonstrating their commitment for low carbon transition. Accreditation from a third party shows the rigorousness of PCF process and strengthen the credibility of PCF result. Without the accreditation, companies' result can be easily challenged by external stakeholders, e.g. some active NGOs, which may bring serious issue to brand reputation. Another benefit sometime overlooked is the third-party verification can also tutor the firms' PCF team of the correct practice therefore the PCF process can be improved in the next round of measurement. Thus, the findings also expand the PAS 2050 interpreting the footprint results and driving reductions stage as Interpretation and accreditation.

Therefore, in the new proposed process (shown in Figure 1), companies can follow the eight steps (in numbers) in sequence, namely preparation, internal scoping, external scoping, internal data collection, external data collection, validation, footprint calculation, and interpretation & accreditation. Within each step, there are multiple mini-steps to finish the task (top-down arrow in Figure 1). For example, in the second step 'Internal Scoping', companies may start the 1st internal workshop to tutor the PCF knowledge and then move to the 2nd mini-step of drafting the simple process map. And once the mini-steps in 'Internal Scoping' are finished, the tasks can move to the 3rd step 'External Scoping'.

6.2. Different types of PCF measurement process

As noticed in the cross-case analysis section (Section 5.2), also demonstrated in Appendices 2–9, three types of PCF processes emerged from the cases. The case firms explained their targets and purposes to conducted PCF during the interview. It was found that the firms' PCF targets and objectives determined the types of PCF they should adopt. Accordingly, three purpose scenarios are identified, and the corresponding PCF types can be named as Trial-oriented, Process-oriented, and Market-oriented. The purpose of PCF is related to the levels of time and effort of those companies that are devoted to PCF, as well as the quality of activity data collected in the process. Hence, further discuss concerns the three PCF types, and compares major aspects that contribute to measurement process difference, which are system scope, data source and data quality.

6.2.1. Trial-oriented PCF

This type aims to make an attempt on carbon footprint measurement (Case 3, 8). This is a brief examination of the product carbon emission performance, and usually it is the firm's first attempt to measure the carbon footprint. The main aim for firms is to initially understand the new carbon footprint requirement and prepare itself for a more detailed measurement in the future. The PCF can be conducted by software or even MS-Excel based models (Case 8). The primary activity data is not required because secondary source data is sufficient for the task. It limits the project's system scope to the main stages of the product, and only uses secondary activity data. Also, external supply chain partners do not provide any data.

6.2.2. Process-oriented PCF

For this type, the company's intention is to have a clear mapping of its product's carbon footprint, which will trigger the improvement of the firm's supply chain carbon emission (Case 1, 2). Hot-spot analysis of the carbon footprint can be analysed so the improvement practices can be more focused. After the first PCF, a footprint can be set as a baseline to enable continuous improvements. To achieve this goal, primary activity data from multi-tiers suppliers, OEMs (Case 1), internal production plants, logistics and product design (for user phase and end-of-life phase) should be collected as much as possible. The use of secondary source data undermines the creditability and validity of the result. Because certificates are not granted after the PCF, the collected data do not require verification.

6.2.3. Market-oriented PCF

For this type, the company aims to achieve carbon footprint labels which may benefit the firm's brand (Case 4, 5, 6, 7, 9) with the purpose being not only for continuous improvement internally but also for external claims and communications. The result of carbon footprint measurement needs to be verified by an independent third-party organization (Case 5, 7). For this type of PCF, firms should ensure that the data collection and calculation procedures are solid, activity data are of the appropriate quality, the reported footprint claims have reflected what has been undertaken with sufficient document proof, and that they are delivered in the given reporting period. These need to be reviewed and tested by the third-party accreditation organizations. Hence, the PCF process should be conducted under a strict mode following standards and so it achieves primary activity data as much as possible. Certificates are granted afterwards.

Due to the different purposes, there are differences among three types of PCF in terms of system scopes, data source, and data quality. First, the system scope is referred to as the boundary of the measurement exercise, from covering the main stages of production (Case 3, 8) to the full product lifecycle (Case 1, 2). The firm's business border can be used to separate internal and external scoping. The internal scope refers to all stages within the firm. And the external scoping refers to the stages in the upstream and downstream suppliers/customers, or say, the full product lifecycle. The above-mentioned three PCFs all need to include internal scoping, while external scoping is mainly implemented in the Process-oriented and Market-oriented scenarios. The data collection stage needs to be consistent with the scoping stage. Similarly, Process and Market-oriented ones conduct an external data collection, in addition to the internal data collection. Second, regarding the data source, the data used in the measurement includes activity data and emission factors (the emission per unit of energy, material, waste, etc.). The emission factors are basically all secondary data. The activity data can be collected primarily from the firm or substituted by secondary sources. Therefore, the quality of these three types is gradually improved—the activity data used in a Trial-oriented PCF are mainly from a database embedded in the LCA software (Case 3, 8) such as Gabi, and SIMAPRO, and activity data in the Process-oriented PCF are collected in the actual business (Case 1, 2), while the data in the Market-oriented PCF are not only primarily collected but also verified by third-party accreditation organizations (Case 4, 5, 6, 7, 9). Third, as for the data quality, the more the primary data are collected from a firm's actual operation, the more valid the footprint result is. Consequently, more time and effort are needed in order to gain the primary data, in contrast to using the secondary data. After the data collection, it may not be a must for the Trial-oriented PCF to evaluate the data quality. But, for the other two types, the internal team needs to evaluate the data validity and adequacy of the PCF procedure (The PCF has been conducted in an adequate way), and, therefore, it will enhance the possibility to get third-party verification for the footprint result. Following the footprint calculation, the Process-oriented PCF may use the result to identify the emission-intensive activities in the product life cycle. But for the Market-oriented PCF, an accreditation of the footprint result is the aim; hence, the result must be verified by a third-party assurance organization.

Accordingly, a summary of the three PCF measurement process types/scenarios is illustrated in Table 3.

In comparison with the existing standards including PAS 2050/ISO 14067/GHG protocol, the scenarios here differentiate organizations according to the PCF measurement motivation. Thus, organizations can follow as pointed out in Appendices 2–9. For instance, a company aiming at improving its internal process and performance can just follow the steps of 'Process-Oriented' without necessarily considering activities from other scenarios. These scenarios-based tailored approaches concerning different industry settings have not been provided by PAS 2050/ISO 14067/GHG protocol.

