Chapter 3
Carbon Footprinting in Supply Chains

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3.1 Introduction

Climate change is a key issue in sustainability, as it may lead to dangerous increases in temperature and sea level, flooding, droughts, etc. (WRI and WBCSD 2004). Scientists all over the world are providing information supporting the fact that the climate is changing and that this change is partly due to human activities through the release of greenhouse gases (GHGs). "Carbon" is often used as a shorthand for GHGs, as carbon dioxide is the main GHG released by human activities. As a consequence, the activity of measuring GHG emissions is often referred to as carbon footprinting, the term we use in the reminder of this chapter.

A carbon footprint may concern an organization, a value chain, or a product (Carbon Trust 2014). The organizational carbon footprint accounts for emissions from all activities across an organization (including building energy use, industrial processes, and the company's vehicles). The value chain carbon footprint includes also emissions outside the organization's own operations (i.e., emissions from both suppliers and consumers, including product use and end-of-life emissions). Finally,

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the product carbon footprint includes emissions over the whole life cycle of a given unit of product or service, from the extraction of raw materials and manufacturing to its use and final reuse, recycling, or disposal. This chapter focuses on the organization and value chain footprints; product-level carbon footprinting is more closely related to life-cycle assessment (LCA), which is covered in Chap. 2 by Guinée and Heijungs (2017).

This chapter is organized into four sections. Section 3.1 provides a brief scientific background on climate change, to the extent necessary to understand the methodology behind carbon footprinting. It also introduces the main motivations for carbon footprinting. Section 3.2 explains how carbon footprints can be measured and describes several carbon accounting methodologies. Section 3.3 focuses on supply chain carbon footprinting and provides an example from the automobile industry. Finally, Section 3.4 provides some challenges related to supply chain carbon footprinting in practice.

3.1.1 The Science of Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC),[1] climate change refers to any change in climate over time due to natural variability or as a result of human activity (IPCC 2007). The scientific community has collected substantial evidence that the climate is changing (IPCC 2013a), as a result of the increased concentration of GHGs in the atmosphere, which is due in part to human activity. The main greenhouse gases are water vapor, carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Some of these GHGs are naturally present in the atmosphere and are responsible for the greenhouse effect, a natural phenomenon responsible for warming the atmosphere and allowing life on Earth. However, in recent times, GHG emissions have increased, among others, due to industrialization and changes in agriculture and land use. Carbon dioxide, for example, is emitted by the combustion of fossil fuels such as coal, oil, and gas. Methane mainly comes from agriculture, livestock, and landfills. Nitrous oxide is found in large quantities in nitrogen fertilizer and chemical processes. These human-made GHGs known as "anthropogenic GHGs" intensify the greenhouse effect.

In order to measure the climate impact of GHG emissions, the life-cycle assessment (LCA) community (see Chap. 2 by Guinée and Heijungs (2017) for more detail) has developed an impact category called the global warming potential (GWP). GWP is the recommended metric to compare future climate impacts of emissions (IPCC 2007). It refers to the heat trapped in the atmosphere by a given amount of GHG over a given time period, relative to that trapped by an equivalent amount of CO_2 during the same period. Table 3.1 shows the GWP of some GHGs over 100-year and 20-year periods, respectively. For example, the GWP of methane (CH_4) over a 100-year period is 28. This means that 1 metric ton (referred to as ton

[1] IPCC is the leading international body for the assessment of climate change (http://www.ipcc.ch/).

Table 3.1 Atmospheric lifetime and global warming potentials of some GHGs

Gas	Atmospheric lifetime	100-year GWP	20-year GWP
CH_4 (methane)	12.4	28	84
HFC-134a (hydrofluorocarbon-134a)	13.4	1,300	3,710
CFC-11 (trichlorofluoromethane)	45	4,660	6,900
N_2O (nitrous oxide)	121	265	264
CF_4 (tetrafluoromethane)	50,000	6,630	4,880

Source: IPCC 2013b, Table 8.7

in what follows) of methane in the atmosphere over 100 years traps the same amount of heat as 28 t of carbon dioxide over 100 years. Carbon dioxide is taken as a reference for evaluating global warming as this is the most important anthropogenic GHG in quantity and in total impact (based on 100-year GWP calculations). Consequently, GHG emissions are often referred to as carbon emissions.

Table 3.1 shows that the GWP and the atmospheric lifetime vary widely between GHGs. The variation in atmospheric lifetimes means that the time period chosen to calculate the GWP may lead to significant differences. For instance, the atmospheric lifetime of methane is about 12 years, much lower than that of carbon dioxide. Consequently, the 20-year GWP of methane is much higher than the 100-year GWP. The opposite effect occurs when the atmospheric lifetime of a GHG is much higher than the lifetime of carbon dioxide, as is the case for CF_4. The 100-year GWP is used by convention in practice. However, the IPCC (2007) highlights that the proper time horizon for evaluating dangerous anthropogenic interference in the climate system has not been determined, neither scientifically, economically, nor politically. We refer to Dyckhoff and Kasah (2014) for more details on the effect of time horizons on LCA.

Using the GWP enables us to aggregate GHG emissions into a single metric commonly expressed in carbon dioxide equivalent (CO_2e) or in carbon equivalent. These two metrics should not be confused: 3 million tons of carbon equivalent is equal to 11 million tons of CO_2e. The conversion between carbon equivalent and CO_2e is related to the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom, i.e., 44/12 (EPA 2005).

Carbon emissions expressed in CO_2e (or in carbon equivalent) are often thought of as an unambiguous measure of the effect of GHGs on global warming. However, this measure is based on various assumptions and imperfect models. Any recommendation based on carbon dioxide equivalent calculations needs to acknowledge that the results are subject to some scientific uncertainty. For instance, the GWPs are revised periodically as the models used in the calculations evolve (Carbon Trust 2014). This can be observed in Table 3.2, which shows three different estimates for methane.

