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FRAMEWORK FOR COMPARISON OF PRODUCT CARBON FOOTPRINTS OF DIFFERENT MANUFACTURING SCENARIOS

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ABSTRACT

The Product Carbon Footprint (PCF) has been established over the last few years as a new control variable in product design to quantify the sustainable impact of a product. However, the calculation of the PCF is subject to numerous uncertainties and assumptions, which are no longer represented in the stand-alone value. The uncertainties and assumptions arise at different stages of the calculation of the PCF and consequently create a multidimensional problem, which means that the PCF does not provide a trustworthy basis for comparing different production scenarios. To face this multidimensional issue, in this paper, a methodology for categorization of the different issues and, therefore, of the final PCF is presented. Through this methodology, which is divided into five levels mainly based on the origin, the quality, and the uncertainty of the data, an assessment can be made as to whether the values of the PCFs are comparable in different scenarios. The methodology can therefore help to improve decisions in product development with regard to environmental sustainability.

Keywords: Product Carbon Footprint, LCA, Sustainability, Decision making, Uncertainty

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1 INTRODUCTION

For some years, the Product Carbon Footprint (PCF) has become the indicator of the ecological sustainability of products. Products from different sectors are labeled with a carbon dioxide equivalent so that it is possible to transfer the creation of a product to an impact on the environment. With this labeling, companies can place their products on the market at a time when the ecological responsibility of individual entities is becoming increasingly important due to climate change. In addition, it is possible to offer services around the PCF, such as promoting compensatory projects to neutralize specific carbon emissions. According to this, the PCF is becoming an argument for buying certain products in modern capitalism.

This suggests that consumers or companies can compare products according to the PCF labeling. However, comparing products from different companies are underlying guidelines that suggest the comparison is subject to certain framework conditions. These conditions, which can be found in DIN EN ISO 14026 (2018), and additional information, such as a comparison with the PCF of a competitor's product, may not be accepted in some countries for reasons that are not specified. It is clarified in the ISO that a PCF addresses a specific area of concern and shall, therefore, not be used as a comparative assertion between products. The stand-alone value of the PCF should not be used for comparison unless further information about it is known. Unfortunately, this is inevitably done in practice, whether by unknowing end consumers or buyers in a value chain.

The reason for comparability without a trustworthy basis of the PCF between different products is the nature of its estimation. The most common method for estimating the PCF is executing a Life Cycle Assessment (LCA). In the LCA, the product creation process is modeled with its material and energy inputs in every creation step. Different impact calculation methods can be used to quantify the result of carbon dioxide equivalents. The different calculation methods result, for example, from the fact that various assumptions are made about the impact of greenhouse gases (GHG), such as targeting 20 or 100 years. Furthermore, if primary data is unavailable, different eco-databases can be used for equivalent processes. The values in the eco-databases differ from each other even if the processes are calculated under approximately the same conditions. Furthermore, even if primary data is available, there is also no guidance on how the data shall be recorded and processed to make comparing different PCFs comprehensible.

This work presents a systematic framework for classifying the PCF to allow a comparison of different products. The framework aims to support designers and engineers in decision-making during product development. With this framework, an assessment can be made as to whether the values of the PCFs of different product scenarios are comparable. The sources of uncertainty are discussed as the basis of categorization in five levels. The overall approach is demonstrated in a case study, where a comparison between CNC steel production and additively PLA manufacturing of the same product is made as a first case during the design phase. In the second case, the comparison is demonstrated by adding primary data to the PCF estimation from the production of prototypes in the two production scenarios.

