PRODUCTION EMISSIONS IN TECHNOLOGY PLANNING

CHALLENGES AND APPROACHES USING THE EXAMPLE OF ELECTRIC DRIVES

Dear readers,

There have always been times of transformation, but rarely have we experienced changes as swift and profound as those occurring today. The pace at which groundbreaking innovations gain momentum and scientific advancements integrate into our daily lives is truly astounding. Electric mobility is no longer a distant vision. It is unfolding before us, here and now, and it is accelerating at an extraordinary rate.
This progression extends well beyond the electric vehicles we now commonly see on our roads. It is permeating all facets of society and economy, reshaping industries and influencing the way we live and work. We find ourselves at a pivotal moment in time when technological innovation must harmonize with environmental responsibility but may also be the key to a sustainable society.
With this rapid advancement comes a new array of challenges. The quest for efficient, reliable, and cost-effective electric drive systems is a complex task of engineering. Adding sustainability into the equation intensifies this complexity. Product Carbon Footprint (PCF) analysis emerges as a crucial tool for quantifying and mitigating carbon emissions. However, PCF analysis is not just a responsibility of dedicated departments; it needs to become part of the daily routine of the development process. By integrating PCF considerations early in product development, companies can make informed decisions that balance performance, cost, and environmental impact.
This paper not only examines the theoretical foundations of PCF analysis but also offers practical solutions and strategies for effectively merging ecological concerns with economic objectives. Through detailed case studies, we demonstrate how theoretical concepts are put into practice within the industry. These examples underscore the vital role of data quality and highlight the challenges of incorporating sustainability considerations early in the product development process. They illustrate that embracing sustainability is not just about meeting regulatory requirements or fulfilling corporate social responsibility, it is about unlocking new opportunities for innovation and gaining a competitive edge in the market.
In these dynamic times we invite you, dear readers, to engage with the insights and discussions presented in this paper. Our aim is to shed light on the exciting developments in electric mobility and to encourage thoughtful dialogue on how we can collectively address the challenges and opportunities that lie ahead.

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INTRODUCTION

In production engineering, it has long been established that error costs during ramp-up and production are predominantly caused at an early stage of product development. As with errors in production, the causes of carbon emissions are also determined at an early stage. Carbon emissions are no longer just socially and politically relevant. The European Union "internalizes" the economic costs of carbon emissions through the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM). Carbon emissions particularly are turning into a direct cost factor. More and more economies are taking a similar approach. For this reason, it is imperative to generate an accurate picture of the emissions of your own products and their impact in relation to CO_2 to be competitive in the long term. One common tool is the so-called Product Carbon Footprint (PCF), a special form of Life Cycle Assessment (LCA). In this publication, we will illustrate how exactly a PCF analysis works, what challenges arise in the process, and what options for action exist using the example of electric traction motors.

WHAT IS A LIFE CYCLE ASSESSMENT?

As part of a comprehensive life cycle assessment, the entirety of all emissions associated with the manufacture, use and recycling of a product and their impact on the environment are recorded. Based on a life cycle inventory – a survey of the material and energy flows in the system under consideration –, all emissions generated are documented. To make the impact of different emissions comparable and to take different types of environmental impact into account, the emissions determined are specified in summarized impact categories. One of the best-known and most frequently used impact categories is the Global Warming Potential (GWP), expressed in CO_2 equivalents. Due to the direct cost impact of carbon emissions, the focus is currently on calculating the GWP under the term Product Carbon Footprint (PCF).

Definition of Life Cycle Assessment (LCA)
Balance of material and energy flows for the manufacture of a product and the subsequent transfer of these flows into associated emissions (also known as life cycle assessment). The impact of these emissions on the environment is indicated in various impact categories.[1] Therefore, providers have an obligation to their customers to meet the planned demand. At the same time, the companies must drive their own innovations and allow room for their suppliers' new developments to unfold. In this way, a tension arises between market pull and technology push in the production of electric drives.

Definition of Product Carbon Footprint (PCF)
Special form of life cycle assessment that focuses on the impact category "Global Warming Potential" expressed in CO_2 equivalents. Other effects such as human toxicity are not considered.[2]

In addition to production, a holistic life cycle assessment also includes the use and disposal of a product (cradle-to-cradle approach). In practice, the assessment of the PCF usually focuses on the process chain up to the delivery of the product, also known as the cradle-to-gate approach.

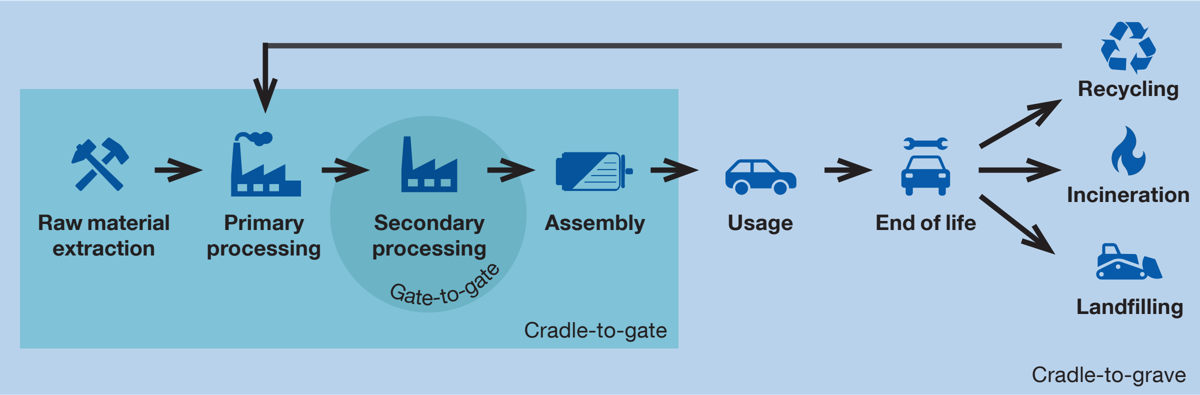

Figure 1: LCA and PCF system boundaries[3]

WHAT IS THE PROCESS BEHIND A PCF?

To determine a PCF in the cradle-to-gate approach, the mass and energy flows required to produce the product up to delivery must be documented. In addition to the amount of electricity used, this includes the materials and semi-finished products used as well as the necessary transportation routes and means. A specific carbon emission value can be assigned to each material and energy flow that has been recorded as part of a life cycle inventory. For example, every kilowatt-hour (kWh) of electricity generated in Block H of the Weisweiler coal-fired power plant is associated with approximately one kilogram of emitted CO_2.[4] As other emissions, such as methane, have a comparable environmental impact to carbon dioxide, these emissions are also recorded and indicated in CO_2 equivalents using a conversion factor. The conversion factor results from the relative impact of the pollutant emission to be compared. Some gases and the associated conversion factor to CO_2 equivalents are listed **in Figure 2**[5]. It should be noted that the conversion factors may change depending on the calculation method and time horizon.

Emission focal points can be derived from the total resulting emissions and their allocation to individual sections of the value chain. Based on this, possible next steps for reducing emissions can be developed in focus points. In the context of product development, this must always be done in relation to the resulting costs and product requirements. The greatest gain in knowledge is possible if the analysis is carried out at the beginning of the product creation process, based on the requirements of the decision-making situation.[6]
However, due to several challenges, the validity of the analysis, particularly in the context of integration into technology planning, must be critically scrutinized. In the following, we will examine what these challenges are and what tools are available to address them. The central challenge of the data basis is highlighted in the first section. We then look at ways and means of designing a software solution for the integrated consideration of ecological and economic impacts. Eventually, we show how these tools may be integrated into product development.

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> “The scope of a PCF and the data sources used significantly impact the results and findings of the analysis. Transparency across assumptions and simplifications is key.”