This has immediate implications for carbon footprinting and reporting as the carbon footprints for different companies and especially at different points in time may be based on different GWPs. An analogy in financial accounting is the effect of currency exchange rates: financial statements are published in a single currency, using whatever collection of exchange rates is appropriate at that time, but changes

Table 3.2 Changes in global warming potential estimates for methane for three IPCC reports

Methane (CH_4)		Global warming potential (GWP) Time horizon		
IPCC report:	Lifetime years	20 years	100 years	500 years
SAR 1995	12	56	21	6.5
TAR 2001	12	62	23	7
AR4 2007	12	72	25	7.6

Source: IPCC (1996, 2002, 2007)

in reported financial metrics may result in part from changes in exchange rates rather than in actual performance. Even though one may not expect GWPs to be as volatile as currency exchange rates, Table 3.2 shows that the 20-year GWP for methane has changed by about 29 % between the 1995 and 2007 IPCC reports. Despite these shortcomings, using the GWP to aggregate different GHGs into a single metric expressed in CO_2e is the most common approach to carbon footprinting.

3.1.2 Motivations for Carbon Footprinting and Reporting

Carbon footprinting has become more widely used (see, e.g., Minx et al. 2009) than other environmental footprints, such as the ecological footprint, land footprint, water footprint, etc. (see Chap. 4 by Hoekstra (2017) for more on water footprinting). The main reasons for this can be linked to legislation around carbon emissions, public awareness of climate change risks, and investors' expectations for carbon emission reporting. Consequently, some companies ask their suppliers and subcontractors to provide data on their emissions. For instance, DHL requires all its carriers to enter data on vehicles used, distance traveled, fuel efficiency, etc., not only to calculate total carbon emissions but also to screen the carriers for environmental performance (WRI and WBCSD 2004). Reducing carbon emissions can also lead to lower costs. For instance, a survey of the Consumer Electronics Association (CEA) found that companies measuring their carbon footprint were able to reduce their electricity consumption by 5–25 % per million dollars of revenue (Vasan et al. 2014).

Regarding regulations on carbon emissions, many governments require carbon emitters to report their emissions annually on a mandatory basis. Other countries have established carbon and energy taxes (e.g., the CRC Energy Efficiency Scheme in the UK) under which financial penalties are associated with carbon emissions. In addition, most countries have signed the Kyoto Protocol[2] that entered into force in 2005; discussions on a follow-up agreement are taking place in Paris in 2016.

[2] The Kyoto Protocol commits its parties by setting internationally binding carbon emission reduction targets (UNFCCC, 2014): 5 % against 1990 levels during the first commitment period (2008–2012) and at least 18 % below 1990 levels during the second commitment period (2013–2020).

As a result, many governments are taking steps to reduce carbon emissions through regional or national policies including the introduction of emission trading programs (e.g., the European Union Emission Trading Scheme or ETS). Under a trading system, permits are required for a given company to be allowed to emit GHGs, and the number of available permits in the market (regional, national, or international) is limited. European companies such as Lafarge and Rockwool International which are covered by the EU ETS report their carbon emissions on a mandatory basis (CDP 2014a). Other companies report their emissions in order to be prepared for future regional, national, or international climate policies (Carbon Trust 2014; CDP 2014a). According to the CDP (formerly the "Carbon Disclosure Project"),[3] despite having no federal regulations on carbon in the USA, 69 US companies disclosed that they are already participating in the EU ETS (CDP 2014a). Moreover, global companies doing business in China and South Korea such as Alstom, Bayer, and Canadian Tire Corporation are closely monitoring emerging Chinese emission trading systems that will soon put a price on carbon (CDP 2014a).

Another incentive for carbon footprinting emanates from the pressure exerted by the public, which is more and more aware of the risks of climate change. Several reports demonstrate that climate change and global warming are nowadays considered among the risks of highest concerns worldwide. For instance, in a global survey, DHL (2010) states that 60 % of all respondents identified climate change as being among the top three most serious current world problems. In the ninth global risks assessment report released by the World Economic Forum in 2014 (WEF 2014), "Failure of climate change mitigation and adaptation" and "Greater incidence of extreme weather events (e.g. floods, storms, fires)" were ranked fifth and sixth, respectively, among the top 10 global risks. In 2014, the European Commission performed its second survey on climate change. The results reveal that climate change is perceived as the third most serious issue worldwide, after "poverty, hunger and lack of drinking water" and "the economic situation" (EC 2014).

Investors also require that the long-term risks related to environmental externalities are managed in order to protect their long-term investments. For instance, the CDP Investor Initiatives, backed in 2015 by more than 822 institutional investors representing over US$95 trillion in assets[4], provide investors with a global source of annual information to support long-term objective analysis, including evidence and insight into companies' carbon footprint and strategies for managing climate change. The CDP's Carbon Action initiative (backed by 190 investors) asks companies in heavy emitting industries to take actions on carbon emission reduction every year, by setting emission targets and making reductions while generating return on investment (CDP 2014b).

[3] The CDP is an international organization that holds the largest collection of climate change-, water-, and forestry-related data reported by companies (https://www.cdp.net/). More than 5 000 companies report to CDP every year. For instance, in 2013, 334 firms in the S&P 500 index have disclosed their emissions to CDP (CDP 2015).

[4] See https://www.cdp.net/en-US/WhatWeDo/Pages/investors.aspx, last accessed December 2, 2015.

To conclude, the first step toward managing carbon emissions is to measure the carbon footprint because "if you can't measure it, you can't manage it" (Kaplan and Norton 1992). The next section is devoted to this question.