7. Conclusion

7.1. Theoretical contribution

Whilst traditionally companies focus on quality and agility to achieve commercial competitive advantages, there is a need to cope with the contradictive challenge to win in the new generation of sustainable development. Guidelines such as PAS 2050 and ISO 14067 have provided the basic steps for carbon footprint measurement, yet, in practice, the knowledge insufficiency and high cost hinders companies to practise the carbon footprint measurement. This paper aims to find out how PCF can be efficiently measured. Through nine cases studies across the ICT, beverage, electronic and steel industries, a holistic PCF measurement process model is proposed alongside three-scenarios with key stages and methods.

The paper makes the following theoretical contribution. First, existing studies are mainly analytical studies, whereas this paper contributes to the understanding of the PCF measurement with empirical observation and evidence. Second, a PCF process framework is proposed covering the whole life cycle (Figure 1), whereas current literature mostly focuses on a certain stage of production or supply chain. Third, the findings highlight five main stages and detailed activities of the PCF measurement. In particular, the preparation and data gathering stages emphasize the decision on the use of primary/secondary data, the firm's resources and

Table 3. Three scenarios of PCF process.

PCF scenario	Target	System scope	Data source	Data quality
Trial-oriented	An attempt to measure carbon emission. To initially understand the new carbon footprint requirement, and prepare for a more detailed measurement in the future	Covers the main stages of the product	Secondary data from the database	The quality depends on the database applied.
Process-oriented	To have a clear mapping of its product carbon profile for continuous improvement, but not aiming to publicly advertise the result	The system scope covers the full life cycle of the product. The firm can expand to a larger scope if the continuous improvement needs to cover more aspects of the product.	Secondary data from the database and primary activity data from the firm's actual business	There is no strict requirement for primary data. Secondary data depends on the database applied
Market-oriented	To certify the carbon footprint result as a part of a marketing tool	The scope has to cover over 95% of a product's total carbon footprint	Secondary data from the database and over 30% of the data is primary activity data from a firm's actual business	The primary activity data has to be internally and externally validated.

capability, the sector in which the firm is in, the firm's position in the supply chain, and other factors. The framework enriches the existing industry standard and guidance with details. Fourth, based on companies' purposes of conducting PCF, three scenarios of PCF measurement namely Trial-oriented, Process-oriented, and Market-oriented PCF are further identified and their differences are analysed in terms of the PCF target, system scope, data source and data quality.

The framework proposed in this paper is different from the existing standards PAS 2050/ISO 14067/GHG protocol in the following four aspects: (1) Existing standards focus on technical details, such as technical issues, system boundary definition and allocation, carbon storage and delayed emission. The framework is process-oriented to provide guidelines for organizations to follow; (2) This framework further adds the preparation and interpretation & accreditation stages. They are crucial for organizations to kick-start the PCF journey, to understand the scope of PCF, to incorporate the measurement in strategy and daily operations plan, to reflect and learn from the projects, and to benchmark with external performance. These two stages are not specified in PAS 2050/ISO 14067/GHG protocol. (3) Existing industry guidelines provide standard tools and ignore organizational differences, whereas the framework here identifies three scenarios based on companies' purpose and organizational settings. Accordingly, organizations can position themselves and follow more tailored process; (4) With the five stages and details of steps and activities, the framework here is more operational and easier to follow.

7.2. Practical implication

In terms of practice implication, the framework is practical and handy for managers to conduct PCF measurement projects from the following perspectives: (1) The framework addresses the engagement activities with internal corporate business units and external supply chain partners in detail, whereas in the PAS 2050 Guide these are mentioned in an aggregated way; (2) The tasks in the preparation and scoping stage are clarified, which can support firms without PCF measurement experience; (3) The data collection process can be divided into two parts: data from internal functions and data from upstream suppliers; and (4) Interpretation and accreditation is needed for improvement purpose. Thus, the framework is a good supplement to the PAS 2050 guideline, serving as a workbook for managers and the business owner who plan to implement PCF. In addition, the three scenario-based approaches illustrate the detailed steps in carbon emission measurement (Appendices 2–9), suggesting companies can use the framework in flexible tailored ways. The action suggested that each step is tailored according to the aims and carbon footprint measurement principles. These approaches cover the advice for the preparation of a project, coordination with suppliers and contractors, and project management during the whole life cycle. The effective implementation of the measurement gives a mapping of the hotspots of carbon emission in the operations, and also lays a foundation for an improvement focus and overall management of the network. The successful implementation of the measurement project can enhance the supplier management and transparency of the supply network as well.

To further illustrate the practice implication, the following shows a validation case. As the EU council has passed the new CBAM (Carbon Boarder Adjustment Mechanism) act, all the products imported to EU in the future will need a PCF measurement to get proper information, which determines the amount of carbon tax (European Commission 2023). Therefore, many companies could potentially utilize the proposed framework in this study to start their PCF measurement journey. Cement, steel, fertilizers, aluminium are in the 1st phase of the CBAM pilot. For companies in these industries, they could start using the framework under the Market-oriented scenario. And for those in the 2nd phase of the CBAM list, companies could use Process-oriented scenario to start preparing rigorous PCF measurement. For companies who do not export products to the EU, they could adopt Trial-oriented scenario for basic PCF mapping. For example, in the cement industry, a Germany company Heidelberg Materials, was thinking to measure carbon footprint of its three cement products (Reichelstein et al. 2023). According to the proposed framework (Figure 1), Heidelberg may choose the Market-oriented approach. In the preparation stage, Heidelberg could organize the project team, which include external consultants for the purpose of validation, and determine the focus to be production stage as it is in the upstream supply chain. Then in the internal scoping stage, Heidelberg could clarify the process mapping and include over 95% of the total carbon emission in LCA. And in the external scoping stage, key material suppliers can be involved. For the cement industry, key raw materials are limestone and slag. As cement is a production-focused product, the external data collection is not necessary. Another focus in PCF is the footprint calculation. In this case the total emission can be balanced into four different product units, because there are four products as finished goods, namely Clinker, CEM I, CEM II, and CEM III. After the footprint calculation, Heidelberg could continuously strengthen the cement footprint reduction targets: reduction of CO_2 emissions to 400 kg CO_2/ton of cementitious material by 2030, a 30% reduction from the 2021 level. The above-mentioned process is documented in the Stanford Graduate School of Business teaching case Heidelberg Material (Reichelstein et al. 2023), which demonstrates the applicability of the proposed framework.

