Sustainable manufacturing practices: A systematic analysis and guideline for assessing the industrial Product Carbon Footprint

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Benjamin Gutwald
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
benjamin.gutwald@faps.fau.de

Nicolas Baumann
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
nicolas.nico.baumann@fau.de

Felix Funk
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
felix.funk@faps.fau.de

Tobias Reichenstein
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
tobias.reichenstein@faps.fau.de

Baris Albayrak
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
baris.albayrak@faps.fau.de

Jörg Franke
Institute for Factory Automation and Production Systems (FAPS)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Erlangen, Germany
joerg.franke@faps.fau.de

***Abstract*— Climate protection has gained significant political and social relevance in the corporate sphere. On the one hand, industry bears a special responsibility towards reducing greenhouse gas (GHG) emissions. On the other hand, adopting sustainable practices presents multiple economic opportunities that surpass mere image and efficiency factors. In various industries, the carbon emissions associated with specific products are becoming a crucial factor in purchasing decisions. One example is the automotive industry, where original equipment manufacturers (OEMs) are increasingly looking to track and manage the carbon footprint of their products throughout the supply chain. Moreover, regulatory requirements obligate companies to measure their products' GHG emissions. This includes the EU's Battery Passport Initiative. From 2026, all batteries installed in electric vehicles must provide basic sustainability-related information, including transparent documentation of their carbon footprint. This shows that the Product Carbon Footprint (PCF) has become a crucial business indicator, increasingly influenced by Life Cycle Assessment (LCA) methodologies. However, obstacles remain with data collection and GHG emission accounting. Comprehensive standards and guidelines exist for the quantitative determination and reporting of GHG emissions. Nonetheless, quantifying the PCF presents challenges for many companies. This is due to high complexity, insufficient data as well as diverse methodologies and the lack of a mandatory standard. Hence, a valid comparison of the results is not always feasible. This publication provides a survey and classification of various standards and software-based solutions for calculating the PCF, integrating LCA principles. The analysis' requirements profile is shaped by international regulations, economic, and political trends. To tackle the primary challenges in PCF determination, essential research trends and solutions are compiled based on a literature review. The final outcomes are presented in the form of a practical guide, assisting users in measuring, and communicating product specific GHG emissions in manufacturing throughout the supply chain.**

Keywords*— Carbon Footprint, PCF, Life Cycle Assessment, ISO 14067, Greenhouse Gas Protocol, Sustainable manufacturing

I. Introduction and Motivation

Global warming, which is significantly driven by emissions of greenhouse gases (GHG), poses a worldwide threat with potentially severe consequences such as an increase in extreme weather events and rising sea levels [1], [2]. Due to its political and social significance, climate protection has become increasingly relevant in the business context, driven by the goals of the Paris Agreement [3]. The industrial sector is a major contributor to GHG emissions. Hence, it holds significant ecological responsibility while also having considerable potential to contribute to climate change mitigation [4], [5]. Companies face growing pressure for decarbonization, particularly within the automotive sector [5]. Implementing environmentally sustainable practices also presents various economic opportunities [6]. In this context, the carbon footprint (CF) has emerged as an indicator of the environmental sustainability of products, processes and companies [7]. The product carbon footprint (PCF) refers to the total amount of GHG emissions, typically measured in carbon dioxide equivalents (CO_2e), associated with a product, derived from a life cycle assessment (LCA) [8]. Therefore, several scholars [2], [9], [10] consider the PCF as an LCA with a limited scope, focusing solely on climate change as the only impact category without considering other environmental issues [2], [8]–[10]. Although the PCF does not allow for a holistic assessment of a product's environmental impacts like an LCA does, it is currently the focus of many industry efforts. Public perception places great importance on GHG emissions. Furthermore, the PCF provides a clear and quantifiable measure of an environmental parameter, which is easily understandable and allows for comparability, even for non-experts. This quality enhances its suitability as a marketing tool, particularly for product labeling. [2], [7], [10], [11]

Not only market demands, but also regulatory requirements are forcing companies to be able to demonstrate the CF of their products to external stakeholders. For instance, the EU Battery Passport will mandate transparent documentation of the CF of all batteries installed in electric vehicles from 2026 [10] [11].

Compared to other stages of the life cycle, manufacturing provides a direct opportunity to reduce GHG emissions as it significantly affects the climate impact of a product. Plus, reporting companies can exert direct influence in mitigating this impact, for example by using renewable energies efficiently [14]. Ideally, a technology comparison should already be carried out during the planning phase of production plants in order to ensure energy efficiency [15].

PCF is gaining prominence not only in a business context but also in scientific spheres [16]. Although accounting for product-related GHG emissions is highly relevant both practically and academically, many companies, particularly small and medium-sized enterprises (SME), face challenges in implementing specific assessment practices. This is due to various factors, including the complexity and lack of transparency of various assessment guidelines, the high level of manual calculation required, and the inadequate availability and quality of emissions-related data [17]–[22]. Studies have shown that companies do not continuously and systematically collect data to calculate and analyze environmental and climate impacts throughout the company [23]. These factors often lead to inconsistencies and make it difficult to compare results between organizations [21].