3.2 How Can a Carbon Footprint Be Measured?

This section is divided into two parts. The first presents the GHG Protocol, the most used framework to account for carbon emissions. The second part highlights the main methods used for carbon footprinting.

3.2.1 The GHG Protocol

The GHG Protocol[5] (www.ghgprotocol.org/) is the guideline for many existing methodologies for carbon footprint measurement. It is developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The first version "The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard" was released in 2001. This is the main framework for carbon emissions accounting worldwide. It is used by government and business leaders to understand, quantify, and manage their carbon footprint. The GHG Protocol also serves as the foundation for nearly every GHG standard and program in the world as well as hundreds of GHG inventories prepared by individual companies (WRI and WBCSD 2004). As an example, the corporate standard serves as the basis for international standards such as ISO 14064-1 (EPA 2014).

The GHG Protocol is now composed of seven standards (corporate standard, project protocol, product life-cycle standard, corporate value chain standard, GHG Protocol for cities, mitigation goal standard, and policy and action standard). At the time of writing, WRI and WBCSD have been scoping the need for a new standard on product innovation. Among these standards, we briefly introduce the two that are directly related to supply chains: the corporate and corporate value chain standards.

The corporate standard, released in 2001 and most recently amended in 2013, provides guidance for companies in preparing a carbon emission inventory. It was designed with the following objectives in mind (WRI and WBCSD 2004):

– "To help companies prepare a carbon inventory that represents a true and fair account of their emissions, through the use of standardized approaches and principles.

[5] Where appropriate, we quote extensively directly from the GHG Protocol throughout this chapter.

– To simplify and reduce the costs of compiling a carbon inventory.
– To provide business with information that can be used to build an effective strategy to manage and reduce carbon emissions.
– To increase consistency and transparency in carbon emission accounting and reporting among various companies and GHG programs."[6]

The corporate value chain standard (also referred to as Scope 3 standard), released in 2011, allows companies to assess their entire value chain emission impact and identify the most effective ways to reduce emissions. The standard was developed with the following objectives (WRI and WBCSD 2011a: 4):

– "To help companies prepare a true and fair scope 3 GHG inventory in a cost-effective manner, through the use of standardized approaches and principles.
– To help companies develop effective strategies for managing and reducing their Scope 3 emissions through an understanding of value chain emissions and associated risks and opportunities.
– To support consistent and transparent public reporting of corporate value chain emissions according to a standardized set of reporting requirements."

These two standards are built on the same underlying principles. In both cases, setting clear boundaries is of crucial importance. The GHG Protocol recommends setting organizational boundaries and operational boundaries.

• *Organizational boundaries*
  Two distinct approaches can be used: the *equity share* and the *control* approaches. Following equity share, a company accounts for carbon emissions from operations according to its share of equity in the operation (i.e., economic interest). Typically, the share of economic risks and rewards in an operation is aligned with the company's percentage ownership of that operation, and equity share will be the same as the ownership percentage. With the control approach, the company accounts for 100 % of the carbon emissions from operations over which it has control. Control can be defined in either financial terms (ability to direct the financial and operating policies) or operational ones (full authority to introduce and implement operating policies at the operation).
• *Operational boundaries*
  This involves identifying carbon emissions associated with a company's operations, categorizing them as direct or indirect emissions, and choosing the scope of accounting and reporting for indirect emissions. The GHG Protocol distinguishes three "scopes" (see Fig. 3.1):

  – *Scope 1*: *Direct carbon emissions*
    Direct carbon emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled

[6] See http://www.ghgprotocol.org/standards/corporate-standard, last accessed December 1, 2015.

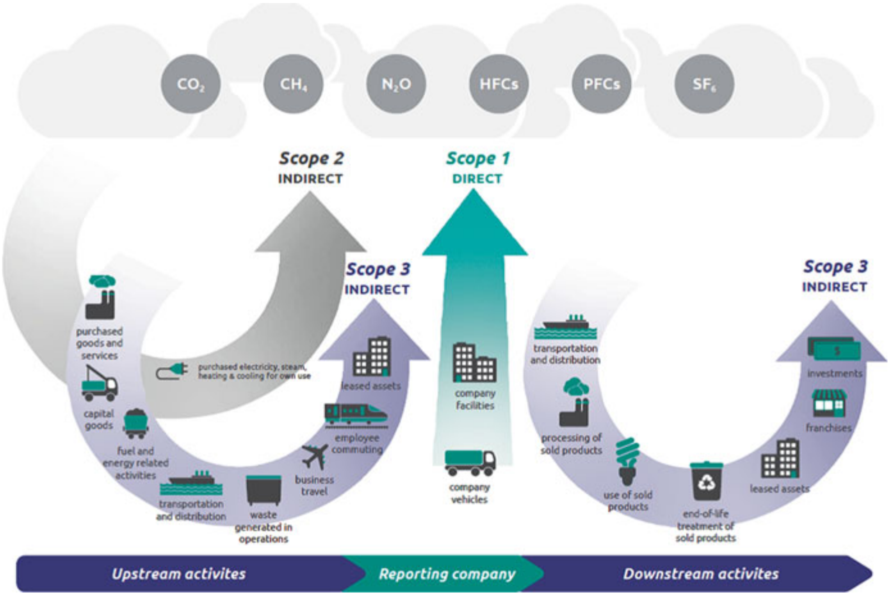

Fig. 3.1 Overview of scopes and emissions across a value chain (*Source*: Fig. 1.1 in WRI and WBCSD, 2011a)

boilers, furnaces, vehicles, etc., or emissions from chemical production in owned or controlled process equipment.

– *Scope 2*: *Purchased energy indirect carbon emissions*
Scope 2 accounts for carbon emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company. Scope 2 emissions physically occur at a facility outside the organizational boundary of the reporting company.