7.3. Limitations and future research

There are some limitations to the study, as it relies on large manufacturing companies who are aware of the existing industry standard and guidance. There are also local companies, especially from the developing countries, which may be affected by their local policy and technology to conduct PCF measurement. This provides future research direction and case studies covering a range of industry sectors, size of business, as well as geographic locations. Although this paper has provided an example to demonstrate the potential to implement the findings, still more research is needed to validate and improve the framework in various business contexts. Furthermore, with PCF scope expanding beyond company boundaries, more research can concern a broader scope of carbon emission measurement in the global supply network. Accordingly, one research area can be regional supply network emission assessment, which is to measure the carbon emission in a local region of multiple firms especially with industrial symbiosis practices. Another area is the linked industry supply network emission assessment, which means to measure the total emission of upstream and downstream supply chain partners and the focal firm together.

Acknowledgements

The authors would like to thank all interviewees from the case companies. The authors would like to acknowledge the Circular Economy Innovation Communities Programme (https://ceicwales.org.uk/) and the Regional Innovation and Regeneration Centre, Cardiff Metropolitan University for the opportunities to disseminate and improve findings of this paper. One of the authors would also like to acknowledge the support of Jiangxi 'Double Thousand' Plan.

Ethical approval

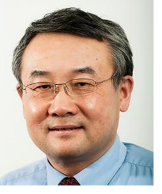
This research has been approved by the Cardiff School of Management Research Ethics Committee, with detailed information as follows. Name of the Ethics Committee: Cardiff School of Management Research Ethics Committee. Its respective institution: Cardiff School of Management, Cardiff Metropolitan University. Approval project title: Developing a process of measuring product carbon footprint.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Jialun Hu (PhD) is a Senior Lecturer at the School of Business and Management in Royal Holloway University of London. With multiple backgrounds in automation engineering, business management and decarbonlization, he has general research interest in topics including low carbon management, business analytics, sustainable industrial system, and operations management.



Yongjiang Shi (PhD) is an Associate Professor of Industrial Systems in the Engineering Department of the University of Cambridge. He is the Research Director at the Institute for Manufacturing's Centre for International Manufacturing. He used to be a Guangbiao Visiting Professor at Zhejiang University Management School. Dr. Shi has led or collaborated to a number of projects on business ecosystems and industrial sustainability, and has developed considerable experiences in industrial symbiosis and circular economy, business ecosystems' strategic patterns and capabilities, value creation networks, best practices for sustainable supply chain management, carbon reduction strategies and resource exploitation during the Chinese industrialization.

Yang Cheng (PhD) is an associate professor at Department of Materials and Production, Aalborg University, Denmark and a visiting professor at School of Business Administration, Jiangxi University of Finance and Economics, China. Dr. Cheng has an extensive research experience in global manufacturing/operations network, supply chain management, and technology management. In these fields, he has published more than 80 articles in academic journals, e.g. International Journal of Operations & Production Management, Supply Chain Management: An International Journal, International Journal of Production Research, International Journal of Production Economics; Production Planning and Control. Meanwhile, he is the Associate Editor for Production Planning and Control and Supply Chain Analytics, the editorial board member for International Journal of Operations & Production Management, Journal of Manufacturing Technology Management, Industrial Management & Data Systems, and Journal of Digital Economy, and the guest editor for International Journal of Production Research, Annal of Operations Research, and International Journal of Physical Distribution and Logistics Management.

Zheng Liu (PhD) is a Senior Lecturer in Strategic Management in the Cardiff School of Management, Cardiff Metropolitan University. Her research interests include innovation ecosystem, digitalisation, open innovation, and sustainability-oriented innovation. The results of her research have been published in several journals and book chapters including Technological Forecasting and Social Change, Technovation, European Planning Studies, and Industrial Management and Data Systems. Since 2016, Zheng has been collaborating with researchers from the Centre for Innovation and Development, Nanjing University of Science and Technology as a research fellow. Since 2020, she has been appointed as a board member of the Open Innovation Academy of Society of Open Innovation: Technology, Market and Complexity (SOItmC).

References

Aikins, F., and U. Ramanathan. 2020. "Key Factors of Carbon Footprint in the UK Food Supply Chains: A New Perspective of Life Cycle Assessment." *International Journal of Operations & Production Management* 40 (7/8): 945–970. https://doi.org/10.1108/IJOPM-06-2019-0478

Alvarez, S., M. Tobarra, and J. Zafrilla. 2019. "Corporate and Product Carbon Footprint under Compound Hybrid Analysis: Application to a Spanish Timber Company." *Journal of Industrial Ecology* 23 (2): 496–507. https://doi.org/10.1111/jiec.12759

BSI. 2011. *PAS 2050:2011 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*. London: BSI (British Standards Institution).

Chaabane, A., A. Ramudhin, and M. Paquet. 2012. "Design of Sustainable Supply Chains under the Emission Trading Scheme." *International Journal of Production Economics* 135 (1): 37–49. https://doi.org/10.1016/j.ijpe.2010.10.025

Chau, C. K., T. M. Leung, and W. Y. Ng. 2015. "A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings." *Applied Energy* 143 (1): 395–413. https://doi.org/10.1016/j.apenergy.2015.01.023

Cholette, S., and K. Venkat. 2009. "The Energy and Carbon Intensity of Wine Distribution: A Study of Logistical Options for Delivering Wine to Consumers." *Journal of Cleaner Production* 17 (16): 1401–1413. https://doi.org/10.1016/j.jclepro.2009.05.011

Carbon Trust. 2006. *Carbon Footprint in the Supply Chain: The Next Step for Business Report No. CTC616*. London: Carbon Trust.

Denzin, N. K. 2009. *The Research Act: A Theoretical Introduction to Sociological Methods*. York, NY: New Routledge.