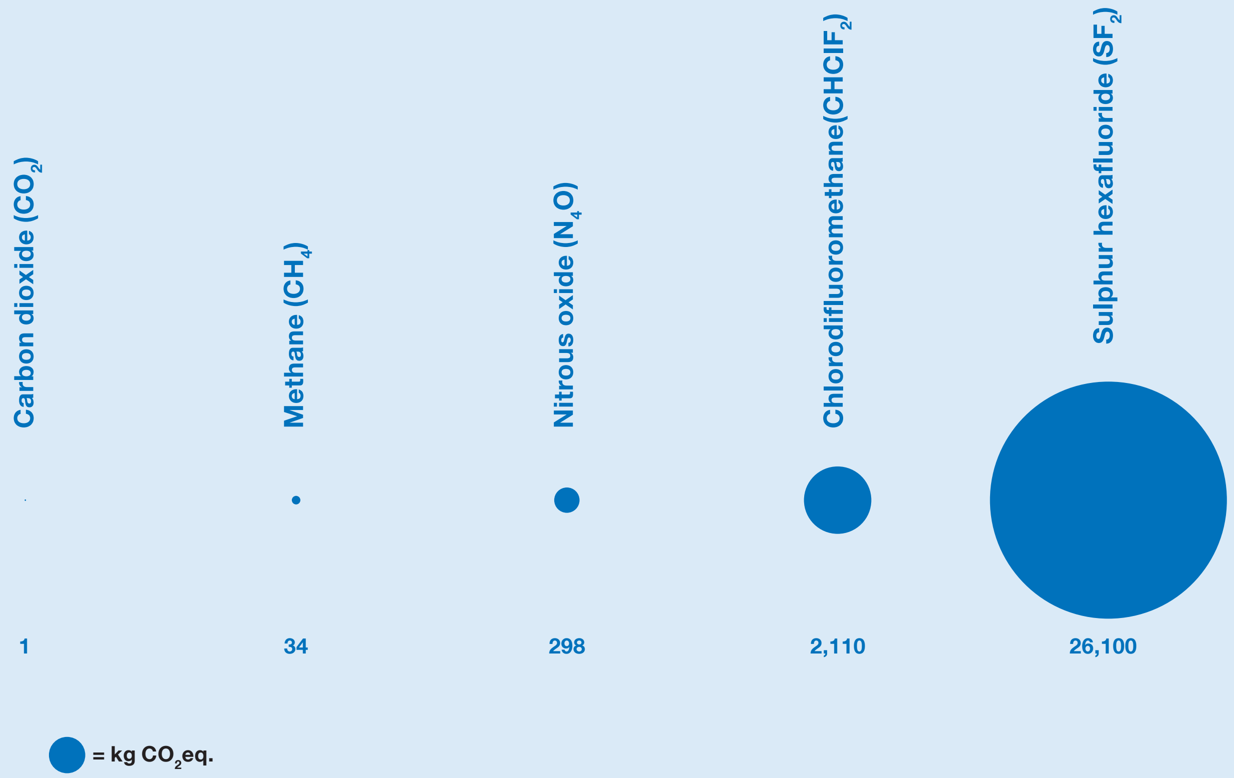


Figure 2: Conversion factors for the CO_2 equivalent of select emissions according to ReCiPe 2016 (H)

PREREQUISITES FOR A PCF

Recording mass flows requires a comprehensive description of the production system. Depending on the product under consideration, very different materials, processes, and supply chains are involved, meaning that a wide range of data points and sources can be relevant for the analysis. The starting point is usually the bill of materials for the product under consideration. Based on this, it is necessary to define production sites and processes as well as supply chains and suppliers for all assemblies and individual components. A distinction must be made here between internal parts of the value chain under the control of the company and external components, particularly against the background of information procurement. While ERP systems can be used to record internal company data in the best-case scenario, collaboration with suppliers is required to record external data.

In addition to the division into internal and external data, a distinction is made between primary and secondary data. Primary data are collected data points that can be assigned to the individual product. An example of a primary data point in electric motor manufacturing is the power consumption measurements for the inductive heating of the rotor's lamination stack for the assembly of a rotor shaft. As it is not always possible to record all product-specific information, estimates must be made, and comparative data have to be used. Secondary data are used when the execution of a process is largely independent of the entity carrying out the process and when primary data are not available. Secondary data can be retrieved from commercial and non-commercial databases whose data points are generated via exemplary surveys. Secondary data are particularly suitable for estimating the emissions associated with electricity generation and supply chain emissions. **Figure 3** shows some examples of the country-specific electricity mixes and the emissions per means of transportation.[I]

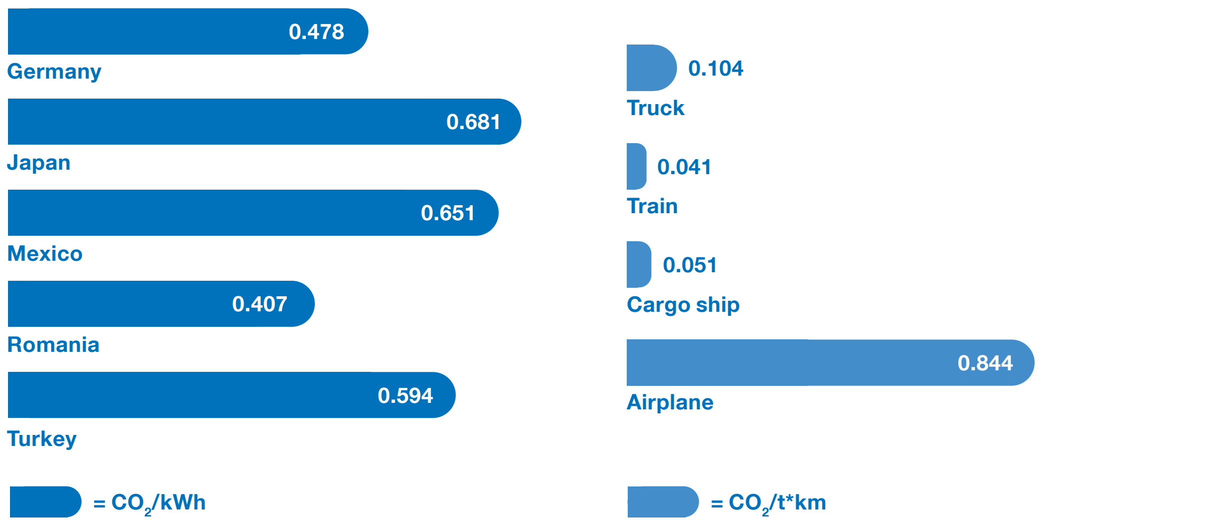


Figure 3: Kilogram CO_2 equivalents "Electricity mix per locstion" & "Means of transportation"

Individual processes with a very individual character and high pollutant emissions, on the other hand, are much more difficult to estimate.

HOW TO CREATE A DATA SET?

A comprehensive and consistent data set is a prerequisite for the creation of a high-quality PCF analysis. The PCF analysis has the highest possible informative value if primary data are available for all internal and external steps, which depicts the emissions along the actual value chain. ERP systems and parts lists can be used to illustrate material flows and electricity requirements within the company. Additional plant-specific emissions data may also be available for emission-intensive processes. While assembly processes are well documented, these typically contribute to the PCF of the product to a very small extent with one possible exception in scrap rates. The emissions associated with the production of the materials used must be obtained from suppliers in the case of purchased products.

Due to the high effort involved in collecting primary data, secondary data are always used in addition when calculating the PCF. Secondary data are usually data sets that have been recorded or simulated by external companies for a predefined observation framework.[7] Typical data sources for secondary data are organizations or companies such as “ecoinvent,” “sustamize,” “ProBas,” “BEIS,” “IPCC,” or “Agri-footprint.” Their databases usually build on each other in certain sub-areas. The ISO 14064-3 standard defines requirements for the assessment of greenhouse gas-related data, information, and information systems, while some databases are certified regarding this.[8]

Due to the dependence of the results on the defined framework and the type of data collection, there are differences in data quality, the methodological approach and the scope of the processes depicted.[9] An additional factor that influences the quality of a secondary data set is its timeliness. Electric mobility is characterized by product and production innovations. These innovations, which often result in a reduction in emissions, are not included in the scope of older data sets. Another consequence of this is that there are no data sets for specific components, processes, and materials in the production of electric motors[10], as the relevance of these has only increased in recent years.