– *Scope 3*: *Other indirect carbon emissions*
Scope 3 allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources owned or controlled by other entities in the value chain (e.g., materials suppliers, third-party logistics providers, waste management suppliers, travel suppliers, lessees and lessors, franchisees, retailers, employees, and customers). Scope 3 emissions are all indirect emissions including both upstream (e.g., purchased products or purchased products transportation) and downstream emissions (e.g., use of sold products or disposal of sold products).

These three scopes are mutually exclusive for the reporting company. Scope 3 emissions do not include any emissions already accounted for as Scope 1 or Scope 2 by the same company. They enable clarifying the distinction between corporate and value chain standards. Under the corporate standard, companies are required to report all Scope 1 and Scope 2 emissions, while reporting Scope 3 emissions is optional. The corporate value chain standard is designed to create further consistency in Scope 3 inventories through additional requirements and guidance for Scope 3 accounting and reporting (WRI and WBCSD 2011a).

Once the organizational and operational boundaries are defined, the carbon footprint can be measured. The next section gives an overview of the main methodologies used to measure the carbon footprint.

3.2.2 Methodologies for Measuring the Carbon Footprint

Various methods for measuring carbon emissions have been proposed. We classify them by the level of extrapolation involved, from the most direct measurement methodology to the one relying most heavily on extrapolation:

- Direct measurement
- Energy-based calculations
- Activity-based calculations
- Economic input–output life-cycle assessment (EIO-LCA)

• *Direct measurement*
  The direct measurement methodology is usually applied to production sites. The measurement of emissions is achieved by continuously measuring the pollutants emitted into the atmosphere in exhaust gases from combustion or industrial processes, often via the use of continuous emission monitoring systems (EPA 2008). Due to their high cost, continuous emission monitoring systems are mainly installed in production sites subject to environmental regulations and process monitoring applications such as the US EPA 40 CFR Part 75 and 40 CFR Part 60. Apart from these sites under regulation, direct measurement of carbon emissions by monitoring concentration and flow rate is not common in supply chains. Direct measurement is generally only applicable for a share of Scope 1 emissions.
• *Energy-based calculations*
  Energy-based calculations determine carbon emissions based on mass balance or theoretical combustion specific to a facility or a process. This methodology applies mainly to fuel consumption, both at production sites and for transportation. Several levels of analysis may be conducted, depending on the information available. Indeed, the amount of fuel combusted is generally not directly monitored, and extrapolation based on the amount of fuel consumed is commonplace. In addition, the carbon content of a given combusted fuel is often estimated based on average values. Energy-based calculations may also be applied for indirect emissions from electricity consumption, as many providers release the average level of carbon emissions per unit of electricity produced. Energy-based calculations require information that is generally available for a share of Scope 1

and Scope 2 emissions. This is most applicable to process-related emissions such as those from cement, aluminum, and waste processing (DEFRA 2009) and to transportation-related emissions.

- *Activity-based calculations*
  An activity-based calculation method aims at deriving the carbon emissions from activity information by using conversion factors. These factors are calculated ratios relating carbon emissions to a proxy measure of activity at an emissions source. They are often referred to as emission factors. Activity-based calculation is the most common approach used to calculate carbon emissions (DEFRA 2009). The available activity-based methods differ in their level of aggregation, some of them requiring more detailed information than other (Velazquez-Martinez et al. 2014). As an example, consider a reporting company that uses truck transportation for inbound deliveries. Assume that transportation is outsourced to a third-party logistics provider and are therefore Scope 3 emissions. Data on fuel consumption (required for energy-based calculation) are generally not shared by third-party logistics providers, as fuel consumption is a key element in the cost structure of truck transportation and the carrier is usually not willing to share information about his cost structure with the customer. In this case, the reporting company can apply activity-based calculation, by converting the weight transported over a given distance and using a given type of truck to estimate average carbon emissions by using emission factors. Several initiatives provide such type of emission factors for the main supply chain activities. Chapter 7 by Blanco and Sheffi (2017) provides more detail in the context of logistics.
- *Economic input–output life-cycle assessment* (*EIO-LCA*)
  EIO-LCA enables converting the expenditures by a company in a given industry sector into an average amount of carbon emissions. For instance, $X spent in the transport industry sector leads on average to Y tons of CO_2e. We refer to Hendrickson et al. (2010) for a detailed exposition of the approach and to Huang et al. (2009) for an application of EIO-LCA to estimate that the carbon footprint of all economic sectors in the US. EIO-LCA is relatively widespread, especially in the USA, due to its ease of use. However, one limitation of EIO-LCA is that it exclusively accounts for upstream emissions.

Methodologies relying less on extrapolation will provide more accurate estimation of the true carbon footprint of operations. For example, Matthews et al. (2008) state that firm-level data such as electricity and energy use will produce more accurate footprint results than EIO-LCA. On the other hand, the data required to apply a methodology that relies less on extrapolation may be harder to gather or simply not available. O’Rourke (2014) mentions that accessing data from full supply chains can be expensive, time consuming, and, sometimes, impossible. There is an inherent trade-off between the scope of measurement chosen (and consequently the portion of the total footprint analyzed) and the accuracy of the estimation made. (We return to the issue of accuracy in Sect. 3.4.2.) Consequently, defining the right scope for carbon emission measurement is of crucial importance as this decision will have strong implications for the type of measurement methods that can be implemented. One of the key questions here consists in assessing the importance of Scope 3 emissions for the reporting company. If Scope 3 emissions represent a small share of total supply chain emissions for the company, it may make more sense to focus on Scope 1 and Scope 2 emissions and to apply a more direct methodology. However, Scope 3 emissions can be of high importance when it represents a large share of a company's carbon footprint, as is true for most firms. We discuss the importance of Scope 3 emissions in more depth below.