Dias, A. C., and L. Arroja. 2012. "Comparison of Methodologies for Estimating the Carbon Footprint – Case Study of Office Paper." *Journal of Cleaner Production* 24: 30–35. https://doi.org/10.1016/j.jclepro.2011.11.005

Eisenhardt, K. M. 1989. "Building Theories from Case Study Research." *The Academy of Management Review* 14 (4): 532–550. https://doi.org/10.2307/258557

Ekvall, T., and B. P. Weidema. 2004. "System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis." *The International Journal of Life Cycle Assessment* 9 (3): 161–171. https://doi.org/10.1007/BF02994190

European Commission. 2023. *Carbon Border Adjustment Mechanism*. Luxemburg: Publication Office of the European Union. Accessed July 10, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism.

Gao, T., Q. Liu, and J. Wang. 2014. "A Comparative Study of Carbon Footprint and Assessment Standards." *International Journal of Low-Carbon Technologies* 9 (3): 237–243. https://doi.org/10.1093/ijlct/ctt041

Gaussin, M., G. Hu, S. Abolghasem, S. Basu, M. R. Shankar, and B. Bidanda. 2013. "Assessing the Environmental Footprint of Manufactured Product: A Survey of Current Literature." *International Journal of Production Economics* 146 (2): 515–523. https://doi.org/10.1016/j.ijpe.2011.12.002

Garcia, R., and F. Freire. 2014. "Carbon Footprint of Particleboard: A Comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration." *Journal of Cleaner Production* 66: 199–209. https://doi.org/10.1016/j.jclepro.2013.11.073

Grodal, S., M. Anteby, and A. L. Holm. 2021. "Achieving Rigor in Qualitative Analysis: The Role of Active Categorization in Theory Building." *Academy of Management Review* 46 (3): 591–612. https://doi.org/10.5465/amr.2018.0482

He, B., S. Qian, and T. Li. 2023. "Modeling Product Carbon Footprint for Manufacturing Process." *Journal of Cleaner Production* 402: 136805. https://doi.org/10.1016/j.jclepro.2023.136805

He, B., Y. Liu, L. Zeng, S. Wang, D. Zhang, and Q. Yu. 2019. "Product Carbon Footprint across Sustainable Supply Chain." *Journal of Cleaner Production* 241: 118320. https://doi.org/10.1016/j.jclepro.2019.118320

Huang, L., Q. Liao, J. Yan, Y. Liang, and H. Zhang. 2021. "Carbon Footprint of Oil Products Pipeline Transportation." *The Science of the Total Environment* 783: 146906. https://doi.org/10.1016/j.scitotenv.2021.146906

Hussain, M., R. N. Malik, and A. Taylor. 2017. "Carbon Footprint as an Environmental Sustainability Indicator for the Particleboard Produced in Pakistan." *Environmental Research* 155: 385–393. https://doi.org/10.1016/j.envres.2017.02.024

ISO. 2006a. *ISO 14040:2006 – Environmental Management – Life Cycle Assessment –Principles and Framework*. Geneva, Switzerland: International Standardisation Organisation.

ISO. 2006b. *ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines*. Geneva, Switzerland: International Standardisation Organisation.

ISO. 2018. *ISO 14067:2018 Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification*. Geneva, Switzerland: International Standardisation Organisation.

Jaegler, A., and P. Burlat. 2012. "Carbon Friendly Supply Chains: A Simulation Study of Different Scenarios." *Production Planning & Control* 23 (4): 269–278. https://doi.org/10.1080/09537287.2011.627656

Jawahir, I. S., O. W. Dillon, K. E. Rouch, K. J. Joshi, A. Venkatachalam, and I. H. Jaafar. 2006. "Total Lifecycle Consideration in Product Design for Sustainability: A Framework for Comprehensive Evaluation." In *Proceedings of TMT (Trends in Development of Machinery and Associated Technology) 2006*, edited by S. Ekinović, S. Yalcin, and J. V. Calvet, 1–10. Keynote Paper. Accessed August 1, 2023. http://www.tmt.unze.ba/proceedings2006.php

Jensen, J. K. 2012. "Product Carbon Footprint Development and Gaps." *International Journal of Physical Distribution and Logistics Management* 42 (4): 338–354. https://doi.org/10.1108/09600031211231326

Karalis, D., and V. Kanakoudis. 2023. "Carbon Footprint of Products and Services: The Case of a Winery in Greece." *The Science of the Total Environment* 878: 162317. https://doi.org/10.1016/j.scitotenv.2023.162317.y

Lee, K.-H. 2011. "Integrating Carbon Footprint into Supply Chain Management: The Case of Hyundai Motor Company (HMC) in the Automobile Industry." *Journal of Cleaner Production* 19 (11): 1216–1223. https://doi.org/10.1016/j.jclepro.2011.03.010

Lee, K.-H., and I.-M. Cheong. 2011. "Measuring a Carbon Footprint and Environmental Practice: The Case of Hyundai Motors Co. (HMC)." *Industrial Management & Data Systems* 111 (6): 961–978. https://doi.org/10.1108/02635571111144991

Liang, Z., H. Deng, H. Xie, B. Chen, M. Sun, and Y. Wang. 2023. "Rethinking the Paper Product Carbon Footprint Accounting Standard from a Life-Cycle Perspective." *Journal of Cleaner Production* 393: 136352. https://doi.org/10.1016/j.jclepro.2023.

Liu, T., Q. Wang, and B. Su. 2016. "A Review of Carbon Labeling: Standards, Implementation, and Impact." *Renewable and Sustainable Energy Reviews* 53: 68–79. https://doi.org/10.1016/j.rser.2015.08.050

Mahapatra, S. K., T. Schoenherr, and J. Jayaram. 2021. "An Assessment of Factors Contributing to Firms' Carbon Footprint Reduction Efforts."

International Journal of Production Economics 235: 108073. https://doi.org/10.1016/j.ijpe.2021.108073

Marti, J. M. C., J.-S. Tancrez, and R. W. Seifert. 2015. "Carbon Footprint and Responsiveness Trade-Offs in Supply Chain Network Design." *International Journal of Production Economics* 166: 129–142. https://doi.org/10.1016/j.ijpe.2015.04.016

Matos, S., and J. Hall. 2007. "Integrating Sustainable Development in the Supply Chain: The Case of Life Cycle Assessment in Oil and Gas and Agricultural Biotechnology." *Journal of Operations Management* 25 (6): 1083–1102. https://doi.org/10.1016/j.jom.2007.01.013

Miles, M. B., and A. M. Huberman. 1994. *Qualitative Data Analysis: An Expanded Sourcebook.* 2nd ed. Thousand Oaks, CA: Sage.