The aforementioned problems with the use of secondary data mean that the calculation of a PCF often requires a high degree of abstraction.[11] As a result, the calculation results have little overlap with reality and are therefore less meaningful.[12] Comparability of calculation results of the PCF of products and components, which were calculated with secondary data sets from different data sources, is often not given.[10, 13]

CASE STUDY: LCA OF E-DRIVE PRODUCTION

Definition of the scope of the investigation and life cycle inventory

To illustrate the effects of data quality and data accuracy on the PCF, the PCF of a permanently excited electric motor was calculated in an exemplary scenario with data of different origin and quality. The scenario describes an exemplary production of an electromagnetically designed stator and a rotor in a production facility in Aachen, Germany, with the integration of a possible supplier network. The analysis focuses solely on the production phase, meaning that the actual use of the motor components and the end-of-life phase are not considered as part of the scenario. Data sets from freely accessible databases, which are often outdated and of low quality, are used as the data basis for calculating the PCF. For comparison, the same calculation is carried out using commercial data sets from “ecoinvent” 3.9.1. In addition, the electricity mix is iteratively changed from a general German electricity mix to a green electricity mix, which many companies purchase via certificates. In a final comparison scenario, the secondary material shares of the metallic parts of the engine components are changed from values defined in the data sets to adjusted, real values from practice.

Life cycle impact assessment

The results of the PCF calculation show that raw materials, particularly steel and copper, account for most of the greenhouse gas emissions in the underlying scenario. Due to the regionally based, exemplary supplier network, direct transport emissions from the component and material suppliers to the assumed production site in Aachen, Germany, are low. In electric motor production, many process-related emissions are caused by emissions from electricity generation. Changing the electricity source can therefore significantly reduce overall emissions. However, the selection and therefore the quality and accuracy of the data sets have the greatest impact on the overall result of the PCF.

Evaluation

Overall, various product-related and data-related insights can be gained from the scenario comparison. For example, optimizing process efficiency in electric motor production makes an important contribution to reducing overall emissions, particularly about CO_2-intensive electricity generation. Since the materials used, the electrical steel, wire, and magnets, account for most greenhouse gas emissions, the dimensioning of the motor, the use of secondary materials, and optimal material utilization in production are important levers for sustainable electric motor production. Regarding data quality, the thesis that the results of a PCF depend largely on the data sets used and their methodology and accuracy in data collection is confirmed. It is therefore not always possible to compare the results of life cycle assessments and the PCF if different, inconsistent data sources are used. The data sets must be adapted to the production scenario to be assessed and the production processes used.

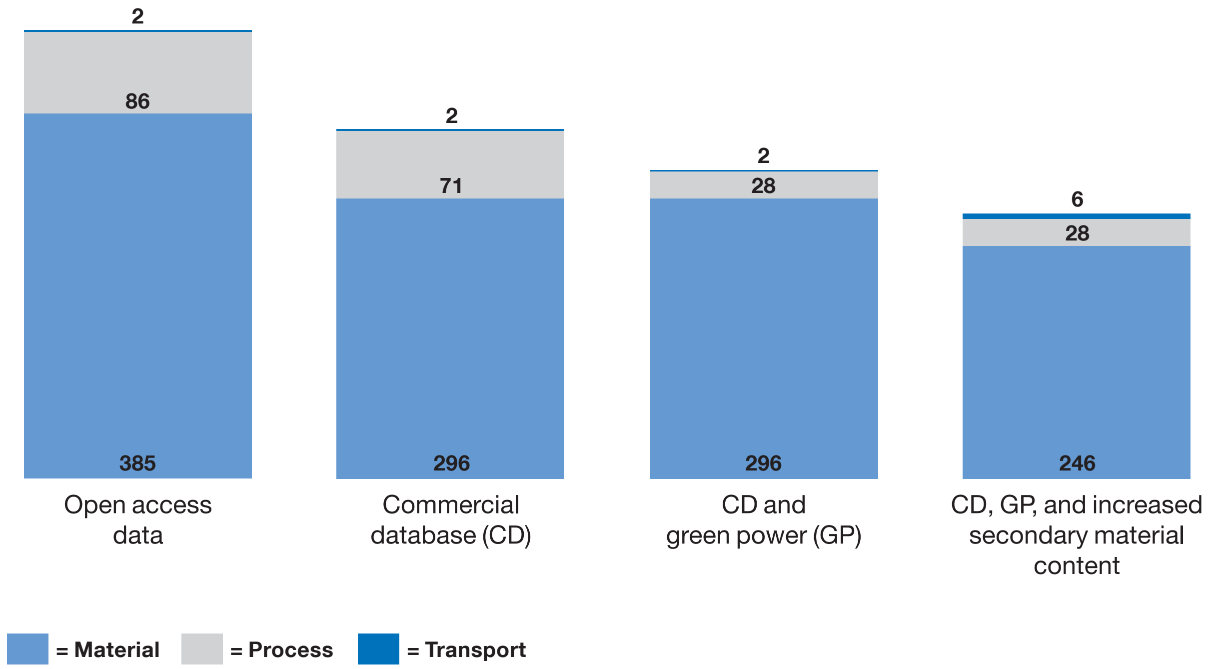


Figure 4: Global warming potential of an electric motor as a function of data accuracy

INFORMATION MANAGEMENT

The integration of manufacturing emissions into technology planning poses several challenges from a business information management perspective: The necessary design, procurement and manufacturing processes are typically spread across many different players in the supply chain, who collect and handle data differently. Many materials and technologies must be taken into account, and the systems under consideration are complex. Multiple people are involved, and several data statuses must be maintained in parallel. After all, much of the data are speculative statements about the future.

Technology planning is rarely carried out entirely according to a greenfield approach. Instead, some existing platforms, kits, assembly sites, and supply chain structures are adopted, while other aspects can be redesigned. This results in requirements for the use of existing data and the reusability of any data and analysis which gets created.

For the integration of production emissions into technology planning from the perspective of a vehicle OEM, the following process can be thought of in simplified terms:

1. The overall vehicle targets are known and have already been broken down to system level. As part of these overall vehicle targets, rough target costs, functional requirements, and – more recently – emission targets for both production and usage phase are known. Rough boundaries on sales figures and assembly plant(s) are available.
2. Different technological variants for the implementation of these objectives are considered, and initial, incomplete bills of materials are generated.
3. For each implementation variant, an assessment is made as to whether the cost, emission and specification targets are met – ideally, this assessment should be carried out simultaneously. The gaps in the bill of materials must be filled with estimates or (scaled) carry-over parts.
4. New implementation variants are generated and evaluated in several iteration loops. The precision of the evaluation can be increased step by step as make-or-buy decisions are taken or simulated and by using supplier/site-specific secondary data.

The process is similar for a first-tier supplier.

> “Professional management of PCF information requires specialized software. Linking it with product cost analysis yields great synergy.”