3.3 Supply Chain Carbon Footprinting

This section is divided into four parts. First, the importance of Scope 3 emissions in supply chain carbon footprinting is analyzed. Second, the process of supply chain carbon footprinting is presented. Then, the process of carbon footprinting in a supply chain is illustrated by referring to the process followed by Hyundai Motor Company (HMC) (as described in Lee (2011)). Finally, some issues related to carbon footprint allocation among different supply chain partners are discussed.

3.3.1 Importance of Scope 3 Emissions

Matthews et al. (2008) estimated that on average 74 % of an industry sector's carbon footprint is attributed to upstream Scope 3 emissions (without accounting for downstream Scope 3 emissions). This average value gives an idea of the importance of accounting for carbon emissions through the supply chain. Huang et al. (2009) focused on upstream emissions of US economic sectors and provided a sector-specific repartition of emissions from Scope 1 to Scope 3.

Huang et al. show that the impact of upstream Scope 3 emissions is substantial for most of the US industry sectors. Moreover, a large share of US companies' upstream Scope 3 emissions can be attributed to their top-10 suppliers. This result may help a company to understand which upstream Scope 3 category contributes most to its total carbon footprint and thus help it focus its measurement efforts on relevant suppliers. In practice, companies often focus on measuring the portion of their Scope 3 emissions related to employee commuting and business travel. However, CDP (2013a) indicates that 72 % of the global 500 companies reporting to CDP report emissions from business travel even if these emissions account for only 0.2 % of total reported Scope 3 emissions. CDP (2013a) concludes that "instead of measuring carbon-intensive activities in their supply chain, companies often focus on relatively insignificant opportunities for carbon reduction."

Huang et al. (2009) also show that the portion of Scope 3 emissions widely varies from one industry sector to another. This explains why it is difficult to provide generic guidance on which emissions of Scope 3 to include in the inventory (see Sect. 3.3.2 for more details), leading Huang et al. (2009) to recommend that protocol organizations develop sector-specific Scope 3 guidelines.

Even companies that voluntarily disclose Scope 3 emissions are under no obligation to be comprehensive. To estimate how (in)complete current Scope 3 emissions reports are, Blanco et al. (2014) compare CDP disclosures by US firms to the predicted breakdown of emissions in Huang et al. (2009). They estimate that US firms that disclose any Scope 3 emissions in 2013 only reported 22 % of their full upstream supply chain emissions to CDP. Scope 3 reporting is generally underdeveloped even though companies are progressively improving. The next section provides some general guidelines on how to perform supply chain carbon footprinting.

3.3.2 The Process of Supply Chain Carbon Footprinting

The supply chain carbon footprint corresponds to Scope 1, 2, and 3 emissions. Accounting for Scope 3 emissions, and therefore the value chain carbon footprint, need not involve a full-blown inventory of all products and operations, which would generally be infeasible. Usually it is most valuable to focus on the major GHG-generating activities. As mentioned above, the structure of Scope 3 emissions varies from one industry sector to another, and consequently, it is difficult to provide generic guidance on which Scope 3 emissions to include in an inventory. However, some general steps can be articulated (WRI and WBCSD 2011a):

1. *Describe the value chain*. It is important, for the sake of transparency, to provide a general description of the value chain and the associated carbon emission sources.
2. *Determine which Scope 3 categories are relevant*. Only some types of upstream or downstream emission categories might be relevant to the reporting company. They may be relevant, for example, because they are large (or believed to be large) relative to the company's Scope 1 and Scope 2 emissions, they contribute to the company's carbon risk exposure, they are deemed critical by key stakeholders (e.g., feedback from customers, suppliers, investors, or civil society), etc.
3. *Identify partners along the value chain*, e.g., customers or users, product designers, manufacturers, energy providers, etc. This is important when trying to identify sources, obtain relevant data, and calculate emissions.
4. *Quantify Scope 3 emissions*. While data availability and reliability may influence which Scope 3 activities are included in the inventory, it is accepted that data accuracy may be lower. It may be more important to understand the relative

magnitude of and possible changes to Scope 3 activities. Emission estimates are acceptable as long as there is transparency with regard to the estimation approach, and the data used for the analysis are adequate to support the objectives of the inventory. Verification of Scope 3 emissions will often be difficult and may only be considered if data is of reliable quality.

3.3.3 An Example from the Automobile Industry

To better understand how carbon footprinting might work in practice, we briefly summarize Lee (2011), who describes a three-step process that HMC took jointly with its ten-key 1st-tier suppliers in a pilot study, to measure carbon emissions in the upstream supply chain. The study focused on Avante passenger car model manufacturing. Lee mentioned that one of the most difficult challenges that HMC faced was determining the emission boundary. Based on the GHG Protocol, direct (in-house) and limited indirect carbon emission boundaries were considered, while downstream stages of distribution, consumers, disposal, and recycling were excluded (Lee 2011). The first step is to identify the key suppliers' carbon footprint. HMC set up guidelines and provided measurement manuals to key suppliers. Based on this, each supplier conducted Scope 1 and 2 emission measurement and reporting, using a direct measurement methodology. The scope of the guidelines prepared by HMC includes raw material suppliers, manufacturers, and distributors. In the second step, a carbon process map was established to identify each component and part at each stage of the simplified supply chain. This process helped HMC and its suppliers to calculate the carbon footprint of each component and part. The carbon process map also helped HMC and its suppliers to identify components and parts with high carbon burdens. Finally, in the third step, HMC and its suppliers calculated the products' carbon footprint by adding the carbon emissions of the supply chain stages. Regarding the front bumper product, for example, it was found that through the simplified supply chain, the raw material stage accounts for 18 % of the carbon emissions, the manufacturing stage accounts for 70 %, and the distribution accounts around 12 % (Lee 2011).