The complexity and inaccuracy of PCF calculations contradict the goal of creating an easy-to-understand and unambiguous ecological indicator. Simultaneously, there is growing external pressure on companies to determine the CF of their products. This research aims to provide practical solutions to overcome these challenges and present them as a guideline for determining the PCF during the manufacturing stage. This will assist users in calculating the GHG emissions of products to meet their stakeholders' demands adequately and identify opportunities for improving environmental sustainability.

II. Preparation for the PCF determination

Before conducting a PCF study, several issues need to be addressed. This includes estimating the costs and time required for the analysis, selecting a suitable standard and software, all in accordance with the main goal and the product system, which is to be reviewed.

A. *Choosing an appropriate reporting standard*

One major criticism of the PCF is the lack of a mandatory standard. Although there are various guidelines, none of them is legally binding [24]. Furthermore, there are diverse country-specific conventions. However, national approaches are not suitable as a reference for the standardized assessment of a product's climate impact. Comprehensive standardization of methodologies can only be achieved through internationally agreed standards and norms [25]. For this reason, only the most important and internationally recognized guidelines for calculating the PCF will be examined in the following section. These include PAS 2050 [26], GHG Product Standard [27] and ISO 14067 [8]. All of these guidelines are based on ISO 14040 and 14044, which are the main norms for LCA. Although there are overlaps in terms of their basic methodology, they differ in some key aspects. Consequently, various scholars have analyzed their similarities and differences. Liu et al. [28] analyze several carbon labels and their underlying standards. The authors emphasize the specific characteristics of each of the three aforementioned norms and compare them with each other. Lewandowski et al. [24] provide a summary of their overlaps and variations with respect to several aspects. Hottenroth et al. [21] present an overview of the most widely used PCF standards as part of their practical guideline for SME. Wang et al. [25] and Garcia and Freire [26] conducted case studies on the PCF of fiberboards and particleboards, respectively, to demonstrate how the selection of a specific norm affects the calculation results. They explain the variations by highlighting the differences between the three guidelines. Table I summarizes the characteristics of the three standards based on relevant criteria, supporting companies in selecting the most appropriate one for their specific context.

TABLE I. Comparison of the three most widely used PCF standards [8] [26] [27]

	PAS 2050	**GHG Product Standard**	**ISO 14067**
Scope	Assessment	Assessment, reporting (and communication)	Assessment, reporting, and communication
Inventory scope	Cradle-to-Gate Cradle-to-Grave	Cradle-to-Gate Cradle-to-Grave	Partial lifecycle Cradle-to-Gate Cradle-to-Grave
Cut-off criteria	Exclusion if <1%; 95% of total emissions must be considered	No specific criteria (ideally 100% completeness); Insignificant processes may be excluded if no data is available	Insignificant material and energy flows can be excluded (mandatory disclosure)
Capital goods	Excluded	Should be considered if relevant	Excluded if not significant to the overall conclusion
Data quality	Primary data for owned/controlled processes; Primary data from suppliers (>10% of total emissions)	Primary data for owned/controlled processes	Site specific (primary) data for financially or operationally controlled processes
Carbon offsetting	Excluded	Excluded	Excluded
Product Category Rules	Sector/product rules in Supplementary Requirements	Product Rules for comparison	Product Category Rules (ISO/TS 14025 and 14027)
Allocation	1. Avoiding allocation 2. Supplementary Requirements 3. Economic allocation	1. Avoiding allocation 2. Physical allocation 3. Economic allocation or other method	

ISO 14067 is a more general standard, while PAS 2050 and the GHG Product Standard have more detailed requirements, leaving less room for interpretation. ISO 14067, which is the latest standard, can be regarded as an all-rounder and can serve as a sound basis if there are no legal requirements for the use of a specific norm. Plus, its results can easily be transferred to a more comprehensive LCA study in accordance with ISO 14044. If ISO 14067 does not provide enough detail for practical application, the GHG Product Standard can be considered for further guidance. However, the choice of a suitable standard depends on the purpose and geographic scope of the PCF study. It is important to consider internal guidelines, corporate strategy, industry initiatives as well as product-specific and legal regulations. [29]

One of ISO 14067's strengths lies in providing specific requirements for the transparent presentation of results within a report, which encompasses all essential information about the assessment of the PCF. When used in combination with other ISO norms, such as ISO 14026 and ISO 14071 it provides additional guidance for communicating and critically reviewing the PCF study. If a company intends to assess and communicate a partial PCF, representing the GHG emissions of one or more selected processes or life cycle stages within a product system, this can only be accomplished within the framework of ISO 14067. If the PCF study is conducted for internal use only, primarily focusing on the identification of main emission sources and assessing reduction potentials, companies have the flexibility to choose the standard, which aligns best with their needs. However, the GHG Product Standard might suit best for this undertaking, as it provides extensive support in this context. Another argument in favor of using the GHG Product Standard is its alignment with the GHG Protocol Corporate Accounting and Reporting Standard. This makes it easier for organizations already familiar with this standard in the context of a corporate-level GHG emissions inventory. [24]