Jakob Etzel, Tset

RELEVANT PROPERTIES OF SOFTWARE SOLUTIONS

Doing repeated calculations of a PCF as described in section 4 with all its challenges requires rather professional software than a simple spreadsheet. Therefore, when designing such a software system, investing significant effort into a good understanding of the requirements is needed. In the following, we derive the requirements for such a software system that is used for the simultaneous calculation of product costs and the product carbon footprint in the design phase.

a) **Granularity:** Calculations must differentiate technological concepts. Low granularity (e.g. parametric models) may miss component-level differences. Material emissions (e.g. aluminum, 1.5 to 15 kilograms CO_2 per kilogram) and their effects on components such as drive housing must be modeled.
b) The sensitivity regarding material selection, recycling rates, and primary energy mix must be accounted for. As an example, aluminum emissions vary widely due to recyclate content, semi-finished product form, and energy mix. Ideally, the software models these factors individually.
c) A link between **production emissions and production costs** is desirable. The description of the production system and the overhead logic can be used for both evaluations. Such a link requires to deal with special direct costs, supplier development costs, transportation (costs and emissions), and the like.
d) Not every component or assembly can be produced anywhere in the world, as certain technologies or expertise might not (yet) be available. These restrictions must be considered **in the supply chain configuration**.
e) A **wide range** of regions, materials, and technologies – designated by different standards – must be supported. As an example, secondary data on emission intensities of electricity vary between regions.
f) At the time of the estimate, the **supply chain's structure, including suppliers, production sites, or lines, may not be fully defined.** Both primary and secondary data must be usable, available as master data, and adjustable in calculations. The distinction between primary and secondary data should be clear.
g) If **large emission sources have to be allocated** allocated (e.g. dedicated machines, molds made of tool steel), production volumes must be considered.
h) **Scrap quantities,** which result from process characteristics (sprue, punching waste, etc.) as well as from the stability of the process (defective parts), or, in extreme cases, even transport damage, including their aggregation across the production steps are to be considered.
i) **Ongoing further development and maintenance** of the software system must be ensured (e.g. Software-as-a-Service model).
j) **Technological and commercial developments** must be considered, e.g. process efficiency improvements and inflation rates for material prices and wages.
k) Many **variants, correction loops, and repetitions** are to be expected, requiring adequately sized data storage and good nomenclature.
l) **Several people** are involved in the assessment. They may be involved in several such assessments at the same time.
m) The estimation scheme and the master data required for it should be **consistent** within the company (and, if possible, in the supply chain).
n) The **quality of the data used and the evaluation's level of detail** often varies within an evaluation and should ideally be described by attributes and aggregated in the simulation.
o) **Different data formats** must be imported and exported. Examples include the import of material master data, bills of materials, and work plans from ERP, PLM or CAD systems as well as output in the structure of the Greenhouse Gas Protocol.

Actual requirements for the software system vary according to the exact purpose, operational processes, industry, own position in the supply chain, the structure of the supply chain, and the products manufactured.

ESTIMATION PROCESS & TOOLS

In the following, we describe examples of individual steps in the process of estimating manufacturing emissions as well as helpful tools.

A certain degree of flexibility should be possible when preparing the bill of materials. At the beginning of the product development process, quick and uncomplicated adjustments are often necessary. Certain components are initially not known in detail and are roughly described and estimated – they may be detailed later. It should be possible to show in the bill of materials which components are procured externally or manufactured in-house and where the production site is located. In the case of detailed considerations, the production quantities should also be recorded. It makes a difference whether a screw is manufactured product-specifically in the amount of 10,000 pieces per year or is ordered from a catalog and a production volume of several million pieces annually can be assumed.

The mapping of the designations and classifications of materials and production processes, etc., poses a challenge. These designations are often not structured and standardized in the internal information, but especially in the information from the supply chain.

The secondary data for the materials should be broken down by material grade, recycled content, semi-finished product form, and material production location. The location data essentially comprise secondary data for electricity and natural gas. A distinction can be made between “ecological grades” for both, e.g. gray and green electricity. All data should contain information about their validity period. The primary data are stored in the same way, but with reference to the actual specific product via the material number. What is primary data for one product can – under certain circumstances – be secondary data for another product. All data are not always available for every combination of “master data dimensions,” so a “fallback mechanism” should be defined. For example, if natural gas emissions are not available for a Canadian state, then those for Canada or North America are used instead. These “fallback mechanisms” should be consistent with each other and well documented across the products under consideration.

The calculation itself can be carried out in varying degrees of detail. A rough calculation applies material group-specific emission factors to the net weight, according to the bill of materials. This ignores different grades within the material group, the variance of the manufacturing processes, and the structure of the supply chain. A rough calculation based on costs rather than weight is somewhat more accurate. Emissions mostly come from processes that consume energy, and these two factors are roughly proportional to each other. The greatest level of detail is provided by a bottom-up approach, where each production system/machine is assigned a component-specific cycle time and energy consumption.

It must be possible to display and export the generated calculation data in various formats. It is recommended that exports in common spreadsheet formats are possible for further manual processing. Formats such as XML or JSON are better suited for transfer to other applications, as they are not restricted to tabular data structures.

If a company already collects standardized data on suppliers' manufacturing processes using cost breakdowns, such information can also be used to estimate the product carbon footprint. The following adaptations or extensions to the standard sheets are possible: additional columns for emissions intensity of electricity/raw materials/transportation routes, recycled content, and location of raw material production.

As someone who creates such carbon emissions reports in the form of breakdowns, it makes sense to create them automatically. There may be great synergies here with the cost analysis, and it must be ensured in terms of processes that the statements from cost and CO_2 breakdowns do not contradict each other.

In the screen display and spreadsheet output, aggregation according to the Greenhouse Gas Protocol is useful. Roughly speaking, this is a compilation from the perspective of a specific manufacturer of which emissions it directly influences (scope 1), which are attributable to its electricity consumption (scope 2), and which are the responsibility of upstream or downstream players (scope 3). The perspective should be freely selectable.

Connecting to other information systems – both for import and export – can sometimes be done at low cost by using no-code or low-code platforms. ERP and PLM systems generally have such a high level of company-specific configuration that “standard connectors” do not bring much improvement. In the material master of the ERP system, emission estimates of different levels of details can be stored, e.g. a statistical top-down assessment, a self-generated bottom-up assessment, and primary data communicated by the supplier. By collecting these data points in parallel, it is possible to retrospectively assess whether the secondary data have a structural bias and to derive adjustments for future estimates.
In any case, the delimitation to specialized software for LCA creation should be clearly defined. A software system described here for the simultaneous calculation of product costs and the product carbon footprint in the design phase fulfills a different task than an LCA solution for regulatory compliance:

- Data quality: While mainly secondary data are used in the conception phase, the classic LCA requires a significant proportion of primary data.
- Certifiability: Estimates in the conception phase are still so imprecise that they are not suitable for a certified LCA.
- Accuracy: In the conception phase, speed usually takes precedence over accuracy.
- Coupling with costs: At the time an LCA is created, the cost structure is typically already contractually fixed. In the conception phase, however, it is still opaque and fluctuating.

However, it is conceivable that the software system used for the simultaneous calculation of product costs and the product carbon footprint in the design phase will also compile the data in the later phases of the product development process, thereby increasing its accuracy and informative value. At a certain point, a one-off or ongoing data transfer to a separate LCA solution can then take place.

CASE STUDY 1: ELECTRONICS COMPONENTS

Several manufacturers of electronic components publish information on the product carbon footprint of individual components. The following example[14] concerns an AURIX™ Microcontroller for automotive applications[15] from the manufacturer “Infineon”:

POSITION	SHARE [%]	CARBON FOOTPRINT [g CO_2e][II]
Energy – electricity	57	8
Energy – other	5	21
PFC (perfluorinated compounds) & direct emissions	23	95
Material – indirect	10	41
Material – chip	2	8
Material – direct (backend)	<1	-
Transportation	3	12
Total	**100**	**413**

Table 1: Produt Carbon Footprint for an infineon AURIX™ Microcontroller for automotive

According to its own statements, Infineon already covers half of its product portfolio with a PCF. These data are only partially public, but they are accessible to partners. The manufacturer plans to cover the entire product range with PCFs. Infineon also makes a so-called Material Content Data Sheet publicly available for some of its products. It is tempting to estimate the PCF from this data. However, this harbors considerable risks, as we show below.