Although reporting Scope 3 emissions is optional and might be difficult (data availability, data reliability, supplier capability, etc.), a supply chain carbon footprint that includes these emissions is very important from a decision-making perspective, as discussed in Sect. 3.3.1. As stated by Lee (2011), reducing the supply chain carbon emissions may be more cost effective for companies than reducing direct or purchased electricity-related emissions (Scopes 1 and 2). Indeed, accounting for carbon emissions along the value chain can help companies to identify where to allocate limited resources in a way that maximizes carbon emission reduction while possibly lowering costs at the same time. For instance, a senior manager of one of HMC's suppliers stated that "we didn't realize how much electricity we wasted during the production stage and the importance of efficient energy management from raw materials to distribution. We learned that carbon footprint identification and measurement practice brought cost savings, and we also began to re-examine our products design to minimize carbon footprint in our products and their supply chain" (Lee 2011: 1221).

3.3.4 Emission Allocation in Supply Chains[7]

In determining the carbon footprint for an organization, value chain, or product, it is generally necessary to allocate shared emissions to separate units. For instance, emissions of a truck need to be allocated to all the products transported on that truck. Emissions caused by heating, cooling, and lighting in a plant need to be allocated to the range of products and customers that it serves. Allocation is a thorny issue in LCA in general (see also Chap. 2 by Guinée and Heijungs, 2017) and hence also for carbon footprinting.

Chapter 8 in "The GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard" (WRI and WBCSD 2011a) provides guidance on allocating emissions. Accordingly, allocation should be avoided or minimized when possible, by collecting more detailed data through (1) obtaining product-level GHG data from value chain partners, (2) separately submetering energy use and other activity data (e.g., at the production line level), and (3) using engineering models to separately estimate emissions related to each product produced.

When allocation is inevitable, companies should select the allocation approach that (1) best reflects the causal relationship between the production of the outputs and the resulting emissions, (2) results in the most accurate and credible emission estimates, (3) best supports effective decision-making and GHG reduction activities, and (4) otherwise adheres to the principles of relevance, accuracy, completeness, consistency, and transparency (WRI and WBCSD 2011a). It is preferable to use a physical relationship between the multiple inputs/outputs and the quantity of emissions generated, through allocation factors such as mass, volume, energy, chemical, number of units, or others (e.g., protein content of food coproducts or floor space occupied by products); otherwise the remaining options are to use economic factors (by value) or other relationships. This is because physical factors are expected to best reflect the causal relationship between the production of the outputs and the resulting emissions. Clearly, different allocation methods are prone to yielding significantly different results.

The general method proposed by WRI and WBCSD (2011a) to allocate emissions from a facility is to multiply total facility emissions by the reporting company's purchases as a fraction of total production. For example, using mass as the allocation factor:

[7] This section draws on "The GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard" (WRI and WBCSD 2011a) and on Caro et al. (2013), both of which sources we cite at various points throughout this section.

$$\text{Allocated facility emissions} = \frac{\text{Mass of Products Purchased}}{\text{Total Mass of Products Produced}} \times \text{Total Emissions.}$$

As for collecting and allocating GHG emissions from suppliers, two basic approaches are suggested:

- Supplier allocation. Individual suppliers report preallocated emission data to the reporting company and disclose the allocation metric used.
- Reporting company allocation. The reporting company allocates supplier emissions by obtaining two types of data from individual suppliers: (1) total supplier GHG emission data (e.g., at the facility or business unit level) and (2) the reporting company's share of the supplier's total production, based on either physical factors (e.g., units of production, mass, volume, or other metrics) or economic factors (e.g., revenue, spend).

It is argued that reporting company allocation is likely to ensure more consistency in methodologies for the reporting company, while the supplier allocation approach may be more practical by avoiding the need for suppliers to report confidential business information. Finally, examples and guidance for determining the most appropriate allocation method to use are also provided by WRI and WBCSD (2011a).

Many GHG emissions are the result of joint processes by multiple parties in a supply chain (Caro et al. 2013). A typical product goes through numerous manufacturing and transportation stages operated by a number of companies in a supply chain. Although joint production can occur anywhere, it is likely to be particularly common in indirect goods and services, which do not become part of the final product or service. Consequently, further reductions in emissions—in addition to those of a firm's own operations—can be achieved by joint effort of multiple parties in a supply chain through collaboration, coordination, or information sharing. This brings in also additional cost-saving opportunities. The CDP 2015 supply chain report notes that companies that engage with one or more of their suppliers, consumers, or other partners are more than twice as likely to see a financial return from their emission reduction investments and almost twice as likely to reduce emissions, as those who do not engage with their value chain (CDP 2015). Nevertheless, when a number of firms jointly affect total emissions, they face a critical and nontrivial challenge in measuring their share of the responsibility for emissions (or that of the emission reductions): How should the emissions be allocated to the various value chains, organizations, final products, or services? The CDP 2011 supply chain report found that 86 % of respondents have a collaborative process in place to jointly reduce carbon footprints with suppliers (up from 49 % the year before), but suppliers face difficulties in allocating their emissions to their multiple customers (CDP 2011).