In essence, all three guidelines are suitable for identifying major emission sources in manufacturing and deriving reduction targets. However, differences in calculation criteria can lead to varying results. This presents challenges, particularly in terms of external communication, due to a lack of comparability. Particularly ISO 14067, along with other guidelines from the ISO 14000 family as well as the GHG Product Standard provide specifications for communicating the results and thus help to establish a consistent and transparent basis. In addition to established standards, the Pathfinder Framework by the WBCSD offers a set of guidelines designed to promote consistency and transparency in PCR calculations [30]. However, a universally valid benchmark is still required to account for discrepancies in calculation methods, facilitating a transparent comparison of results across different PCF studies.

B. *Selecting suitable software tools*

Basically, PCF calculation can be done using standard spreadsheet software. However, technical tools are often necessary due to the large amount of data, which needs to be processed. Relevant software tools are useful for conducting LCA through standardized procedures, enabling the integration of LCA databases and visualizing results for easier interpretation. Unfortunately, using such applications is often associated with software training and licensing costs. [10]

LCA software simplifies PCF assessment by reducing complexity and manual calculations as well as streamlining data collection. Given the variety of software tools, the following chapter helps companies to find a suitable solution. Firstly, it provides an overview of selected applications. Secondly, it compares the four most popular LCA software tools with each other. Kiemel et al. [10] present methods and tools to enhance the practicality of LCA. They provide an overview of commonly used LCA and PCF software and databases, forming the basis for the selection of the software presented below. For reasons of clarity, the collection of applications displayed by Kiemel et al. [10], has been narrowed down based on the tools' relevance for this guideline. Moreover, additional software solutions have been added to list based on personal knowledge. Plus, further information, regarding applicable standards, accessibility, and pricing, was gathered from the respective providers' websites. The selection of applications was made without any bias towards specific developers, resulting in a list of cross-industry software solutions. Table II comprises the most commonly used LCA software tools [31]–[34], such as GaBi [35], openLCA [36], SimaPro [37] Umberto [38], as well as other LCA and PCF applications like CCalC [39], Ecodesign Studio [40], and FRED [41]. Additionally, it encompasses alternative software concepts such as Ecochain Mobius [42], SiGREEN [43], and SAP Sustainability Footprint Management (SAP-SFM) [44]. While Ecochain Mobius is specifically designed for users with limited LCA experience [42], SiGREEN and SAP-SFM do not represent conventional LCA tools as such. Instead, they take a comprehensive approach for capturing and managing product-related GHG emissions across the entire value chain [43], [44].

Due to the contextual relationship between both concepts, LCA software can obviously be used for PCF calculation, especially when a thorough and detailed analysis is required. However, in some cases, LCA tools may offer an abundance of features, making them too complex for simpler PCF assessments. In such cases, dedicated PCF tools may be more suitable, serving as a less comprehensive and more cost-effective alternative. Nevertheless, purchasing more extensive LCA software may be appropriate if other impact categories are to be included in future studies. [25]

TABLE II. OVERVIEW OF VARIOUS LCA AND PCF SOFTWARE

Software	Type	Access Mode	ISO 14040	ISO 14067	GHG	PAS 2050	Pricing
CCaLC	PCF	Software	x			x	Free
Ecochain Mobius	LCA	Software	x				Paid
Ecodesign Studio	LCA	Browser/Software	x				Paid
FRED	PCF	Browser		x	x		Paid
GaBi	LCA	Software	x	x	x	x	Paid
openLCA	LCA	Software	x				Free
SiGREEN	PCF	SaaS		x	x		Free
SimaPro	LCA	Software	x	x	x	x	Paid
SAP SFM	PCF	SaaS	Not specified				Paid
Umberto	LCA	Software	x	x	x	x	Paid

GHG = GHG Product Standard
SFM = Sustainability Footprint Manager

The applications listed in Table II differ from each other in terms of various features. Table III compares the four most popular LCA software tools based on different aspects, rating them on a scale from '++' to '- -' in relation to certain criteria. For a transparent assessment of the selected applications, existing publications have been consulted and complemented by information published by the providers of the software. Several studies compare the most commonly used LCA software, offering a useful overview of their different characteristics [31]–[34]. However, it is important to consider their publication year due to the dynamic nature of the software sector. Therefore, the results shown in Table III mainly draw on the analysis from Su et al. [31], which represents the latest publication in this context.