Due to licensing restrictions, the emission intensities of the individual materials are not stated but instead aggregates by categories. However, the calculation was based on individual values for weight and emission intensity for iron, epoxy resin, gold, copper, nickel, palladium, phosphorus, carbon black, silver, silicon, silicon dioxide, and zinc.[III]
The estimate from the material data sheet results in a value that is smaller by a factor of more than 150. This large deviation can presumably be explained by the following two considerations:

- According to Infineon’s PCF, the inputs from the direct material account for only eight grams. In contrast, 98 percent of the PCF is defined by indirect materials, energy inputs, direct emissions from chemical or physical processes, and transportation.
- The input weight is significantly greater than the net weight. There are process-related additional quantities and, of course, rejects both during chip production itself and when punching the lead frames, setting the wires, the various coating processes, etc.

The estimate from the material data sheet is unsuitable without post-processing and expertise. Instead, (primary) data should be obtained from the manufacturer. This discrepancy is significant for electronic components but also applies to cast and sheet metal products. The published PCF and material weight suggest an emission intensity of 1,470 kg CO_2e/kg, while secondary data for microcontrollers show much lower values (around 10 kg CO_2e/kg). Material data sheets often lack weight data, making rough estimates impractical for electronic components.
The manufacturer also publishes the PCF for other product groups, and we use the data below to evaluate the applicability of the expenditure-based estimate. For each of 16 product groups, a randomly selected component that is active in the manufacturer’s portfolio was chosen, and the price for 100 units was requested from a reputable distributor.[IV]

CONSTRUCTION ELEMENT	SUBSTANCES	WEIGHT [mg]	CARBON FOOTPRINT [mg CO_2e]
Chip	Silicon	17	195
Leadframe	Phosphorus, zinc, iron, copper	92	182
Wires	Gold, palladium, copper	1	110
Encapsulation	Carbon black, epoxy resin, silicon dioxide	159	825
Leadfinish	Palladium, silver, gold, nickel	1	67
Plating	Silver, palladium, gold, nickel	5	263
Glue	Epoxy resin, silver	5	678
Total		**281**	**2,321**

Table 2: Produt Carbon Footprint estimated from material content data sheet for an Infineon AURIX™ Microcontroller for automotive

Within the data published by the manufacturer, a clear linear relationship between costs and emissions can be observed, which can subsequently be used for rough estimates in various scenarios. Using linear regression, an emission factor of approximately 33 kilograms CO_2e per US dollar can be determined. For the microcontroller from the detailed example, this would result in emissions of around 215 grams CO_2e per unit. Compared to the weight-based estimate, this value is at least in the right order of magnitude.

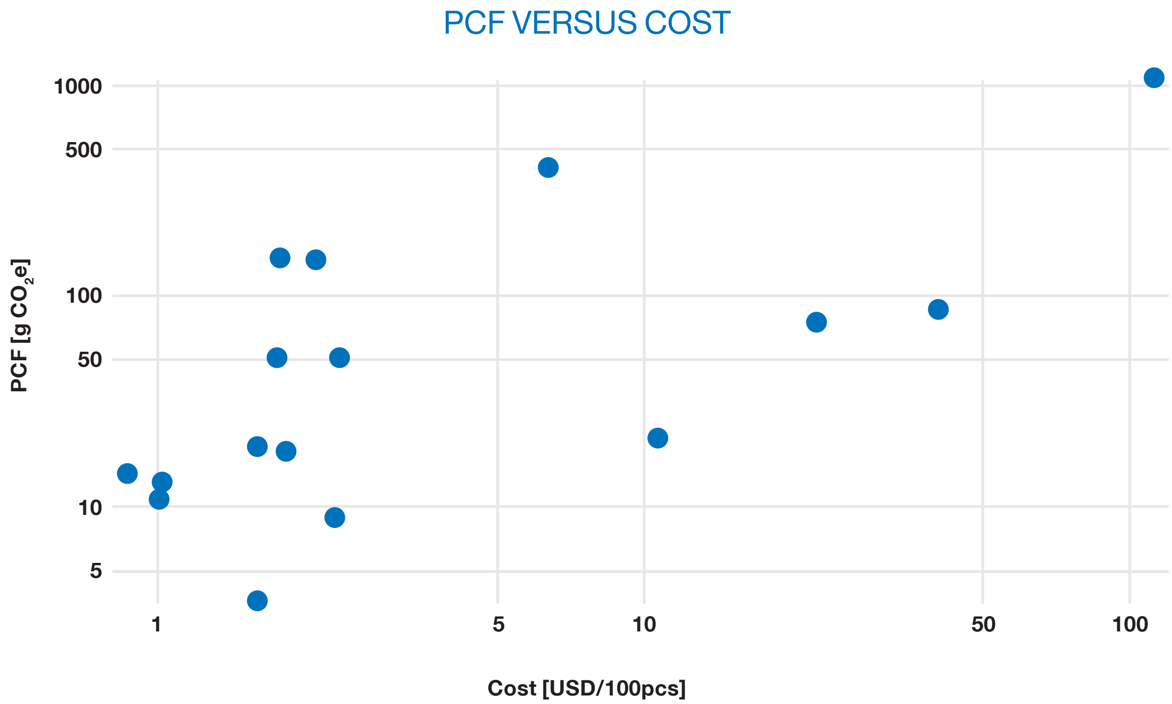


Figure 5: Published PCF and weight of electronic components with an approximated emission factor of 33 kg CO_2e/$

CASE STUDY 2: PSM ROTOR ASSEMBLY

While the example in section 4 assesses an electric drive as a whole, in this example we take a deeper look only at the rotor assembly with the following parts list and manufacturing processes[18]:

- Rotor assembly: rotor and shaft joining
  - Rotor shaft: cold forming, machining, hardening, cleaning
  - PSM rotor package: magnet assembly, magnet fixing, magnetization
    - Lamination stack: cutting, laser marking, cleaning
    - Magnets: melting, hydrogen decrepitation, milling, pressing, sintering, annealing, cutting, grain boundary diffusion, passivation, cladding, cleaning
    - End caps: cutting, turning, cleaning

To simplify the example, smaller components – such as the deep groove ball bearing – are not considered. In the base scenario, we consider a start of production in 2023 with a production period of eight years, 150,000 units annually, and assembly in Germany. The magnets are manufactured in China, whereas all other components are sourced from Germany.
The rotor and stator are stamped from the same sheet metal strip to save raw material. We assume that both laminations together have a net weight of 31 kilograms and the rotor laminations account for 40 percent of the net weight. The excess sheet metal is allocated proportionally. The scrap rates of the subsequent processes are considered.

If only the materials consumed and their net quantities were considered – which means disregarding the additional quantities required for production, the production processes themselves, and the rejects – and applying the same emission factors, a material value of just around 62 kg CO_2e would have been calculated. It is therefore necessary to consider exactly which manufacturing processes are included when researching the emission intensities.

For production in Germany (except for magnets, which are produced in China), the total PCF cradle-to-gate is approximately 105 kg CO_2e per assembly, being a part of the footprint of 280 to 473 kilograms CO_2e for the total drive as described in section 4. Alternative locations can be quickly assessed with the help of an appropriate software system. As the NdFeB magnets are always located in China in every location scenario, and as these magnets already account for a fourth of the PCF in the base scenario, the overall result does not vary that much. However, the emissions of electrical steel and the round steel of the shaft as well as the electricity consumption of the production steps differ by location.