2 FUNDAMENTALS

The PCF is a key indicator that results from the performance of an LCA. It is defined as the sum of GHG and GHG removals in a product system, expressed as CO_2 equivalents (CO_2e) and based on an LCA using the single midpoint impact category of climate change (DIN EN ISO 14067, 2019). Other examples of the 18 midpoint impact categories are water use, particulate matter, or marine ecotoxicity. A common use of LCA is to aim for the smallest possible environmental impact. This differs from the use of other assessments, such as chemical risk assessment. In the latter, a conservative approach is used to assume realistic worst-case scenarios to be on the safe side in case of potential risks, as seen in Hauschild (2007). So, the PCF only considers one impact category. When trying to keep the PCF as small as possible, other strong environmental influences may increase, which is no longer reflected in the PCF. It has to be mentioned here that the DIN EN ISO 14026 (2018) defines a PCF communication in a way that information shall be included where (1) a clear indication of the area of concern is addressed, (2) the functional unit or declared unit to which the PCF communication refers, (3) identification of the life cycle stages that are covered by the PCF communication and (4) an unambiguous indication on how to access the publicly available supporting information. In addition, a full report shall be made available upon request.

Data availability on a product or process is required to calculate the PCF. In most cases, fully comprehensive data is unavailable, and assumptions must be made. In this work, primary data is defined as data that can be measured directly and product-specifically, and secondary data as data taken from eco-databases (DIN EN ISO 14067, 2019). In order to be able to make transparent statements about the PCF, it must be taken into account that data and models are subject to a certain degree of uncertainty. It must first be explained where the uncertainty can come from. In technical systems, uncertainty is categorized differently. In physical sciences research, Bevington et al. (1993) describe uncertainty with the two classes of systematic and random errors. More detailed categories are described in Morgan et al. (1990) with statistical variation, subjective judgment, linguistic imprecision, variability, inherent randomness, disagreement, and approximation. A division into three categories can be made by the classes data uncertainty, model uncertainty, and one class that is named structural uncertainty by Pelz et al. (2021) or completeness uncertainty by Funtowicz and Ravetz (1990). Regarding the PCF, data, and model uncertainty are the main originators, which is why they are explained as follows.

2.1 Uncertainty of data

To calculate a PCF, the necessary processes to create the product can be broken down into subtotals. Each subtotal consists of either the direct emission of GHG or equivalents resulting from multiplying a primary data set by a conversion factor.

2.1.1 Primary data

The primary data set is subject to classical uncertainty sources, which are also used in many other technical applications. An example of such a primary data set is the data recording of used coolant lubricant in a CNC (Computerized Numerical Control) machine. In order to calculate the equivalent, the flow of the coolant lubricant must be measured and processed using suitable sensor technology. The values of the final data set have several uncertainties, such as measurement uncertainty, derived data uncertainty, interpolation uncertainty, scaling uncertainty, and data management uncertainty (McMillan et al., 2018). The absolute uncertainty can be calculated theoretically if knowledge about all sources is available and can also be quantified. However, the relative distribution can often be very different and unpredictable and is difficult to calculate. The most important undertaking is the identification of the main causes. The Monte Carlo Simulation (MCS) represents one approach to investigate different sources of uncertainty in a model (McMillan et al., 2018). This can also be useful not only in the investigation of primary data but is also used as a tool of an LCA to quantify uncertainty.