TABLE III. COMPARISON OF COMMON LCA SOFTWARE TOOLS

	GaBi	openLCA	SimaPro	Umberto
Suitability for PCF	++	+	++	++
Size and flexibility of the database	++	++	++	+
Presentation and visualization of results	+	+	++	+
License fee	o	++	o	o
Product lifecycle definition	++	+	+	++

+ + Represents excellent performance
+ Indicates above-average qualities
o Represents a neutral position or lack of information
- Indicates below-average qualities
- - Represents poor performance

The differences in the rating are derived as follows:

- Suitability for PCF: GaBi, SimaPro, and Umberto explicitly facilitate PCF calculation according to established guidelines, while openLCA, as an LCA tool, inherently allows for PCF assessment but lacks specific information on supported PCF standards (see Table II).
- Size and flexibility of the database: Each application integrates extensive databases. However, Umberto does not allow for data adaptation and expansion.
- Presentation and visualization of results: All four applications provide similarly extensive and detailed presentation of results, with SimaPro offering slightly better visualization of product comparisons.
- License fee: Comparing software fees is difficult due to partially undisclosed pricing information and varying package offerings. However, openLCA, being a free open-source application, holds an advantage (see Table II).
- Product lifecycle definition: This aspect only applies to the modelling of the product lifecycle and unit processes. GaBi and Umberto stand out for their ability to provide an intuitive visualization of the lifecycle through their graphical user interface.

The examined software solutions have different strengths and weaknesses. To make an optimal selection, individual usage requirements must be taken into account. It is important to note that particularly the evaluation of the product lifecycle definition and the presentation of results can vary depending on subjective perception. GaBi, SimaPro, and Umberto offer (partially) time-limited free trial versions, which allow users to test functionalities and user interfaces themselves. This can be helpful in the decision-making process.

III. ASSESSING THE PCF

The process of conducting a PCF study following ISO 14067 is similar to preparing an LCA in accordance with ISO 14044. Both involve the following four main phases: defining the study's goal and scope, conducting a life cycle inventory analysis, performing an impact assessment, and interpreting the results [8], [45]. These phases are further subdivided into smaller steps. While it is crucial to have a comprehensive understanding of the entire process, this analysis does not delve into every individual step. Instead, it focuses on the two key phases illustrated in Fig. 1: defining the scope of the study and determining the PCF.

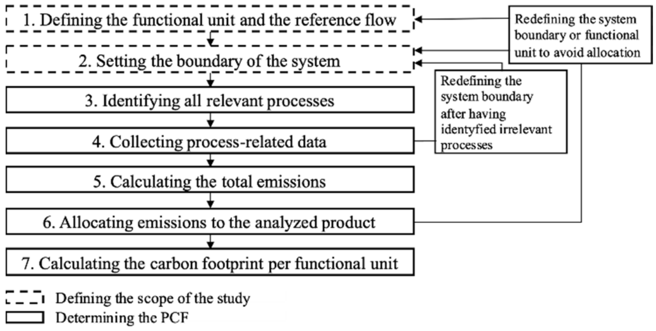

Fig. 1. Crucial steps for assessing the PCF (based on [8], [45])

The first section encompasses the definition of the functional unit and the reference flow, as well as the establishment of the system boundary. The second section encompasses both inventory analysis and impact assessment. While the individual steps are carried out sequentially, they can influence each other retrospectively, requiring adjustments of previous phases. This iterative approach enables continuous improvement of the study in terms of consistency, comprehensiveness, and accuracy. [8], [45], [46]

A. *Defining the scope of the study*

The concept of the functional unit is central to LCA and is also utilized in the context of PCF. It serves as a standardized reference, to which all inputs and outputs of the product system refer. According to ISO 14067, the functional unit is defined as the "quantified performance of a product system […] for use as a reference unit" [8, p. 23]. Determining the PCF based on the functional unit is particularly relevant when comparing the climate impact of different products [8]. The aim is to compare systems with similar performance rather than the products themselves. This approach allows for the consideration of relevant criteria such as differences in quality, performance, and product lifespan [8], [25], [27]. In the context of battery technology, the cumulative energy storage capacity over the lifespan may be an appropriate functional unit. This metric proves to be a more precise indicator for evaluating and comparing different batteries than the absolute storage capacity listed in datasheets. This is because it captures various technological differences, service life parameters, and performance specifications. Currently, manufacturing companies and standardization bodies are working to define such a standardized functional unit as part of the Battery Passport Initiative to enable consistent and comparable assessment of battery performance in the automotive sector. [47]

The definition of the functional unit is followed by the definition of the associated reference flow, both of which must be documented and communicated in the PCF study report according to ISO 14067. The reference flow is defined as the "measure of the inputs to or outputs from processes […] in a given product system […] required to fulfil the function expressed by the functional unit" [8, p. 24]. In essence, the reference flow represents the quantity of a product necessary to meet the function specified by the functional unit [25], [48]. Referring to the battery example mentioned above, a suitable reference flow would be the precise quantity and type of a battery required to match the defined cumulative energy storage capacity over the lifespan.