LOCATION	PCF [kg CO_2e/pc]
Germany	105,387
France	99,233
USA	105,347
Mexico	106,021
China	108,671
India	110,553

Table 3: PCF depending on location

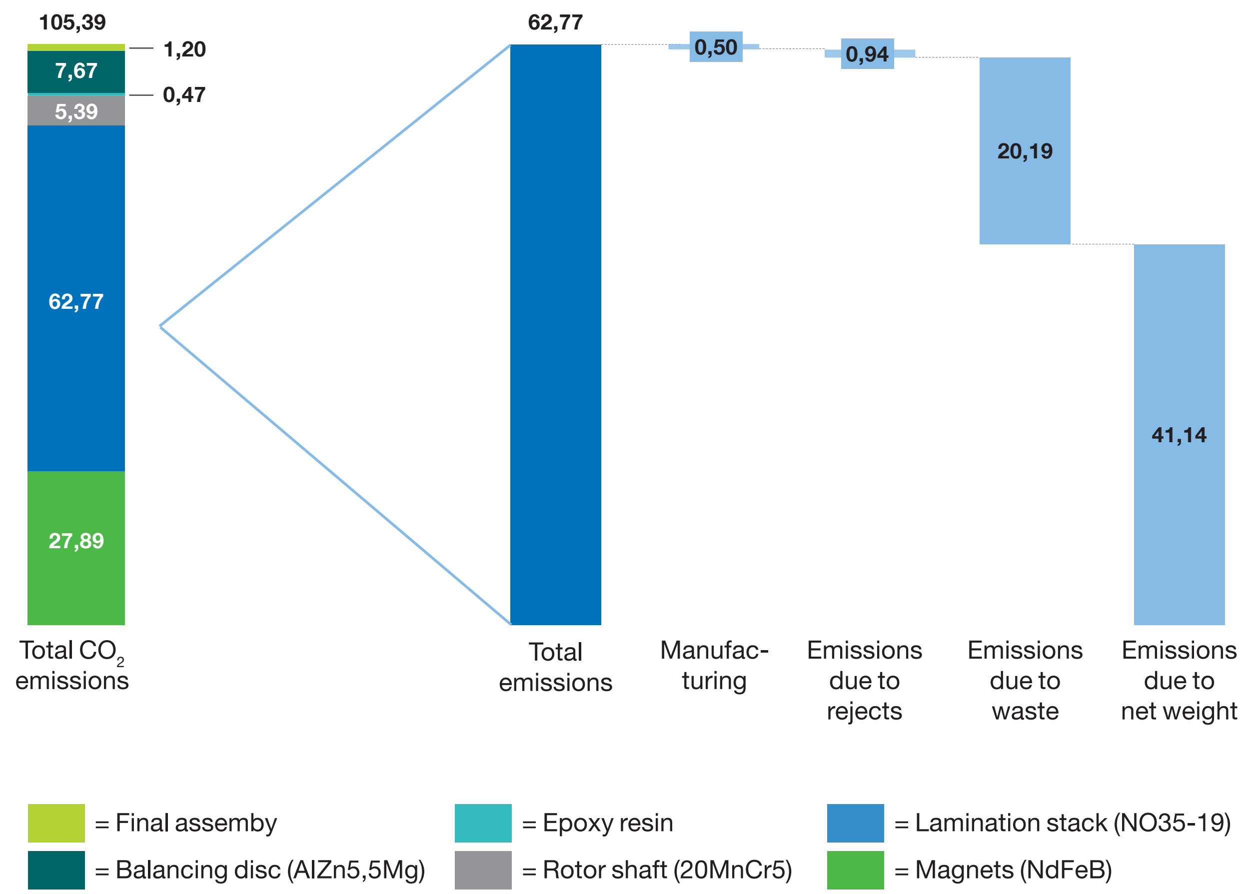
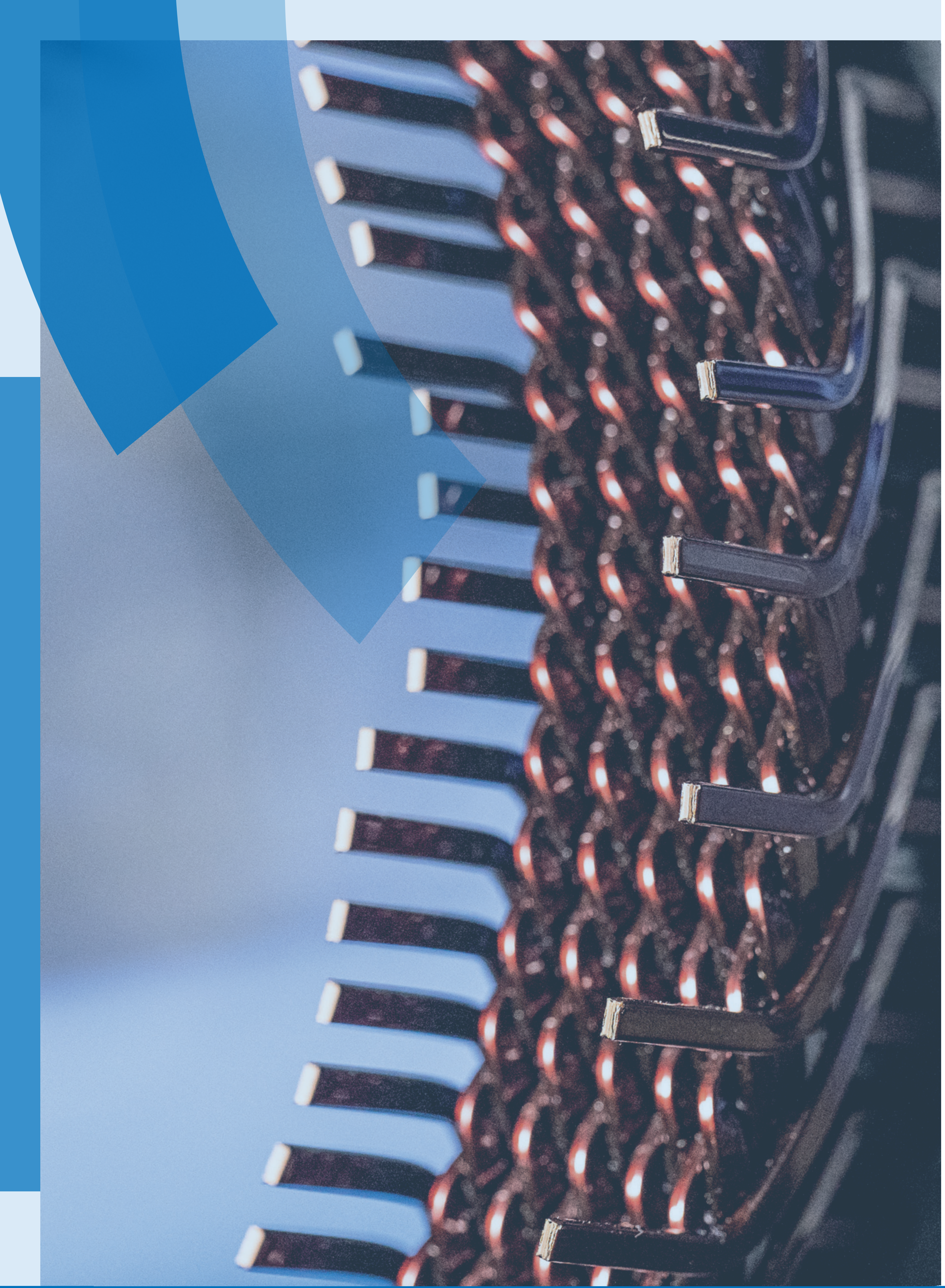


Figure 6: Key contributors to total PCF



EVALUATION AND DESIGN RELEVANCE

INTEGRATION INTO DECISION-MAKING PROCESSES

Carbon emission tracking in the automotive industry: internal and external requirements
The automotive industry faces increasing pressure to address climate change by reducing carbon emissions across the entire value chain of vehicle production. Apart from the "use phase," a key focus remains on analyzing, tracking, and improving the carbon footprint of relevant components starting in early development phases. The delivered transparency is essential for ensuring compliance with environmental regulations, meeting consumer expectations, and supporting global sustainability goals. The process involves a complex interplay of internal and external requirements that guide companies in accurately measuring and reporting their carbon emissions.