2.1.2 Secondary data

When primary data is unavailable or equivalents have to be estimated, secondary data sets are often used to calculate the PCF. In practice, one common example of secondary data sets is the calculation of transport emissions. Transportation vehicles such as trucks do not have built-in sensors to measure the emissions they produce. Therefore, a database value from an eco-database is used, which indicates the average consumption based on distance and load mass. The values from the eco-database are based on primary data from example processes, which serve as approximations for other processes. For example, the distance and load mass is used for the calculation, which usually does not correspond to the real value, but to an approximated value. The real value can only be calculated by adding sensors on the transportation vehicle. In addition, there is no database value for every process, so in practice, values from similar processes are often used. Another example is the compressed air production which can be found as a process for compressed air production per liter in eco-databases. The eco-database provides the process as a single multiplier for compressed air per cubic meter (ecoinvent Association, 2022). Compressed air generation is not proportional to the energy consumed over time. For these reasons, the final value is biased, and we can speak of secondary data uncertainty. There is a wide range of secondary data sources. Public eco-databases by national and international organizations have been released in recent decades. Some of them are updated and expanded regularly. Examples are the German PROBAS eco-database (Umweltbundesamt, 2015) and GaBI database (sphera, 2014), Swedish SPINE@CPM eco-database (CPM, 2006), the Swiss ecoinvent eco-database (ecoinvent Association, 2022), the Japanese JEMAI eco-database (Japan Environmental Management Association for Industry, 2013), the US NREL database (National Renewable Energy Laboratory, 2012), the Australian LCI eco-database (AusLCI, 2011) and the European Platform on Life Cycle Assessment (European Comission, 2014). Finnveden et al. (2009) points out that the usefulness of aggregate industry data provides reliable and representative data on the one hand. However, on the other hand, it may also contain hidden biases and a lack of transparency. The importance of ensuring the quality of such data is suggested.

2.2 Uncertainty of models

Mathematical models are used to describe and quantify the environmental impact of products and processes. Mathematical models are affected by uncertainty because models can only approximate a real physical behavior (Pelz et al., 2021). In terms of sustainability, LCA has become a common model for estimating impacts on the environment. This model is underlying specific sources of uncertainty, which are explained at this point. The LCA targets product design and improvement, strategic planning, policy-making, marketing, and others (DIN EN ISO 14044, 2018). It can be used as a tool to compare different products (Heijungs, 2021). Uncertainty in LCA is a point that has already been widely investigated in different ways over the last few decades. Heijungs and Huijbregts (2004) made a classification after summarizing different studies of uncertainty categories in LCAs by the division into the three types: (1) data for which no value is available, (2) data for which an inappropriate value is available, and (3) data for which more than one value is available. The main categories for uncertainty from Morgan et al. (1990) are derived in subsequent publications regarding LCA by Hofstetter (1998) and Lloyd and Ries (2007), where the LCA mathematical model uncertainty for the seven categories is added with examples: (1) random errors and statistical variation like measurement error in physical constants or modeled relationships, (2) systematic error and subjective judgment such as extrapolating relationships from well-studied processes to similar processes, (3) linguistic imprecision like building models based on qualitative descriptions of relationships, (4) variability such as inherent variability in process relationships, (5) inherent randomness and unpredictably like inconsistent process characteristics, (6) expert uncertainty and disagreement such as disagreement about process mechanisms and system behavior and (7) approximation like simplifications of real-world systems, such as system boundaries. A comprehensive example of a concrete but popular error that can occur when using LCA is the truncation error as described by Perkins and Suh (2019). In summary, the LCA method highly depends on the user's assumptions about how they want to describe a scenario. These assumptions are then further calculated in a complex way, which can lead to a large source of uncertainty. This does not provide a trustworthy basis for comparing the results. Finnveden et al. (2009) summarizes that uncertainties are often not considered in LCA studies, although they can be high.

The PCF as a stand-alone value is affected by user and sector-specific assumptions, different frame conditions, the used calculation method, sustainability conversion factors, and other parameters. As a result, it is not possible to use the PCF to compare it with other products coming from different productions or sectors. There are existing approaches to reduce uncertainties to make the PCF more meaningful. Heijungs and Huijbregts (2004) describe three ways. The first way is the scientific way: more research has to be done, better data has to be found, and models have to be improved. The social way is to include stakeholders deeply and discuss the uncertain issues to find consensus on data and choices. The statistical way describes incorporating uncertainties like using MCS or calculating with different data values. Igos et al. (2019) proposed recommendations for the different steps of uncertainty treatment, following a basic, intermediate, and advanced approach in LCA, such as defining the range of results based on optimistic and pessimistic scenarios. In addition, Kuczenski (2019) notes that synthetic variability models like MCS, which are often very popular for studying uncertainty, can lead to false confidence in practice, and more authentic estimation of uncertainty should be studied.