In the LCA and carbon footprinting literatures, various guidelines exist on how to allocate shared emissions. A common attribute in those guidelines—including that of the GHG Protocol covered in this section—is that the sum of the allocated emissions for each output of a system should equal 100 % of emissions from the system. Given that LCA is aimed at making product and process design decisions based on an accurate inventory of environmental impacts, it is natural that the LCA literature seeks to avoid over-allocation, i.e., "double counting," of impacts (see, e.g., Lenzen 2008). Similarly, in trading schemes, avoiding double counting of GHG emissions is crucial due to the financial consequences involved. More recently the LCA literature has started investigating how to reconcile allocating responsibility for impacts while avoiding double counting. Lenzen et al. (2007), building on Gallego and Lenzen (2005), propose a scheme by which producers and consumers share responsibility for emissions in such a way that adding total emissions across all producers and consumers yields the correct economy-wide emissions. Nevertheless, Caro et al. (2013) argue that whenever emissions (or reduction in emissions) result from multiple parties, double counting is necessary to induce the optimal level of abatement effort among the supply chain members. Accordingly, even if the true social cost of carbon emissions is internalized (e.g., by applying a carbon tax to all supply chain members), the abatement efforts implemented would be less than the optimal level when double counting is avoided. Even in the absence of an optimal allocation rule (which would require double counting), firms with an interest in overall supply chain efficiency should at a minimum include the full cost of all GHG emissions that they can influence when they decide where to focus their efforts. The fact that double counting is unlikely to be implemented on a large scale in practice should not preclude firms from identifying where their efforts may have the greatest effect. If the greatest return on firm 1's effort is on emissions currently allocated to firm 2, then firm 1 could explore mechanisms to share the costs and benefits of reducing emissions with firm 2. Without at least allowing double counting in a pro forma fashion, many valuable opportunities for joint improvement will go unexploited.

3.4 Discussion

This section discusses several issues related to supply chain carbon footprinting. We first introduce the challenges related to gathering information necessary to calculate a carbon footprint. Second, we discuss the issue of accuracy. Third, we highlight the need to extend the horizon of sustainable supply chains beyond carbon emissions.

3.4.1 How to Get Information in Practice?

The amount of data required to calculate the carbon footprint of a company is substantial, and the data are often difficult to gather, especially when performing a value chain carbon footprint. For instance, when Fujitsu carried out a carbon footprint analysis on its desktop PC and servers to show customers its product's superiority through reduced carbon emissions, it faced some challenges to gather data in the use and disposal phases and had to make numerous assumptions to be able to conduct a cradle-to-grave LCA (Vasan et al. 2014).

Even when the data exist, most companies are not organized to systematically and automatically collect these data, although ERP systems are progressively including information on carbon footprint and other sustainability metrics. In this regard, SAP, IBM, SAS, and other software vendors have built tools to extract energy data from supply chain procurement systems (O'Rourke 2014). Some companies have also developed their own software. For instance, in the energy sector, an Excel-based data management information system called SANGEA™ Energy and Greenhouse Gas Emissions Estimating System has been implemented by Chevron Corporation in 2002 to gather carbon emissions and energy usage data from energy operations (exploration and production, refining and marketing, petrochemicals, transportation, electricity generation, manufacturing, real estate, and coal activities) at its facilities worldwide. The company used the software to compile its first corporate-wide carbon inventory (Chevron 2002). SANGEA™ streamlines corporate-level data consolidation by allowing the inventory coordinator at each facility to configure a spreadsheet, enter monthly data, and send quarterly reports to a centralized database (WRI and WBCSD 2004). The software, which was available free of charge for other companies in the oil and gas sector, has been donated to the American Petroleum Institute (API). More recently, Chevron developed in 2009 its GHG and Energy Reporting System CGERS™ to align with existing and emerging regulatory requirements (Chevron 2009). In 2010, the company completed enterprise-wide deployment of the software and improved it in 2012 by incorporating mechanisms to facilitate electronic reporting to the US Environmental Protection Agency (CDP 2013b).

However, currently most companies need to manually combine data from disparate sources to compile the carbon footprint, often in spreadsheets. As data collection and compilation is not standardized, the process is reiterated every year. This is often a time-consuming task, subject to errors and/or approximations. Thus, DEFRA (2009) recommends that companies include carbon emissions reporting into existing reporting tools and processes of the organization. Interface, Inc., the world's largest manufacturer of carpet tiles, has developed an environmental data system based on its corporate financial data reporting. This system provides activity and material flow data from the company's business units (the USA, Canada, Australia, Europe, etc.) and metrics (the Interface's EcoMetrics) for measuring progress on environmental issues including carbon emissions. The data are reported to a central database each quarter and made available for establishing Interface's annual inventory and enabling data comparison over time (WRI and WBCSD 2004).

The manual, time-consuming compilation of data from separate sources also causes a transparency issue. Indeed, it is very hard to keep all the calculations transparent and it is quite easy to introduce mistakes. Several organizations propose expertise and data to support companies in the process of carbon footprint measurement. For instance, in the transportation sector, DHL, through its GREEN SERVICES portfolio, offers a suite of tools such as Track and Trace, Carbon Report, and Carbon Dashboard to assist companies in reporting their carbon emissions and identifying reduction opportunities. The Carbon Dashboard (a web-based version of the Carbon Report) allows companies to access statistics on the carbon emissions generated by the transport of their freight, and based on this information, they can consider scenarios to reduce their carbon footprint.[8]

Some other organizations have also developed carbon footprint certification programs to enable companies to report a verified carbon footprint. For example, DHL states that the reporting methodologies and calculation tools used in its express and air, ocean, and road freight divisions have been verified by the Swiss-based Société Générale de Surveillance (SGS) since 2011 (DHL 2015). However, even third-party audits may miss errors by focusing more on whether correct conversion factors were used than on whether the input data are correct and complete. The question of how to collect and organize verifiable information in an efficient way, without having to redo it every year, is of crucial importance for companies and deserves particular attention.