Internal requirements for carbon emission tracking stem from a company's strategic objectives, operational practices, and technological capabilities.

Corporate sustainability goals: Automotive manufacturers often set internal targets for reducing carbon emissions as part of broader sustainability initiatives. These goals require detailed tracking of carbon emissions from all stages of product development, including material sourcing, manufacturing processes, and logistics. Companies must implement robust data collection systems that monitor energy use, material inputs, and waste outputs across various departments.

Product life cycle assessment: LCA is a process used internally to evaluate the environmental impact of a product during its entire life cycle. Concentrating on the cradle-to-gate perspective, this assessment requires gathering data on raw material extraction, component manufacturing, and assembly processes.[19] The results inform design decisions, allowing companies to choose lower-carbon materials and more energy-efficient processes. LCA also helps in identifying hotspots where emissions are highest, guiding efforts to reduce the carbon footprint before mass production begins.

Supply chain management: Internally, companies must engage with their suppliers to ensure that they are also tracking and reducing their emissions. This involves setting expectations for suppliers to provide detailed carbon footprint data for their materials and components. Companies may adopt internal standards and guidelines that suppliers must adhere to, ensuring consistency and accuracy in carbon tracking throughout the supply chain.

External requirements for carbon emission tracking in the automotive industry are driven by regulatory frameworks, market expectations, and industry standards.

Regulatory compliance: Governments and international bodies have implemented regulations requiring automotive companies to disclose their carbon emissions. They often mandate specific reporting frameworks, such as the Greenhouse Gas (GHG) Protocol, which provides guidelines on how to calculate and report emissions. Compliance with these regulations is crucial for avoiding legal penalties and maintaining market access.

Industry standards and certifications: The automotive industry is subject to various standards that dictate how carbon emissions should be tracked and reported. For example, the ISO 14040 series provides guidelines for conducting life cycle assessments, which are essential for carbon footprinting. Achieving certifications based on these standards can enhance a company's reputation and provide a competitive advantage by demonstrating a commitment to sustainability.

Consumer and market expectations: Increasingly, consumers are demanding transparency regarding the environmental impact of the products they purchase. Automotive companies must respond by providing clear, accurate information about the carbon footprint of their vehicles. This external pressure drives the need for rigorous emission tracking systems and transparent reporting practices that can be communicated to the market.

Investor and stakeholder demands: Investors and other stakeholders are increasingly focusing on environmental, social, and governance (ESG) criteria when evaluating companies. Accurate carbon emission tracking is a critical component of ESG performance, and companies are often required to provide detailed emissions data in their sustainability reports. Failure to meet these expectations can result in decreased investor confidence and reduced access to capital.

Product carbon footprint analysis; value analysis as a decision driver in early development stages

Value Analysis (VA) is a systematic approach used in the early stages of product development to improve the value of a product by optimizing its functions relative to its cost. It involves evaluating the essential functions of a product to enhance its performance, reduce costs, and increase customer satisfaction.[20] In the context of growing environmental concerns and sustainability goals, integrating product carbon footprint analysis and optimization into the existing framework of value analysis (including its established tool chains) offers an excellent solution to address previously described requirements. This integration not only aligns with the traditional goals of VA but also adds a new dimension of environmental responsibility as well as market relevance.

Understanding value in the context of sustainability

Value analysis defines value as the ratio of function to cost. However, in today's market, where sustainability is a key concern, the concept of value extends beyond just cost-effectiveness and functionality to include environmental impact on both sides. A product that performs its intended function at a lower environmental effort – such as reduced carbon emissions – can be regarded as an offering of greater value, particularly to environmentally conscious consumers.

Redefining functions with environmental considerations: In Value analysis, the first step is to identify and prioritize a product's functions. By incorporating carbon footprint analysis, companies can redefine these functions with an added focus on minimizing environmental impact. For example, in the automotive industry, reducing the carbon footprint of a vehicle's production process might be considered an essential function alongside traditional aspects such as safety, performance, and durability. This redefinition helps companies align their product development with both customer expectations and environmental goals.

The function-cost-carbon relationship: Traditionally, VA focuses on the relationship between function and cost. When carbon footprint analysis is integrated, it introduces a third variable: carbon emissions. This expanded function-cost-carbon relationship requires companies to assess how changes in product design, materials, or processes affect not only costs but also carbon emissions. For instance, switching to a lower- carbon material might slightly increase costs but significantly reduce the product's overall carbon footprint, thus enhancing its value from an environmental perspective.

Optimization for enhanced value

Optimization in value analysis aims to maximize the product's value by improving functions and reducing costs. When carbon footprint is factored in, this optimization process becomes even more nuanced and the demand for accurate data more crucial, focusing on how to deliver essential functions with minimal environmental impact.

Example – material selection and process improvements: Carbon footprint analysis provides critical data that can inform decisions on material selection and manufacturing processes. For example, selecting materials with lower carbon content or optimizing manufacturing processes to be more energy-efficient can significantly reduce a product's carbon footprint. These changes not only contribute to cost savings but also enhance the product's environmental value, which can be a key selling point in the market.

Life cycle perspective

Value analysis traditionally focuses on immediate cost and function. However, incorporating carbon footprint optimization encourages a life cycle perspective where the long-term environmental impact is considered alongside initial costs. By optimizing the carbon footprint during the product development phase, companies can create products which offer a higher value over their entire life cycle, reducing future environmental costs and aligning with consumer and regulatory expectations for sustainability.

Differentiation of potential outcome scenarios

When analyzing the costs & CO_2e footprint for production in different locations, a distinction can be made between 3 potential outcome scenarios. Each scenario leads to a different optimum in relation to the economic decision to be made by the company.

Best-case scenario

In a comparison of all relevant production sites/countries, France as the most sustainable assembly site (lowest CO_2e generation, 63,2 kg CO_2e/pcs) also proves to be the most cost-effective and therefore the most attractive alternative from a business perspective. Assembly of the PSM Rotor in France therefore clearly represents the optimum solution in terms of cost calculation.

Trade-off scenario

The cost analysis shows marginally higher costs for assembly in France as the most sustainable site. However, these marginally higher costs are acceptable from a business perspective and do not automatically exclude France as an assembly site. From a customer perspective, a slightly higher price for a sustainable assembly can be value-added and therefore can be the preferred solution. From a business perspective, a decision must be made as to whether the additional costs for a more sustainable assembly should be accepted or whether a decision should be made in favor of the more cost-effective location.

Unpropitious scenario

PSM Rotor assembly in France is associated with significant and unreasonably higher costs for the company. In this case, a decision in favor of a less sustainable alternative needs to be taken. However, if a second-best option (e.g. assembly in USA or Germany) is cost effective, Co_2e emissions can still have a significant influence on the decision. This holds particularly true when considering non-monetary factors and their dependencies when selecting a suitable assembly site.

COST INFLUENCE AND REGULATORY LANDSCAPE

Influence on cost calculation through CO_2 pricing

A straightforward way of influencing cost calculation and thus the scenarios described is the fixed and mandatory pricing of carbon emissions caused during development and production. The groundwork for this has already been laid at the national and international levels with the introduction of the European ETS (“Emissions Trading System”) and its German counterpart, the nEHS (“nationales Emissionshandelssystem”), as well as the globally enforced CBAM (“Carbon Border Adjustment Mechanism”).

National level

The ETS, which has been active since 2005 and is currently in its fourth phase since 2021, regulates the mandatory purchase of CO_2 certificates at the national level for all emissions generated during the product development process. This involves an annual price increase and an artificial shortage of available emissions to achieve the CO_2 targets that have been set by the countries and the EU[21]. This effect allows carbon emissions to be included in companies’ cost calculations using defined prices and thus favors more sustainable production methods and materials.