All in all, the investigation of the PCF shows that there are different ways to reduce uncertainties, but only if the origin of the data is known and transparent. A methodology is needed that identifies the different data origins and quality in the balancing process as well as an included investigation of the balancing process itself in order to classify them. This will make it possible to assess the value of the PCF better, whether it is suitable for making comparisons with other productions or sectors.

3 METHODOLOGY OF PRODUCT CARBON FOOTPRINT ANALYSIS

The presented method consists of three parts. First, general information and data origins of all relevant data for the accounting of the PCF are determined. Based on this determination, the PCF can be divided

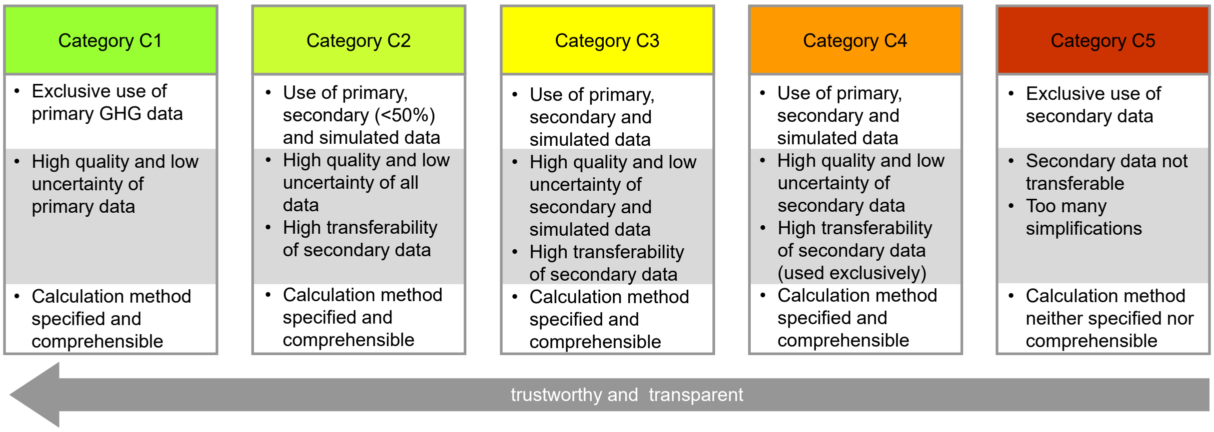
into five categories, followed by comparison possibilities regarding in between categories. Two perspectives are considered:
(1) the PCF is determined parallel using this method or
(2) the PCF has already been determined (e.g., by another company)

3.1 Origin of data

The data origin plays one of the main roles in the methodology. A further statement can be made only if the data origin is known. If no information about the origin is known, the PCF has no significance for the environmental impact of the product under consideration and cannot be used for comparison. The origin of data is divided into three classes: primary, simulated, and secondary. Primary data is derived from physical measurements such as energy consumption data sets from a production machine or directly emitted GHG measurements with a flow meter. Primary data must be acquired, pre-processed, transferred, and in the correct format to use the data in LCA. This usually generates the most effort but ensures the PFC can be calculated validly. Simulated data is generated by simulation programs, such as Computer Aided Manufacturing (CAM) simulation, and is a newer approach in LCA. This can be used to estimate the consumption of machines based on the travel paths or the required resources, such as coolant lubricant. Other computer-aided (CAx) simulations can also be used. Creating simulated data is an option when the product only exists virtually because it is currently being developed. This allows product-specific values to be determined if no primary data is available. Secondary data includes all data taken from eco-databases or internal databases from product series. The critical factor here is how applicable the secondary data is to the product at hand. In most cases, it is unavoidable to use secondary data. An example of using secondary data is when information of a supplier is missing, or the recording of primary data is too complex.

3.2 Categories

The methodology distinguishes between five categories. These are based, on the one hand, on the origin of the data and the quality and uncertainty of the data and, on the other hand, the transparency and traceability of the calculation. Depending on the category, products from different production scenarios can be compared. Figure 1 shows the five categories with the respective explanation of division.