Montoya-Torresa, J. R., E. Gutierrez-Franco, and E. E. Blanco. 2015. "Conceptual Framework for Measuring Carbon Footprint in Supply Chains." *Production Planning & Control* 26 (4): 265–279. https://doi.org/10.1080/09537287.2014.894215

Nuber, C., P. Velte, and J. Hörisch. 2020. "The Curvilinear and Time-Lagging Impact of Sustainability Performance on Financial Performance, Evidence from Germany." *Corporate Social Responsibility and Environmental Management* 27 (1): 232–243. https://doi.org/10.1002/csr.1795

Pandey, D., M. Agrawal, and J. Shanker. 2011. "Carbon Footprint: Current Methods of Estimation." *Environmental Monitoring and Assessment* 178 (1–4): 135–160.https://doi.org/10.1007/s10661-010-1678-y

Plassmann, K., A. Norton, N. Attarzadeh, M. P. Jensen, P. Brenton, and G. Edwards-Jones. 2010. "Methodological Complexities of Product Carbon Footprinting: A Sensitivity Analysis of Key Variables in a Developing Country." *Environmental Science & Policy* 13 (5): 393–404. https://doi.org/10.1016/j.envsci.2010.03.013

Rebitzer, G., T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, G. T. Rydberg, W.-P. Schmidt, S. Suh, B. P. Weidema, and D. W. Pennington. 2004. "Life Norris, Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications." *Environment International* 30 (5): 701–720.https://doi.org/10.1016/j.envint.2003.11.005

Reichelstein, S. J., T. J. L. Lorenzo, P. Liebmann, R. Meier, and M. Sutherland. 2023. "Heidelberg Materials: Assessing Product Carbon Footprints." Stanford Graduate School of Business Teaching Case No.365. CA: Stanford University. Accessed July 10. https://www.gsb.stanford.edu/faculty-research/case-studies/heidelberg-materials-assessing-product-carbon-footprints.

Scrucca, F., C. Baldassarri, G. Baldinelli, E. Bonamente, S. Rinaldi, A. Rotili, and M. Barbanera. 2020. "Uncertainty in LCA: An Estimation of Practitioner-Related Effects." *Journal of Cleaner Production* 268: 122304. https://doi.org/10.1016/j.jclepro.2020.122304

Siggelkow, N. 2007. "Persuasion with Case Studies." *Academy of Management Journal* 50 (1): 20–24. https://doi.org/10.5465/amj.2007.24160882

Sinden, G. 2009. "The Contribution of PAS 2050 to the Evolution of International Greenhouse Gas Emission Standards." *The International Journal of Life Cycle Assessment* 14 (3): 195–203. https://doi.org/10.1007/s11367-009-0079-3

Singh, A., N. Mishra, S. I. Ali, N. Shukla, and R. Shankar. 2015. "Cloud Computing Technology: Reducing Carbon Footprint in Beef Supply Chain." *International Journal of Production Economics* 164: 462–471. https://doi.org/10.1016/j.ijpe.2014.09.019

Suh, S., M. Lenzen, G. J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, et al. 2004. "System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches." *Environmental Science & Technology* 38 (3): 657–664.https://doi.org/10.1021/es0263745

Sundarakani, B., R. De Souza, M. Goh, S. M. Wagner, and S. Manikandan. 2010. "Modeling Carbon Footprints across the Supply Chain." *International Journal of Production Economics* 128 (1): 43–50. https://doi.org/10.1016/j.ijpe.2010.01.018

Velte, P. 2021. "Environmental Performance, Carbon Performance and Earnings Management: Empirical Evidence for the European Capital Market." *Corporate Social Responsibility and Environmental Management* 28 (1): 42–53. https://doi.org/10.1002/csr.2030

Voss, C., N. Tsikriktsis, and M. Frohlich. 2002. "Case Research in Operations Management." *International Journal of Operations & Production Management* 22 (2): 195–219. https://doi.org/10.1108/01443570210414329

Wang, G., F. Li, F. Zhao, L. Zhou, A. Huang, L. Wang, and J. W. Sutherland. 2021. "A Product Carbon Footprint Model for Embodiment Design Based on Macro-Micro Design Features." *The International Journal of Advanced Manufacturing Technology* 116 (11–12): 3839–3857. https://doi.org/10.1007/s00170-021-07557-7

Wang, S. S., W. F. Wang, and H. Q. Yang. 2018. "Comparison of Product Carbon Footprint Protocols: Case Study on Medium-Density Fiberboard in China." *International Journal of Environmental Research and Public Health* 15 (10): 2060. https://doi.org/10.3390/ijerph15102060

WBCSD and WRI. 2004. "The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (revised ed.)." Accessed November 1, 2022. https://ghgprotocol.org/corporate-standard.

Winter, M., and A. M. Knemeyer. 2013. "Exploring the Integration of Sustainability and Supply Chain Management: Current State and Opportunities for Future Inquiry." *International Journal of Physical Distribution & Logistics Management* 43 (1): 18–38. https://doi.org/10.1108/09600031311293237

Wong, E. Y. C., F. F. Y. Chan, and S. So. 2020. "Consumer Perceptions on Product Carbon Footprints and Carbon Labels of Beverage Merchandise in Hong Kong." *Journal of Cleaner Production* 242: 118404. https://doi.org/10.1016/j.jclepro.2019.118404

Wong, E. Y. C., D. C. K. Ho, S. So, and M. C. Poo. 2022. "Sustainable Consumption and Production: Modelling Product Carbon Footprint of Beverage Merchandise Using a Supply Chain Input-Process-Output Approach." *Corporate Social Responsibility and Environmental Management* 29 (1): 175–188. https://doi.org/10.1002/csr.2193

WRI. 2015. *GHG Protocol Scope 2 Guidance*. Washington, DC: World Resources Institute.