3.4.2 How Accurate Is Accurate Enough?

Carbon footprinting is always associated with a certain level of uncertainty. More particularly, as Scope 3 covers activities that are not under the reporting company's ownership or control, companies are likely to face additional challenges that contribute to uncertainty in Scope 3 accounting (WRI and WBCSD 2011a). Lee (2011) reports that one senior manager from HMC stated: "we had some difficulties in terms of scopes and measurement of carbon footprint. In our case, Scope 1 and 2 carbon footprint measurements are completed with over 95 % confidence. But Scope 3 CO_2 measurement is still limited with regard to the supply chain network. We should explore further feasible methods and practices to track CO_2 emissions from the supply chain."

Uncertainties related to carbon inventories can be categorized into scientific uncertainty and estimation uncertainty (WRI and WBCSD 2004). Scientific uncertainty arises when the science of the actual emission is not completely understood. For example, many direct and indirect factors associated with GWP values involve significant scientific uncertainty (IPCC 2000). The evolution of the 100-year GWP of methane from 21 in the second IPCC report in 2005 (see Table 3.2) to 28 in the fifth IPCC report in 2013 (see Table 3.1) is an example of scientific uncertainty. Analyzing and quantifying scientific uncertainty is challenging and best addressed by the scientific community rather than by companies (IPCC 2000).

Estimation uncertainty occurs any time carbon emissions are quantified. Therefore each carbon footprint is associated with estimation uncertainty. Estimation uncertainty can be further classified into two types: model uncertainty and parameter

[8] See for instance http://www.dhl.com/en/logistics/green_logistics_solutions.html, last accessed December 2, 2015.

uncertainty (IPCC 2000). Model uncertainty occurs when the emissions are not directly measured (i.e., under energy-based calculations, activity-based calculations, and EIO-LCA). In this case, a model translates a given input into a certain amount of carbon emissions. The way this translation is handled is subject to uncertainty referred to as model uncertainty. For instance, estimating emissions from truck transportation under an energy-based calculation methodology would lead to uncertainty in the precise amount of carbon emissions released by the motor, as this depends on the quality of the combustion and thus on the operating conditions of the vehicle.

Parameter uncertainty refers to the uncertainty associated with quantifying the parameters used as inputs into estimation models (IPCC 2000), for instance, the amount of fuel consumed by the truck.

Given that uncertainty is an intrinsic part of any carbon footprint assessment, an immediate question is what level of uncertainty is acceptable. On the one hand, high-quality information has greater value and more uses, and even if a company does not anticipate future regulatory mechanisms, internal and external stakeholders may demand high-quality inventory information (WRI and WBCSD 2004). On the other hand, in the context of carbon emission regulations, low-quality information may have little or no value and may even incur penalties. Defining the level of accuracy depends on the carbon footprinting analysis objective, as well as on the capability of the company. However, this decision may greatly influence the estimated carbon footprint of a company. This decision is referred to as the application of a cutoff threshold in the LCA literature.

Once the desired level of accuracy has been determined, the next question is how to report uncertainties in carbon footprints. Given that only parameter uncertainties are within the feasible scope of most companies, uncertainty estimates for carbon inventories will necessarily be imperfect (IPCC 2000). Parameter uncertainties can be evaluated through statistical analysis, measurement equipment precision determinations, and expert judgment (IPCC 2000). Statistical analysis may be difficult due to a lack of complete and robust sample data. Most of the time, a single data point is available (e.g., liters of fuel for truck transportation). In case the data is obtained from an instrument, precision and/or calibration information may be used. However, IPCC (2000) states that expert judgment is often the only possibility for companies. Experts can either be the source of the necessary data, or they can help identify and explain uncertainties. The problem with expert judgment is that it is difficult to obtain in a comparable and consistent manner across parameters, source categories, or companies (WRI and WBCSD 2004).

The GHG Protocol Corporate Standard has developed a supplementary guidance document on uncertainty assessments along with an uncertainty calculation tool (WRI and WBCSD 2011b). The guidance document describes how to use the calculation tool in aggregating uncertainties. It also discusses in more depth different types of uncertainties, the limitations of quantitative uncertainty assessment, and how uncertainty estimates should be properly interpreted. Additional guidance and information on assessing uncertainty can also be found in EPA (1999) and in IPCC (2000).

3.4.3 How to Extend the Horizons Beyond Carbon?

We highlighted in Sect. 3.1.2 some of the reasons explaining why there is nowadays a strong focus on carbon emissions. However, sustainability cannot be reduced to carbon emissions. For example, water scarcity, its quality, and the regulations affecting it are a growing business problem (The Economist 2014). Other environmental dimensions of sustainability as well as social impacts should not be overlooked because of too much focus on carbon emissions. We refer to Chap. 4 by Hoekstra (2017) for more on water footprinting, to Chap. 5 by Blass et al. (2017) for more on managing nonrenewable materials, and to Chaps. 20 and 21 by Lee and Rammohan (2017) and Sodhi and Tang (2017) for more on socially responsible supply chains.

The strong current focus on carbon emissions may be an opportunity for other environmental indicators to be developed and adopted, in the sense that platforms and accumulated experience related to carbon footprinting can be beneficial. For example, once acquainted with environmental reporting through carbon emissions, a company may be more prone and able to develop an overall sustainability assessment. This trend is also reflected by CDP's commitment to use the experience and reputation obtained from carbon footprinting to develop new initiatives related to water use and forest management.

One important observation here is that the capability developed through carbon footprinting may not necessarily be directly transposed to other sustainability aspects. Indeed, companies, non-governmental organizations, and governments need to take into account that the other sustainability aspects might have different characteristics than carbon emissions. For example, location and timing play a major role in water footprinting, but not in carbon footprinting. Extending the capabilities being built up for carbon footprinting to other dimensions of sustainability presents an exciting opportunity but one that should be approached thoughtfully.

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