The system boundary represents the interface between the product system under consideration and its environment. It is where the exchange of inputs and outputs, in the form of materials and emissions, occurs. The system boundary is defined according to the objective of the PCF study. It determines which unit processes are included in the analysis and how detailed they are examined. A unit process is defined as the "smallest element considered in the life cycle inventory analysis […] for which input and output data are quantified" [8, p. 23]. It can either represent a specific manufacturing operation or general activities, such as logistics processes. The system boundary is defined based on various criteria, which must be described and explained in a clear and comprehensible manner. These criteria depend significantly on the selected guideline and the cut-off criteria defined therein (see Table I), as they outline which processes, inputs, and outputs should be considered in the inventory. For instance, individual life cycle stages may be intentionally excluded or omitted due to practical reasons. It is essential to transparently describe all decisions regarding the exclusion of specific processes, inputs, and outputs and explain their consequences. In some cases, it may be necessary to adjust the system boundary retrospectively in response to new circumstances, which arise during the course of the study. [8], [25], [45]

B. Determining the PCF

This chapter follows the approach by Kaur et al. [20] for determining the PCF, which is based on the GHG Product standard, but is also compatible with ISO 14067:

1. Identifying all relevant processes
2. Collecting process-related (primary) data
3. PCF calculation: evaluation of the total emissions based on emission factors and allocation to the specific product.

Identifying relevant processes via process flow diagram

Collecting emission-relevant data is usually a resource-intensive task, depending on the complexity of the product system and the defined system boundaries. A useful tool for visualizing the system and estimating the data needs is a process flow diagram, including the system boundary and all unit processes across the entire life cycle as well as their interrelations. An example of such a diagram is illustrated in Fig. 2. The LCA software presented in Table II can be used to model such a scheme. The process flow diagram depicts unit processes as boxes, with input and output flows, symbolized by arrows, connecting them with each other or the environment. External inputs and outputs are classified as either elementary flows or product flows. Elementary flows refer to materials or energy, which are directly taken from or released to the environment without previous or subsequent human transformation. Product flows are inputs and outputs, which are obtained from or transferred to other product systems. A process flow diagram additionally illustrates internal flows such as intermediate products or waste, providing a holistic view of the overall system. Even if only specific life cycle stages are to be examined, it is recommended to model the full lifecycle for a comprehensive understanding of the entire product system. This allows for a clear definition of each phase and an adequate consideration of their interactions. [8], [25], [45]

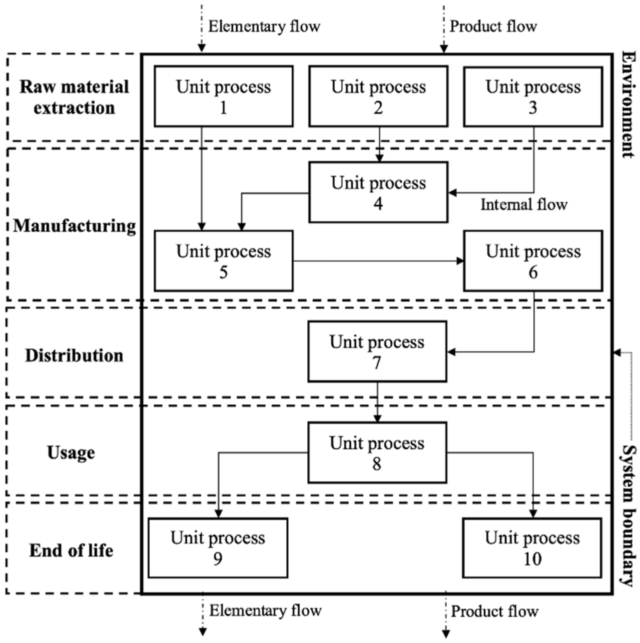

Fig. 2. Generic illustration of a process flow diagram (based on [25], [48])

Collecting process-related data

The following step involves capturing all input and output data associated with each unit process in the system. Input flows usually consist of energy or materials, while output flows include emissions, waste materials, or intermediate products. The scope of each unit process is determined by the availability of data and the desired level of detail. Ideally, a unit process represents an operation, which cannot be further broken down. In case of insufficient data, multiple activities or an entire process chain can be grouped into a single unit. To ensure accuracy in determining the carbon footprint, each unit process should have maximum granularity, covering individual and specific manufacturing processes such as cutting or joining operations. This approach helps to avoid allocation issues, which can arise with larger units. [25]

Machine tools are the primary source of GHG emissions on the shopfloor. However, internal logistics and other ancillary activities also contribute to the overall PCF. GHG emissions in manufacturing are closely linked and therefore often difficult to track separately. The key factors, which influence the PCF are energy, material, and waste flows. Thus, it is necessary to quantify energy and material consumption as well as direct GHG emissions and emissions from waste treatment in order to determine the PCF during the production phase. [49]