WRI. 2013. *Technical Guidance for Calculating Scope 3 Emissions*. Washington, DC: World Resources Institute.

Xiao, J., Z. Zhen, L. Tian, B. Su, H. Chen, and A. X. Zhu. 2021. "Green Behavior towards Low-Carbon Society: Theory, Measurement and Action." *Journal of Cleaner Production* 278: 123765. https://doi.org/10.1016/j.jclepro.2020.123765

Yin, R. K. 1981. "The Case Study Crisis: Some Answers." *Administrative Science Quarterly* 26 (1): 58–65. https://doi.org/10.2307/2392599

Yin, R. K. 2018. *Case Study Research Design and Methods*. 6th ed. London, UK: Sage.

Appendix 1. Sample interview questions

- When did you start the PCF measurement project?
- What was the purpose?
- What did you do first for the PCF measurement project?
- What did you do next?
- Who were involved?
- What was the process inside your company?
- How did you work with your suppliers on the project?
- What were the focused areas?
- Where did you get the data?
- How did you calculate the footprint?
- What happened after the calculation?
- What has worked so far?
- What are the challenges?
- What is the next plan regarding your company's PCF measurement?

Appendix 2. Preparation stage across different PCF cases

		Steps	Explanation	Case 3,8	Case 1,2	Case 4,5,6,7,9
Preparation	Project Initiation, aims and targets	Organize the Project Team	To set the project team, allocate enough staff and resources into the team	A small team of PCF experts	PCF team and representatives from other business functions	PCF team, representatives from other business functions, and a separated internal validation team
		Project Kick-off, gaining support from Senior Management	The start of the project. The support level from senior management has a significant impact on the project	Senior management support is not very critical. The operation can be conducted by pure desk research	Senior management support is critical because the cooperation is needed between the PCF team and other business functions	Senior management support is critical because the cooperation is needed between the PCF team and other business functions
		Position the focal firm in the supply chain	The position of the focal firm in the supply chain will reflect the pressures they received. That will be taken into consideration when the focal firm determines their PCF strategy	Because the primary activity data is not collected, so this issue is not critical	The focal firm in the upper position of the supply chain usually covers fewer suppliers and focuses on the internal production: the ones in the downstream of the supply chain usually cover more suppliers. But it depends on the industry category as well	The focal firm in the upper position of the supply chain usually covers fewer suppliers and focuses on the internal production: the ones in the downstream of the supply chain usually cover more suppliers. But it depends on the industry category as well
		Determine which standards & guidelines to use	PAS2050 is only one of the standards for product carbon footprinting. The other options include ISO14067.	It is usually embedded in the software	Life cycle assessment	Life cycle assessment
		Setting the aims, targets, goals of PCF	The aims, targets, and goals of the PCF determine the procedure of the PCF and the resources which are allocated to the project	A quick scan to the product carbon emission profile, mainly focuses on the result. So secondary data will be used without primary activity data	Internal communication and continuous improvement. So primary activity data will be used	Carbon footprint accreditation & labelling. So high quality & validated primary activity data will be used.
	Set Function unit	Determine the function unit for PCF	Check whether PCR (product category rules) exists, if not, then the function unit has to be set	Selected product is required by customer	Mainstream products	Mainstream products
		Initially determine the priority of the PCF	(according to the PCF aims and the product characteristics, and the company's position in the supply chain, to decide on the focus / priority of PCF, the focus / priority is just an initial decision, not as detailed as setting the system boundary), this determines whether the priority should be in the production part or the supply chain part	It is not needed to consider the PCF priority	The PCF team should make an initial decision on the focus of the project: the production stages or supply chain	The PCF team should make an initial decision on the focus of the project: the production stages or supply chain

Appendix 3. Internal scoping stage across different PCF cases

		Steps	Explanation	Case 3,8	Case 1,2	Case 4,5,6,7,9
Internal Scoping	Map of Product Life Cycle	1st Internal Workshop tutoring PCF knowledge	The first meeting should be organized within internal departments, in order to get a good idea of what is the process map and what are the related parts and input flows, because the PCF team may not be the expert of each team, so may not be well aware of all the related information of the product. But the internal meeting should be the training to different departments, because they may not be prepared in the knowledge of PCF. The tuition content of the workshop should include: (1) Introduction to international corporate carbon management practices; (2) PAS2050 standards, system boundary, data collection/calculation and quality assessment; (3) Emission allocation principles; (4) How to complete data collection template forms; (5) Overall process of calculating carbon footprint; (6) Footprinting routine report and overall carbon footprint report; and (7) Training to internal validation	This meeting is not applicable for this strategy.	PCF team and representatives from other business functions need to attend the training.	PCF team, representatives from other business functions need to attend the training.
		Use product specification and BOM to detail and expand process map	The product specification and BOM (Bill of Material) can give a clear information list of product's components.	Obtain from product management department	Obtain from product management department	Obtain from product management department
		draw the initial process map	The map of linked processes to make the product	The process map can be simply divided into several stages: R&D, manufacturing, transportation, usage and disposal	Draw the process map with detailed stages	Draw the process map with detailed stages
	Set System Boundary	Setting initial system boundary	After drawing the initial process map, according to the goal of PCF, the focal firm can decide how wide to involve suppliers, if yes, what suppliers need to be involved? Companies use PCR to help to determine the system boundaries, but, in many situations, there are no PCRs to reference from	Covers partial product life cycle	Covers full or partial product life cycle	Covers full product life cycle; include 95% of the total carbon emissions
		Re-examine the priority of PCF	It is usually not worth spending significant time and effort getting precise and accurate data for a life cycle stage that has very little impact on the overall footprint. Efforts and priorities should also be linked to the intended purpose of the study. It is suggested to identify potential emissions 'hotspots' at a high level early on in the process	Not applicable	Determine the focus of PCF to ensure sufficient effort into the emission factors with significant impacts	Determine the focus of PCF to ensure sufficient effort into the emission factors with significant impacts
		Determine primary activity data collection scope	The general rule in PAS2050 is that primary activity data are preferred. So, it has to be considered whether supply chain partners' primary data should be covered	Only secondary data applied	Primary data and secondary data	Primary data in most cases; supplemented by secondary data
		Task Allocation to internal team including PCF team and other function units	The detailed tasks to collect data from different processes are allocated to relevant departments.	Tasks are only allocated to PCF team	Data collection tasks are allocated to other internal business functions	Data collection tasks are allocated to other internal business functions and internal validation team