Category C1	Category C2	Category C3	Category C4	Category C5
• Exclusive use of primary GHG data	• Use of primary, secondary (<50%) and simulated data	• Use of primary, secondary and simulated data	• Use of primary, secondary and simulated data	• Exclusive use of secondary data
• High quality and low uncertainty of primary data	• High quality and low uncertainty of all data • High transferability of secondary data	• High quality and low uncertainty of secondary and simulated data • High transferability of secondary data	• High quality and low uncertainty of secondary data • High transferability of secondary data (used exclusively)	• Secondary data not transferable • Too many simplifications
• Calculation method specified and comprehensible	• Calculation method specified and comprehensible	• Calculation method specified and comprehensible	• Calculation method specified and comprehensible	• Calculation method neither specified nor comprehensible

Figure 1. Five categories to classify the PCF

Category C1 is the category that should be targeted by all PCF calculations. Only primary GHG data is used here, so no conversion factors are needed. In addition, the uncertainty of data acquisition, pre-processing, and transfer is kept low, and the data quality is high. The transparency and traceability of the calculation are present, and the calculation method is mentioned and valid. An example of this is the naming and implementation of ReCiPe Midpoint H with GWP 100, which is often used in practice and addresses a global warming potential for a period of 100 years. This method is recommended because of the simplicity and transparency of implementation shown by Huijbregts et al. (2017). The naming and implementation through a valid calculation method is a condition for categories C1, C2, C3, and C4.

Category C2 allows using primary data with conversion factors, simulated or even secondary data up to the limit of 50% of the final PCF sum. When using secondary data, for example, from eco-databases, these must be transferable to the application, and the data origin of the secondary data must be valid. A negative example is if a material is unavailable in a database, such as PLA (polylactide) in additive manufacturing, and a material with properties similar to PET (polyethylene terephthalate) is used instead.
In Category C3, a mix of primary, simulated, and secondary data is used, but the share of secondary data is not limited. Primary and secondary data can be available exclusively with additional simulated data. Examples of different C3 scenarios are:

- Exclusively usage of primary data, but the quality or the uncertainty is insufficient. An example is low data quality because the data acquisition of the sensor system is disturbed or faulty in the pre-process due to the wrong choice of algorithms.
- Exclusively use of primary or secondary data with additional simulated data and transferability of secondary data.
- Mix of primary data and secondary data with additional simulated data. This may be due to the fact that data from a previous series is primarily available, which can only be transferred to the new series to a limited extent. Another example is the production of a prototype, where a first physical model is available.

In category C4, only secondary data, secondary with additional simulated data or a mix with primary data, is used where the data's quality or uncertainty is insufficient or the transferability of the secondary is not given. One example of this category is when a first estimation of the PCF is made in the virtual product design phase. This can be seen in LCA plugins for computer-aided design (CAD), like the sustainability tool for the CAD software SolidWorks (Dassault Systèmes SolidWorks Corporation, 2012). Category C4 can be used for a first estimation but should not be used for comparing different production scenarios.
Category C5 is the last category and is to be avoided in all cases. Here it is not clear where the value of the PCF comes from. The secondary data used are not transferable to the use case. This category is also applied when there are too many simplifications. The system boundary plays an important role in the calculation of the PCF. If the boundary is drawn too small, this can lead to a bias in estimating real impacts. In C5, neither the calculation method is defined, nor the value can be independently understood and calculated.
The flowchart in Figure 2 shows how to determine the individual categories of a given data set.