Understanding the GHG emissions associated with various manufacturing processes is therefore crucial. Table IV compiles relevant studies, which focus on the energy and material flows of different manufacturing processes in the context of environmental assessment. Although most of these studies do not explicitly target PCF, they offer valuable methods and concepts for internal data collection, providing guidance for companies conducting a PCF study – not only in terms of data collection, but also for other steps such as defining the functional unit and the system boundary. The studies are categorized into six main groups, according to DIN 8580 [50]. The table exclusively contains quantified inputs and outputs from the listed studies. Other material and energy flows, such as the use of solvents and binding agents [51], the generation of waste heat [51], waste or defective products [52], which are mentioned but not included in the calculation assessment, are not included. Furthermore, it should be noted that some studies explicitly exclude certain activities from the calculation, such as the manufacturing and maintenance of machines [53], as well as internal transportation of semi-finished products [52]. The terms 'energy' (E) and 'gases' (G) are used to encompass various representatives of their respective categories. Raw materials and (semi-)finished products are not listed separately for each process, as they are considered standard inputs and outputs, respectively.

TABLE IV. STUDIES ON ENERGY AND MATERIAL FLOWS OF DIFFERENT MANUFACTURING PROCESSES

	Study	Process	Material and energy flows
Primary forming	[54]	Sand casting	E, G
	[51]	Metal injection molding	E
	[55]	Injection molding	E
	[56]	Injection molding	E
	[57]	Selective laser melting	E, process gas, G, aerosols, waste material
	[58]	Selective laser melting	E, process gas, G, waste material
	[57]	Selective laser sintering	E, waste material
	[59]	Stereolithography	E, G, waste material
	[60]	High speed laser directed energy deposition	E, process gas, G, waste material
Forming	[53]	Press braking	E
	[61]	Incremental forming	E
	[52]	Hot Forming	E, die plate, lubricant
	[62]	Hot forming of sheet metal components	E
Cutting/Machining	[63]	CNC-based machining	E, tool wear, chips, cooling lubricant
	[53]	Milling	E
	[64]	Turning	E, chips
	[65]	Turning	E, G
	[66]	Drilling	E, chips, cooling lubricant
	[66]	Laser cutting	E, process gas, G, aerosols
	[67]	Grinding	E, cooling lubricant
	[68]	Grinding	E, tool wear, chips, cooling lubricant
	[69]	Grinding	E, tool wear, chips, abrasive waste
Joining	[70]	Laser beam welding	E, process gas, aerosols
	[71]	Friction stir welding	E
	[72]	Friction stir welding	E
	[71]	Gas metal arc welding	E, process gas, electrode consumption
	[73]	Gas metal arc welding	E, process gas, electrode consumption, G

The studies on conventional processes of primary forming focus on measuring the energy consumption, including electricity and natural gas [54]. In the case of additive manufacturing processes, process gases and waste material are also accounted for as outputs [51], [58], [59]. The case studies on forming processes only assess process inputs. While other authors who deal with sheet metal forming [53], [61], [62] exclusively determine energy consumption, Buis et al. [52] also investigate the use of dies and lubricants in massive forming. When it comes to cutting and machining processes, energy, chips, and cooling lubricants are mainly considered as inputs and outputs. However, some studies also include tool wear [63], [68], [69]. In the case of laser cutting, process gases and emissions (gases, aerosols) are assessed in addition to electrical energy consumption [66]. Besides energy usage, some studies dealing with joining activities include aerosols, process gases, and electrode consumption respectively [70], [71], [73]. In summary, the case studies primarily develop models for predicting energy and resource usage, based on specific process parameters, sometimes combined with measurements of power, time, and material flow rate. However, the overall focus across all case studies is to quantify the energy demand.

Regarding data quality, both the GHG Product Standard and ISO 14067 distinguish between primary and secondary data [8], [27]. Primary data is collected through measurements or detailed calculations based on activities, while secondary data is derived from other sources. The GHG Product Standard further categorizes data into direct emissions data, activity data, and emission factors. Direct emissions data quantifies GHG emissions, which are directly released by a particular process, such as from combustion, other chemical reactions, as well as volatile gases. These can be measured directly on-site using continuous emission monitoring systems or determined using stoichiometric equations and mass balances. Activity data records the physical inputs and outputs of processes or activities, which cause the release of GHG emissions. These data can be modeled, calculated, or measured in terms of various attributes such as energy, mass, volume, distance, or time. Emission factors represent the GHG emissions caused per unit of a specific activity, enabling the conversion of activity data into carbon dioxide equivalents (CO_2e) [27].

Especially for complex manufacturing processes where multiple sources of information need to be accounted for, manual collection of emissions data is very resource intensive. Furthermore, it carries the risk of errors and inconsistencies. Digital tools within the context of Industry 4.0 can facilitate automated and scalable recording of emissions as well as the integration of various data sources. Simulation models and technologies like the digital twin can also help to determine and reduce the carbon footprint in manufacturing footprint [74]–[76]. Simulation-based software solutions can accelerate the engineering process, e.g., for the design of production plants or the electrical network infrastructure by allowing the system to be analyzed for fault and safety-critical aspects while taking economic and environmental considerations into account [77]. These analyses can be conducted at different levels within production systems, from individual components to production lines or networks of factories, using different simulation and modeling paradigms, especially when considering energy aspects [78].