Appendix 4. External scoping stage across different PCF cases

		Steps	Explanation	Case 3,8	Case 1,2	Case 4,5,6,7,9
External Scoping	Supplier Mapping & System Boundary	Determine list of suppliers involved in the project	According to the process map and decision on system boundary, a list of suppliers which make the raw material for the focal firm can be generated	Not applicable	Select key raw/materials/ components	Select key raw/materials/ components
		1st Meeting with key suppliers to tutor and gain the process map of suppliers' product	The second meeting should be organized with key suppliers to tutor or directly get the process map from the supplier's site. This meeting aims to help the focal firm to get a clear idea about the product life cycle map of the component parts produced from suppliers. Because the focal firm may already have a clear idea of suppliers' product life cycle, this can be finished directly by the focal firm without discussion with suppliers.	Not applicable	Tutor suppliers with basic knowledge of PCF	Tutor suppliers with basic knowledge of PCF
		Drawing process map for the parts in 1st tier suppliers	The process map of the producing procedure for the specific raw material	Not applicable	Get the process map of supplier's key product which are inputs to focus firm	Get the process map of supplier's key product which are inputs to focus firm
		Setting the system boundary for 1st tier suppliers	System boundary for the components that is made in suppliers' plant	Not Applicable	Setting boundary for suppliers' products. In most situations it only considers the raw material and its production stage	Setting boundary for suppliers' products. In most situations it only considers the raw material and its production stage
	Timetabling	Set Timetable	The timetable and milestones for the whole project, including the data collection, footprint calculation procedure, internal validation and result verification by third party.	2–4 Months for first-time PCF	4–7 Months for first-time PCF	6–8 Months for first-time PCF

Appendix 5. Internal data collection stage across different PCF cases

		Steps	Explanation of Steps	Case 3,8	Case 1,2	Case 4,5,6,7,9
Internal Data Collection	Data Collection Plan	Draw a data collection plan	Draw a data collection plan	Rough collection plan	Data collection plan involves multiple internal and external partners	Data collection plan involves multiple internal and external partners
		Design data collection tools or forms for all related parties	Design data collection tools or forms for internal departments and suppliers, and downstream logistics providers.	Generated from software	According to PCF standards (e.g. PAS2050) and external consultancy advice if provided	According to PCF standards (e.g. PAS2050) and external consultancy advice if provided
		Established detailed data collection requirement	choosing between primary data and secondary data, following the principles: ● relevance – selection of appropriate data and methods for the specific products ● completeness – inclusion of all GHG emissions and removals arising within the system boundary that provide a material contribution ● consistency – applying assumptions, methods and data in the same way throughout the assessment ● accuracy – reducing bias and uncertainty as far as practical ● transparency – where communicating externally, provide sufficient information.	Using secondary data	Supported by standards or external consultancy	Supported by standards and external consultancy
	Collect Internal Data	2nd meeting with internal departments to train data collection process and on-site tuition	2nd Meeting with internal departments, focus on the Data Collection Training, engaging these internal departments to complete data collection forms. The collection process follows the process map in the scoping stage. These tasks are allocated across internal departments	This type does not need to collect primary data so no need to train representatives from internal departments	Training to representatives of internal departments (R&D, procurement, production, logistics, etc.) and on-site tuition for data collection	Training to representatives of internal departments (R&D, procurement, production, logistics, etc.) and on-site tuition for data collection
		Obtain and confirm the Data from Internal Departments	Collect data through the representatives from internal departments. Communication between PCF team and representative can be quite frequent.	Not applicable	Collect data from multiple departments	Collect data from multiple departments
		Collect data for downstream activities	These data include distribution to customer, usage and end-of-use phrase of product. These tasks should be conducted by transportation/ distribution department, and product R&D department, and the PCF team	Collect downstream data from software	Collect downstream data from internal departments	collect downstream data from internal departments
		Build up the data collection routine system	Build up the data collection routine system, which can support the business for future footprint collection and good traceability of data source	Not necessary for Pilot-oriented PCF	The data collection routine can save time for new PCF project and easily scale up to cover other product's PCF profile. And it can help on product-level carbon continuous improvement.	The data collection routine can save time for new PCF project and easily scale up to cover other product's PCF profile. It makes PCF validation process more efficient in the future
		Collect secondary data from multiple sources	The source of secondary data includes aggregated data such as emission factor and disaggregated data such as inventory data sources	Secondary data is usually embedded in software	Use secondary data embedded in software or other sources	Use secondary data embedded in software or other sources

Appendix 6. External data collection stage across different PCF cases

	Steps	Explanation of Steps	Case 3,8	Case 1,2	Case 4,5,6,7,9
External Data Collection	Select the sampling of the products	Selected average from upstream source. Not every supplier is needed to be involved in data collection. The result can be sampled from typical or selected suppliers	Not necessary	Select some suppliers that supply key components	Cover the majority of suppliers
	2nd Meeting with suppliers for tuition on data collection procedure, and distribute forms to suppliers	This meeting should be organized with suppliers to tutor them with the data collection forms, and the procedure of how to collect data. Also, the data collection templates forms are distributed to suppliers.	Not applicable	Organize suppliers conference to tutor suppliers on detailed procedure of data collection, the requirement and related forms which have been designed by PCF team or external consultancy	Organize suppliers conference to tutor suppliers on detailed procedure of data collection, the requirement and related forms which have been designed by PCF team or external consultancy
	Site-visit suppliers' plant to support data collection	Site-visit in suppliers' plant to support data collection	Not applicable	For some of the suppliers, PCF team to visit their plants to tutor data collection method	For some of the suppliers, PCF team to visit their plants to tutor data collection method
	Retrieve the forms from suppliers, and obtain the activity data	Retrieve the forms from suppliers and obtain the activity data. This process and the previous tuition step can be iterated several times because the suppliers may not be well trained to collect data, so the data quality is not as good as required	Not applicable	collect the forms with primary activity data	collect the forms with primary activity data