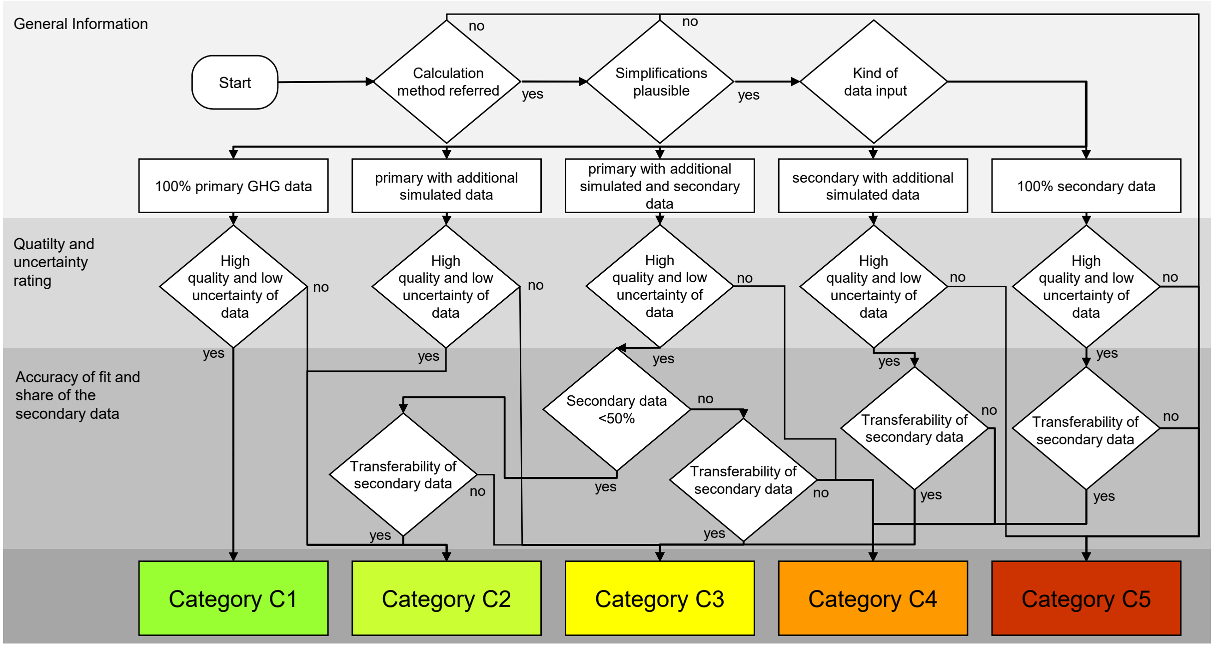


Figure 2. Flowchart of the method to categorize the PCF

3.3 Comparison between different PCFs

A comparison between different PCFs is only possible under limited circumstances. The categories presented are supposed to help to carry out the possibility of a valid comparison. Comparisons are only valid if the same calculation method or the same conversion factors were used for the environmental impacts. First, the categories must be determined based on the flowchart in Figure 2. Whether the PCF itself has to be determined or whether a value of comparative products is available does not matter. The methodology is applicable in both cases. If C5 has been determined in one of the comparison values, no connection can be made between the values. A comparison must therefore be rejected. Also, in C4, no comparisons should be made if one of the values fulfills the criteria for this class. If both comparison values are C4, no decisions should be made based on the ratio. C4 can only be used to make an initial assessment of the environmental impact of a product in virtual product development.

A comparison between different production scenarios can be performed up from categories C3. In this category, however, the calculation of the PCF and the data sources must be examined in detail. Making comparisons here is not always valid, especially between manufacturing sectors. In C3, it is, therefore, a case-by-case decision whether a comparison should be made or not. A comparison can take place if, for example, different possible development paths of a product are to be investigated. Here, the framework conditions and simplifications are to be considered the same.

Comparisons with a valid data basis and data source are possible within the first two categories, even if one value is in C1 and the other in C2. Comparisons exclusively within the first category, however, are to be preferred in any case and have a higher significance. It should be mentioned here that in most cases, it is impossible to reach 100% primary data because within a process chain many actors contribute to the product development, such as the raw material, purchased parts, the energy mix, lubricants, and many more. Primary data must be available from all of these actors to fulfill the class's conditions, some of which are impossible or difficult to measure. In many cases, suppliers have no interest or human respectively financial resources to collect primary data. Data sovereignty between company boundaries can also be an issue.