If plant data is unavailable and needs to be collected from scratch, emissions should be estimated beforehand using secondary data. This allows for prioritization in line with the cut-off criteria, which keeps the effort to a manageable level.

Enterprise Resource Planning (ERP) software as well as an established Energy Management System (EMS) can serve as a suitable source for information on process materials, process-related waste, and energy usage, respectively. Ideally, ERP and MES can be directly linked to machine-specific data from the Manufacturing Execution System (MES) to capture material and energy flows in real-time, convert them into CO_2e, and assign them to specific products. [25], [74], [75]

If primary data collection is not feasible or requires disproportionate effort, secondary data from external sources can be used. LCA databases are a useful source of secondary data as they contain activity data and emission factors for various products and processes. LCA software also integrates data from such directories. There are numerous databases available, some with a geographical or industry-specific focus. LCA databases can significantly reduce data collection efforts. However, the wide range of options can make it challenging to select appropriate datasets [10]. Kiemel et al. provide an overview of some common LCA databases. Table V presents a shortened version of their list, focusing on those databases, which are relevant for this research and integrate the highest number of datasets.

TABLE V. OVERVIEW OF SEVERAL LCA DATABASES

Database	Number of datasets	Sector	Region
ecoinvent	18.000+	Generic	Worldwide
GaBi	15.000+	Generic	Worldwide
cm.chemicals	10.000+	Chemicals, plastics	Worldwide
ProBas	8.000+	Generic	Worldwide
US LCI Public	6.000+	Generic	USA

Additionally, LCA databases can be found in the Global LCA Data Access Network (GLAD), which is one of the largest database directories currently available. The European Platform on LCA also maintains a directory containing datasets from various providers [79]. As part of openLCA Nexus, GreenDelta provides a list of databases, which can be used in combination with openLCA [80].

Calculating the total emissions

After collecting all relevant data for each unit process, the corresponding energy and material flows are assessed in terms of their climate impact. To do so, they must be converted into a common unit. On-site direct emissions data only need to be converted if they were not measured in the form of carbon emissions. In these cases, they must be transformed into CO_2e using the GWP factor of the respective GHG [25]:

$$E = D \cdot GWP \tag{1}$$

E	Emissions in kg CO_2e
D	Direct emissions in kg THG
GWP	Global warming potential in kg CO_2e/kg GHG

Emission factors enable the standardized and efficient conversion of activity data into GHG emissions or CO_2e. They indicate the amount of GHG emissions emitted by a specific process in relation to a suitable reference value. By multiplying activity data by the corresponding emission factors, the GHG emissions of the input and output flows of this specific process can be determined [25]:

$$E = A_i \cdot EF_i \cdot GWP \tag{2}$$

E	Emissions in kg CO_2e
A_i	Activity data in i units
EF_i	Emission factor in kg CO_2e per i unit
i	Energy, mass, volume, distance, or time, …
GWP	Global warming potential in kg CO_2e/kg GHG

Emission factors can be obtained from LCA databases. The availability of precise emissions data varies depending on the sector and region. However, the standard LCA databases can effectively cover many industrial processes. The use of emission factors may result in inaccuracies in certain circumstances, particularly if the process' specific conditions deviate significantly from the assumptions on which the emission factor is based. Therefore, emission factors should accurately reflect the underlying conditions of the process under consideration.

Allocating emissions

In production, different products often emerge from the same process or are handled together. Therefore, process-related inputs and outputs, along with the resulting GHG emissions, must be allocated accordingly. However, this can be challenging, since it is not always possible to establish a causal attribution based solely on objective, scientific-technical criteria. If one of the outgoing products is waste rather than a commodity, then all inputs and outputs, as well as the associated emissions, are attributed to the main product, making allocation obsolete in any case. If the process being considered generates two or more products in a commercial sense, both ISO 14067 and the GHG Product Standard suggest the following approach [8], [25], [27]:

1. Avoidance of allocation through process subdivision, redefinition of the functional unit, or system extension
2. Allocation based on physical relationships (e.g., mass or volume)
3. Allocation based on economic value.

To enhance the accuracy of the PCF study and avoid allocation issues, it is recommended to select small unit processes, which represent indivisible process steps Therefore, it is crucial to assess whether the process being considered can be divided into smaller sub-processes, each of which can be assigned precisely to one product to prevent allocation. Another way to avoid allocation is to redefine the functional unit or expand the system boundaries so that the analyzed product includes the functions of the by-product as well. If neither of these options is feasible, emissions must be attributed based on the physical relationship between the products or their economic value, respectively.

Calculating the PCF per functional unit

Eventually, the total amount of carbon emissions is assessed by adding up all GHG emissions of the relevant unit processes. It is crucial to ensure that all emissions relate to the specified reference flow to ensure that the PCF refers to the defined functional unit.