International level

At the European level, the CBAM program was set up primarily to ensure that the prescribed CO_2 certificates and their costs do not negatively impact the competitiveness of European industries. Specifically, the intention is to prevent production capacities from being shifted to non-EU countries to circumvent the CO_2 certificate prices and thus generate a cost advantage. This is done by introducing a mandatory declaration of carbon emissions for production in non-EU countries for all goods that are to be imported into the EU. These are then subject to import fees equivalent to the CO_2 costs of intra-EU production. These costs can be offset against any national CO_2 certificates already acquired in the producing countries.[22]

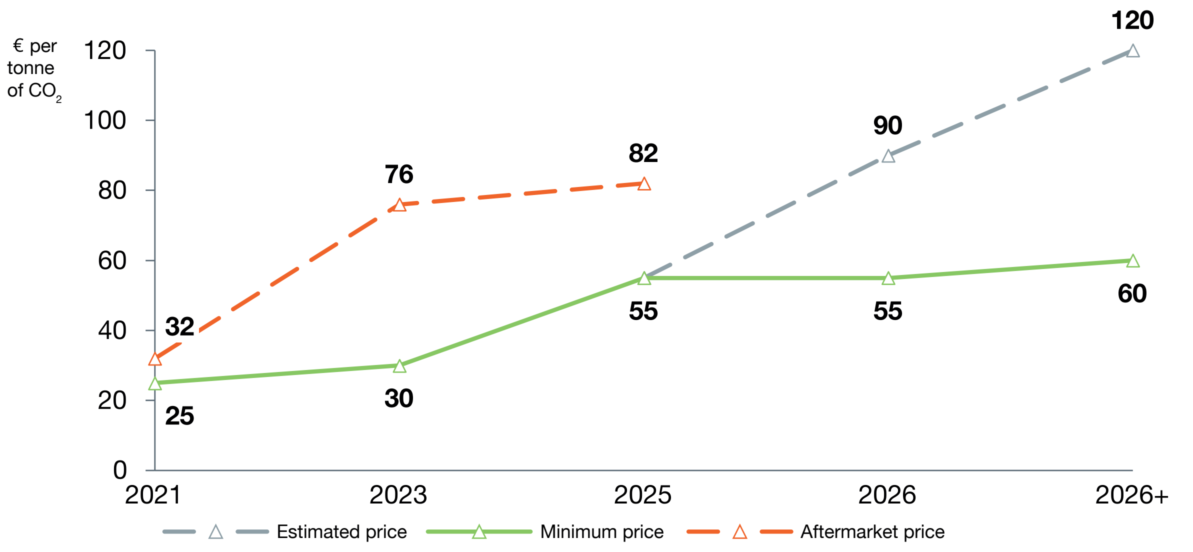


Figure 6: Development of CO_2 prices in germany from 2021 to 2025 with estimated price range until 2026+

Combined effects and CO_2 prices

The national and international regulations on CO_2 pricing are leading to a necessity to rethink production processes, materials, locations, logistics and sourcing strategies due to changes in the cost structures. The currently fixed CO_2 price of €30/tonne of CO_2 will rise to €55/tonne of CO_2 by 2026 as regulated in the nEHS. On the listed aftermarket, the certificates are as of today traded at a noticeably higher price. This currently fluctuates in a price range of around € 80-90/tonne of CO_2.

> Due to the artificial shortage of available certificates and the opening of the market after 2026, it is therefore expected that the price will continue to rise to an even higher level while still be subject to the already existing fluctuation of the market.
> This development should be considered by companies when making decisions. The CO_2 price therefore becomes an integral part of every cost calculation in product development and influences strategic decisions early in the development process.

CONTROL MECHANISMS

Due to the heterogeneity of the methodology itself, the data collection procedures and the final implementation of an LCA, testing, and validation is an important step in ensuring the reliability, credibility, and quality of the results. Indicators to be evaluated include the completeness of the data, the temporal and geographical correlations and the technological connection between the LCA and the actual production system. Due to the complexity of the overall system of a life cycle assessment as well as heterogeneous data models and processes in the preparation of a life cycle assessment, many companies consult external experts to review the LCA. This requires specialized knowledge through training in relevant scientific and technical areas.

The following assessments and tests can be used for quality control and validation of the LCA results:

a) **Analysis of data estimation according to ISO 14044:** Focus analysis (analysis of the data that make the greatest contribution to the indicator value, corresponding data can be examined with higher priority), error estimation (determination of how uncertainties and assumptions in the data are propagated in the calculation and affect the reliability of the results of the impact assessment), sensitivity analysis (analysis of the influence of changing inputs on the result).[23]

b) **Consistency check:** Determining whether assumptions, methods, and data are in line with the objective and the scope of the study. Ensuring comparability with other studies.

c) In the DIN EN ISO 14040 standard, which is decisive for LCA, a general critical review of the methodology and data used as well as the evaluation and reporting is recommended. The review can be carried out by internal or external experts or by a committee of interested parties.[1]

d) **Conformity assessment** of a life cycle assessment in accordance with DIN EN ISO 14071:2023: Critical review of the methodology, data quality, models, and assumptions used as well as evaluation and overall report by external experts in accordance with standard DIN EN ISO 14071:2023. The objectives selected for the study will not be verified or validated in the process. Independent accreditation for the auditor is not yet required; proof of qualification is provided via a self-declaration.[24]

e) In addition, some companies involved in LCA have set up their own data quality systems to check and classify the data.

In early development phases, a detailed analysis of the production and transportation processes is generally not yet possible, as the production network has not yet been defined. This makes it difficult to collect primary data, which means that estimates and secondary data must increasingly be used. Accordingly, full conformity assessments in accordance with DIN EN ISO 14071:2023 cannot yet be fully applied on the basis of these assumption-based life cycle assessments in the early phases of the product development process. To check critical influencing factors and data sets, it is advisable to analyze the applied data estimation using focus analyses, error estimates, and sensitivity analyses. In this way, additional emission drivers within the product value chain can be identified and optimized.

> "Carbon footprint evaluation is key in automotive development – driving innovation, cost efficiency, and compliance while future-proofing products for a low-carbon economy."

Steven Schumacher, Berylls

CLOSING WORDS & OUTLOOK

As we navigate the complexities of sustainable mobility, it becomes clear that traditional approaches to product development are no longer sufficient. Integrating sustainability considerations into the early stages of product design is essential. This calls for innovative methodologies that address both economic and environmental objectives simultaneously.

An effective approach in this context is Value Analysis. By systematically examining the functions of a product relative to its cost, this method seeks to optimize performance while minimizing expenses. When expanded to include environmental impacts, specifically through the integration of Product Carbon Footprint (PCF) analysis, it becomes a powerful tool for sustainable innovation.

The tools and strategies outlined in this white paper demonstrate how augmenting value-focused analysis with PCF considerations can guide companies toward more sustainable and economically viable solutions. Central to this approach is the knowledge transfer of PCF analysis into development teams, ensuring that sustainability principles are understood and applied at every level. Additionally, the targeted implementation of software solutions serves as a cornerstone in enabling both transparency and accurate as well as efficient PCF calculations.

By adopting this integrated approach, organizations can make informed decisions that balance performance, cost, and environmental impact right from the inception of the product development process. Incorporating PCF analysis into value evaluation allows for a holistic assessment of products from both economic and ecological standpoints. This synergy enables companies to identify opportunities for innovation, optimize resource utilization, and enhance competitiveness in a market increasingly driven by environmental consciousness.

In these dynamic times, integrating such approaches into the daily routines of product development is not just advantageous but imperative. It empowers organizations not only to meet regulatory requirements and fulfill corporate social responsibility but also to unlock new opportunities for growth and leadership in the industry. By fostering a culture of continuous learning and leveraging advanced software solutions, we can collectively drive meaningful progress toward a future where technological advancement and environmental stewardship go hand in hand.

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