Appendix 7. Data validation stage across different PCF cases

		Steps	Explanation of Steps	Case 3,8	Case 1,2	Case 4,5,6,7,9
Data validation	Internal validation	Conduct data quality analysis, and validating data with the forms & supporting documents	These data are collected by both internal business units and suppliers. These data are validated with the forms & supporting documents provided by internal departments and suppliers. The data quality should follow the underlying PAS 2050 principles: relevance, completeness, consistency, accuracy and transparency. And there are multiple data quality assessment methods	Not applicable	Check and confirm the quality of primary activity data & secondary data. This process includes examining the rationality of data with background documents from internal departments and suppliers	Check and confirm the quality of primary activity data & secondary data. This process includes examining the rationality of data with background documents from internal departments and suppliers
	Data quality assessment	Set up Internal Validation Team to validate all internal and external data	Internal Validation Team is set up for the purpose of an internal check before applying for the 3rd party accreditation.	Not applicable	For the process-oriented type PCF it is not necessary to set up the internal validation team	Internal validation team is for the purpose to double check the accuracy of the data, and ensure procedural accuracy of PCF
		Validation team conduct site-visit internally to check data credibility	Internal validation to the data collected from internal departments	Not applicable	Not necessary	Check data credibility of internal data
		Validation team conduct site-visits in suppliers' plants to check data credibility	The internal validation team need to conduct site-visit to suppliers to check Data credibility	Not applicable	Not necessary	Check credibility of external supply chain data

Appendix 8. Footprint calculation stage across different PCF cases

		Steps	Explanation of steps	Case 3,8	Case 1,2	Case 4,5,6,7,9
Footprint calculation	Initial calculation	General calculation process	Use the process map, which already maps out all of the inputs, outputs, distances and other useful 'activity' data for each process stage. It can be used to calculate the emission quantities	Executed in software or Excel worksheet	Executed in software or Excel worksheet	Executed in software or Excel worksheet
		Balance the data into product function unit (calculate the provision of functional unit of product to the overall process)	Because activity data are often collected in many different formats and relating to different units, so the important step is to balance the data into a function unit	Executed by software	The allocation method of primary activity data needs to be discussed with PCF team and internal departments. Some of the typical allocation units are weight, monetary value, per working hour, etc.	The allocation method of primary activity data needs to be discussed with PCF team and internal departments. Some of the typical allocation units are weight, monetary value, per working hour, etc.
	Calculation adjustment & final result	Making simplifying assumptions	Use simplifications or estimations to streamline the carbon footprinting process, including a generic emission factor for a group of similar chemicals, and to assign a set of general assumptions for transportation calculation.	Software dataset has embedded the simplified assumptions	Make these assumptions on less-impact emissions activities but make sure the high-impact activities are carefully examined	strictly follows the requirements of footprinting standards
		Making the co-product allocation	Split/divide the emission footprint between the main product and the co-product	This issue is usually omitted by software	Conducted by PCF team according to product production process	Conducted by PCF team according to product production process
		Apply the secondary data	The secondary data were collected in the data collection stage, including the emission factor database	Data in software are all secondary type	Apply the secondary data	apply the secondary data but ensure it complies with the PCF standards requirement on usage of primary data
		Calculate specific aspects of carbon footprint	Including: biogenic carbon accounting and carbon storage, energy and combined heat & power (CHP), grid electricity, renewable energy and renewable electricity tariffs, on-site electricity production, agriculture, land use change, refrigeration, transport emissions, storage emissions, recycling, residual waste disposal	This issue is usually omitted by software	Special aspects should be carefully considered by PCF team	Special aspects should be carefully considered by PCF team and make sure it complies with standard requirement
		Integrate the result of footprints from different stages	Summarize the emission results in different stages of product life cycle	Automatic conducted by software	Integrate the footprint result	Integrate the footprint result

Appendix 9. Interpretation & accreditation stage across different PCF cases

		Steps	Explanation of Steps	Case 3,8	Case 1,2	Case 4,5,6,7,9
Interpretation and accreditation	Footprint result Impact assessment	Understand the carbon footprint results	Conduct life cycle impact analysis to the result, which shows the emissions hotspots across the life cycle	Hot spot' analysis, but due to using the secondary data, the analysis may not be accurate	Hot spot' analysis	Hot spot' analysis
		Uncertainty analysis to carbon footprint result	A formal uncertainty analysis can be undertaken by employing a statistical approach such as Monte Carlo analysis to quantify these uncertainties	Conducted within the software	Formal uncertainty analysis may not be necessary for this PCF type	A formal analysis should be carried out
		Sensitivity analysis to carbon footprint result	It shows how key data and assumptions Influence the results. It involves simply changing the value (activity data or emission factor) over which there is uncertainty, to see how this affects results.	Conducted within the software	Formal sensitivity analysis may not be necessary for this PCF type	A formal analysis should be carried out
	Certify footprint result	Writing the carbon footprint report	Generating the footprint report	Simple basic report	The report is served as internal reference	written by PCF team or external consultancy which complies with standards
		Communication of the carbon result to concerned stakeholders	These stakeholders include internal departments and external supply chain partners, and external stakeholders	This type of PCF serves the request from clients or customers	The result is revealed to internal departments	The result is revealed to internal departments and external consultancy
		Verify the footprint result with third-party assurance	There are three levels of assurance: self-verification, other third-party verification and independent third-party certification	No need to verify for this type of PCF	No need to verify for this type of PCF. But self-verification can be an option	The result should be verified by 3rd-party verification; The focal firm should gain independent 3rd party certification
		Determine carbon disclosure types	The focal firm can accredit the result but does not disclose it	Usually only disclose to customers that ask for the result	The result may be disclosed in the focal firm's annual corporate social report, and disclose in some professional conference	The footprint result is certified and disclosed to the public.
	Reduction plan	Setting reduction amount target, reduction strategy, and reduction action plan	Based on the footprint mapping, further plans and analysis for carbon performance improvement can be conducted	Due to using secondary data, the detailed solution for improvement may not be applicable	Set up related reduction plans according to the PCF result	Set up related reduction plans according to the PCF result
		Use footprint result to drive reductions: efficiency, design, and work with supply chain partners.	Emission reduction action	To guide the improvement according to footprint result	The detailed information in PCF result can support the decisions of improvement practices	The detailed information in PCF result can support the decisions of improvement practices