IV. Conclusion and Outlook

Despite PCF's growing relevance, many companies, particularly smaller ones, face challenges in implementing carbon assessment practices at the product level. This guideline addresses these challenges by providing a systematic analysis and guidance for determining the PCF within the context of sustainable manufacturing practices. By means of a literature-based approach this practical guide covers crucial elements such as choosing an appropriate reporting standard, selecting suitable software tools, and collecting process-related data. It focuses on two central issues. It outlines the process of a PCF study, providing a structured step-by-step guide for practical implementation and presents solutions to specific challenges, which may occur within the respective phases.

The comparison of three common PCF standards, PAS 2050, the GHG Product Standard, and ISO 14067, sheds light on their similarities and differences, aiding companies in choosing the most appropriate one for their specific circumstances and objectives. When selecting a standard, it is crucial to consider various factors such as the study's purpose, internal policies, legal regulations, industry-specific initiatives, and the geographical scope. While ISO 14067 offers a flexible, broad approach, PAS 2050 and the GHG Product Standard provide more detailed requirements. ISO 14067 serves as a versatile option, especially in the absence of specific regulatory requirements. Additionally, its results can be seamlessly integrated into a more comprehensive LCA in accordance with ISO 14044. ISO 14067 excels in providing clear requirements for transparent reporting also in the context of a partial PCF. Where ISO 14067 lacks practical applicability, the GHG Product Standard can provide additional guidance. With focus on internal use, all three guidelines are suitable for determining the PCF in production. However, the GHG Product Standard offers comprehensive guidance on identifying reduction potentials. PAS 2050, the GHG Product Standard and ISO 14067 can complement each other due to methodological overlaps. However, despite efforts towards standardization, there are methodological variations in the examined approaches, which must be carefully considered when interpreting results.

LCA software helps to tackle the complexity of PCF assessment by reducing manual calculation efforts and easing data collection, improving the efficiency of CF analysis. Therefore, this guideline provides an overview of various LCA software and databases, as well as a qualitative evaluation of the four most widely used tools: GaBi, openLCA, SimaPro, and Umberto. This supports companies in the selection of a suitable application. For companies with limited budgets or expertise, openLCA may be a cost-effective solution. GaBi and Umberto stand out for their ability to provide an intuitive visualization of the product lifecycle through their graphical user interface, while SimaPro offers a slightly better visualization of results.

Following this, crucial steps of PCF assessment such as defining the functional unit, establishing the system boundary, and collecting process-related data are addressed. Users are guided through each of these phases as essential terms and key concepts are explained. Several key aspects of each phase are presented as follows:

- Defining the scope of the study: The functional unit is a standard reference, defining the product system based on its quantified performance. The system boundary represents the interface between the product system and its environment, including all relevant unit processes.

- Identifying all relevant processes: The process flow diagram models the system boundary, all relevant unit processes as well as the associated inputs and outputs. It serves as the basis for capturing primary data in production.

- Collecting process-related data: GHG emissions in manufacturing are driven by energy, material, and waste flows. Digital tools can facilitate data collection by linking different data sources. Integrating ERP software with EMS and MES enables real-time recording of material and energy flows as well as their allocation to the analyzed product. LCA databases can be useful for filling data gaps when collecting primary data is not feasible. In order to support companies in assessing the environmental impact of their own shopfloor, a concise compendium of 24 case studies across different manufacturing technologies is presented. Intended as a handbook, it serves as a valuable reference for collecting PCF data.

- Allocation of emissions: Allocation should be avoided through process subdivision, redefinition of the functional unit, or system extension.

- Calculating the PCF: Process inputs and outputs flows are assessed for their climate impact, using emission factors to convert activity data into GHG emissions or CO_2e eventually. It is crucial to ensure that emission factors reflect the specific conditions of the regarded process as accurately as possible and that all carbon emissions refer to the defined functional unit.

This guideline provides a solid foundation for PCF assessment in manufacturing. However, further research and improvement opportunities exist, particularly regarding its practical orientation. Future work may include implementing the guide in actual manufacturing environments to validate its effectiveness. At a university's production laboratory, the measurement based automatic PCF assessing for electrical drives, the regarding energy grid executed on Direct Current and the influences of bidirectional charging based on this guideline is in research [81]-[84]. The methodology might also be used in other areas of the automotive industry beyond battery manufacturing. Studies focusing on wire harness production, e.g., have so far only considered the material and logistic implications but not the actual manufacturing emissions [85], which mirrors current best practices in life cycle assessment for academic purposes [86]. Additionally, expert interviews or the inclusion of industry stakeholders could help provide insights into sector-specific requirements and challenges, enhancing the guide's practical feasibility. Furthermore, future research could aim to advance methodologies for collecting PCF data and explore innovative approaches to streamline the assessment process. However, this research already supports manufacturing companies in their efforts to contribute to climate change mitigation and meet the environmental expectations of various stakeholders. Thus, the proposed solutions have the potential to empower businesses to achieve both environmental and economic sustainability.

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