4 CASE STUDY

In the following, the implementation of the methodology presented in section 3 is shown by a practical example. The product creation of a marble maze serves as an example. The PCF comparison during the design and prototype phases is demonstrated.

The question to be investigated is:

What are the PCFs of a product made of steel respectively of plastic, and can they be compared?

In the first case, the product is made of steel and by CNC machining. Production from plastic is supposed to be by additive manufacturing (material extrusion (MEX) process). In the estimation, two values are determined by using LCA:

(1) the production from steel with a CNC machine and

(2) the production from PLA by a MEX process.

The modeling takes place during the design phase with secondary data using the LCA software "Activity Browser" based on the framework "Brightway". The eco-database ecoinvent (version 3.5 APOS) with ReCiPe midpoint H calculation method is integraded into the software. Raw material production (steel and PLA) and the marbles maze's manufacturing (CNC and MEX) are considered in the LCA. Impacts form transportation or buildings are ignored. The reference unit is one produced part. The result of scenario 1 is 4.86 kg CO_2e, whereas scenario 2 gives a value of 0.29 kg CO_2e. After performing the method, the result for both cases is category C4 as seen in Figure 3 because only secondary data with high transferability is used. So the values can only be used to make an initial assessment of the environmental impact and provide guidance for decision-making. Since a valid comparison of the two scenarios is aimed, it is decided to compare the PCFs during the prototype phase. Relevant primary data can be acquired by adding sensors to the production machines ((1) CNC machine + pre- and post-process machines, (2) MEX process machine).

For the calculation, the consumption values in the production of the individual machines are recorded and used with conversion factors from the eco-database. The real production and the recording of the values took place in the ETA factory of TU Darmstadt as part of the research project ArePron (2020). The result is 3.90 kg CO_2e. With the help of the developed method, the category has increased to C2 by

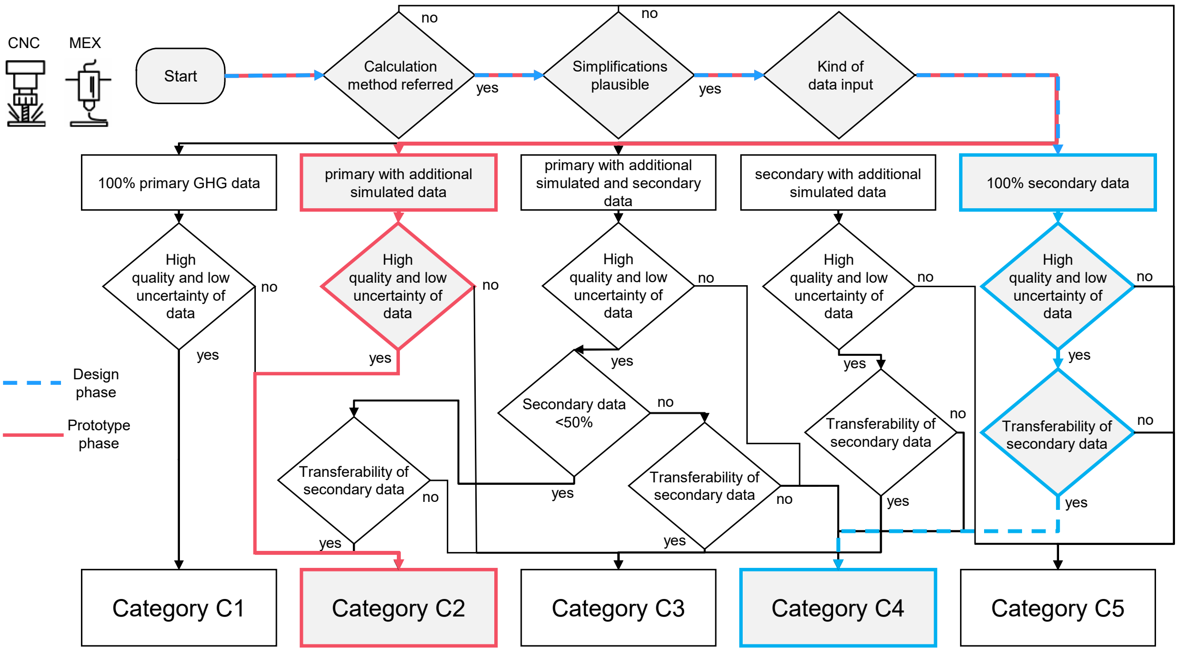


Figure 3. Flowchart during the design phase and prototype phase for CNC and MEX production scenarios

using the primary data, as seen in Figure 3. Adding primary data to the additive manufacturing process increased the category from C4 to C2 as well. The result in the MEX process is 0.59 kg CO_2e. To make the comparison meaningful, it was ensured that the same conversion factor was used for the energy mix. The factor is 0.61 kg CO_2 per 1 kWh and is taken from the ecoinvent database 3.5. Moving both scenarios to C2 allows a more trustworthy comparison than during the design phase. Both values differ from the estimation before during design phase. The value of additive manufacturing nearly doubled with the primary data. The value of the CNC process decreased by almost 20%. The result shows that the environmental impact of additive manufacturing is still significantly lower, but the difference in the values has decreased.

5 CONCLUSION AND OUTLOOK

The PCF has been established as a new reference value and control variable in product design. However, the calculation of the value is accompanied by many restrictions and assumptions. Therefore, the value can only be used for certain applications to a limited extent. In order to use the value as a control variable, however, comparisons must be made with different production scenarios. These comparisons need a framework structure in order to be able to make valid statements. This paper gives such a framework using a methodology for categorizing the PCF value. As a stand-alone value, no conclusions can be made about the trustworthiness of comparisons. With the help of this method, this is now possible. Using the example of a development of a marble maze, it is shown how comparisons can be made between different production scenarios. In the first step, this investigation is limited to the design phase. Investigating two virtual production scenarios uses secondary data from an eco-database, resulting in a large difference in the final values. Since the methodology results in category C3 for both values, the values are only comparable to a limited extent. The methodology can be used to see what is needed to make more valid comparisons. By integrating the primary values during the prototype phase, category C2 is achieved, which makes the values more comparable. It is noticeable that the value of scenario 1 (CNC) decreases by 20%, and the value of scenario 2 (MEX) increases by 110% due to the integration of the primary data. This shows the high uncertainties of modeling with secondary data. So the recommendation remains to integrate as much primary data as possible. The methodology can provide motivation for this.

Even if the PCF gives a value for converted CO_2 emissions, this value can still only be considered as a guide value. The real impact of a product can only be seen at the end of its life cycle. There are several reasons for this. Important to mention in this context that the system boundary greatly impacts the final result. If the boundary is only placed around the product, relevant sources of CO_2 equivalents will be ignored. Examples are a high scrap rate due to production errors, emissions from buildings, or emissions from the production plant itself. If a machine is used with 100% solar energy, the share of used energy in the PCF is zero. The value will increase if the solar modules' production and development are considered. It remains to be said that the value can only represent a fraction of the real environmental impact. This is also shown by the different periods of the GHG evaluation (Global Warming Potential) to 20, 100, or 500 years.

However, the PCF can be used as a comparative value between options. The method provides a framework for this, but concrete limits must be defined. For example, the threshold values due to uncertainty and quality are a further research subject. Integrating existing approaches, such as MCS, also need to be further integrated into the concept. In the PCF, only one variable is presented concerning the environment. The other midpoint categories, such as water use, are not shown. Thus, it can happen that due to the minimization of the PCF, another variable increases drastically in value. To work around this, the concept should include a way to warn about this problem.

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