Data Relevance and Sources for Carbon Footprint Calculation in Powertrain Production

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Abstract. The purpose of this work is to point out the importance of the production phase for the carbon footprint calculation of powertrain components and to improve the understanding of necessary data for this calculation. Evaluation of lifecycle assessment data from numerous studies showed, that there is often a shift from the emissions in the use phase to emissions in the production phase, when alternative powertrain concepts are used. Therefore, in this work our focus is on the carbon emissions in the production phase of powertrain components. Data of raw materials used, production processes and supply chains is necessary and the uncertainties associated also have to be considered. At present, there is only little sufficient support for design engineers regarding the collection of relevant data for the carbon footprint calculation of powertrain production. In this work a data structure, which supports the collection of relevant data, including possible data sources, is presented.

Keywords: carbon footprint · powertrain · data relevance · data collection · production phase

1 Introduction

The reduction of lifecycle carbon emissions from powertrains plays an important role towards achieving the ambitious long-term goal of the European Union, a transition to a climate-neutral society [6]. In the past, driven by legislation, the focus was on the emissions deriving from the use phase of powertrains. In the future, a comprehensive assessment of all lifecycle phases will be required to evaluate different powertrain concepts. Especially when alternative powertrain concepts are considered, a shift from the carbon emissions in the use phase to carbon emissions in the production phase can be observed. For example, a vehicle powered by an internal combustion engine (ICE) causes around 16% of its total carbon emissions in the production phase. For a battery electric vehicle (BEV) this value is about 40%. In addition to the environmental reasons for low CO_2 production, economic reasons will also become more important in the future. Possible carbon taxes or carbon customs duties will increase the demand for low CO_2 production processes. For simplification, in this publication the terms CO_2 and carbon emissions are used instead of the term carbon dioxide equivalent emission (CO_{2eq}), which covers all relevant greenhouse gasses (GHG). For the realization of low carbon powertrains, it will be necessary to include methods for the calculation of the whole lifecycle carbon emissions right from the design phases of a powertrain. In these phases design decisions with a huge impact on the full lifecycle carbon emissions are made and modifications of the design are still possible with moderate effort. A wide range of data is required to calculate the carbon footprint of a powertrain. This work should provide an overview of the required data and possible data sources.

2 Powertrain Components and their Contribution to the Single Lifecycle Phases

Coming from a fossil fuel propelled past, the technology of powertrains has experienced a significant change in recent years. Today customers can choose between internal combustion engines, fueled by gasoline, diesel or gas, different hybrid configurations (mild hybrid, full hybrid, plug-in hybrid), purely battery-powered vehicles, or fuel cells as a propulsion system for their vehicle. Fig. 1 gives an overview of possible powertrain configurations and the main components. For the upcoming years all these configurations will remain on the market, even though the market shares are changing significantly.

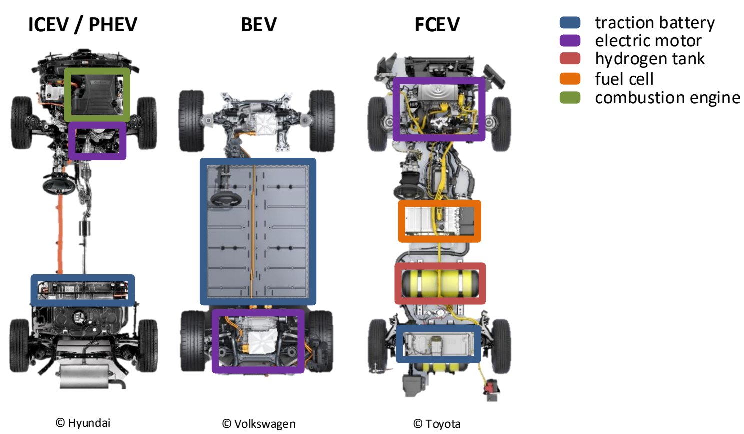

Fig. 1. Main components of different powertrain configurations

While the powertrain of a conventionally powered vehicle consists mainly of the internal combustion engine (ICEV) and the gearbox, the powertrain of a battery electric vehicle (BEV) consists mainly of a high-voltage battery, an electric traction motor and the electronic controller. For a plug-in hybrid electric vehicle (PHEV) all components of the before mentioned powertrain concepts are necessary, of course with different performance characteristics. The powertrain of a fuel cell electric vehicle (FCEV) consists mainly of a fuel cell stack, a hydrogen storage tank, and the electronic components to control the system. Additionally, a battery is necessary as a buffer to compensate for a lower maximum power-output of the fuel cell stack.

Fig. 2 gives an overview of the phases that need to be considered in a carbon footprint calculation of an automotive product. The production phase, on which the focus of this paper lies, can be subdivided into the extraction of raw materials, the fabrication of parts, the manufacturing of components, and finally the assembly of the vehicle itself. All these phases are linked by numerous logistics processes. Due to the fact that the high number of parts and components of an automotive powertrain (more than 10,000) are produced and supplied by an extensive global network of suppliers, the overall assessment of the carbon emissions of a vehicle is very difficult, leading to evident differences in the lifecycle results published in various studies. Further factors influencing the results of a holistic approach like a Life Cycle Assessment (LCA) are the different system boundaries and differences in the inventory chosen and assumptions made for materials, production processes and sites, etc. Such an approach is in-line with ISO 14040 [3] and 14044 [4] standard protocols.

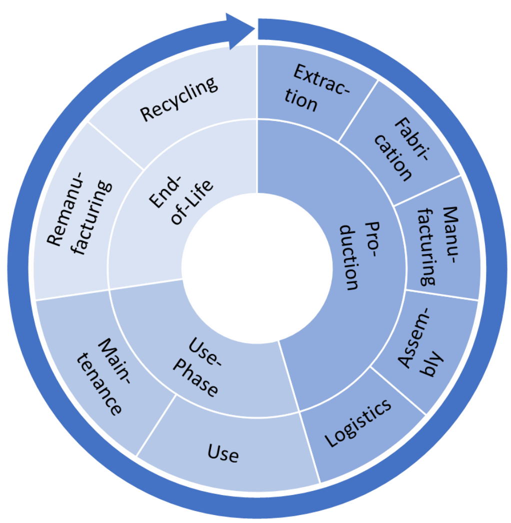

Fig. 2. Major life cycle phases for automotive products

To evaluate the numerous different values defined by already conducted LCAs on ICEVs, BEVs, PHEVs and FCEVs, a survey was executed. The results of this survey on more than 80 publications on vehicle-LCAs, including the standard deviation, min and max values is given in Fig. 3. Apart from the fact that the single production processes are well-known, the studies analyzed show that many assumptions and simplifications had to be made for the production phase. Despite an acceptable standard deviation, the min/max values of the carbon footprint differ by a factor of 3, even for a well-known product like an ICEV (see Table 1). For new powertrain concepts like a BEV or FCEV the differences are even greater. The part 'freight and logistics' is either not considered at all or included as a lump sum. In Europe alone the sector 'Transport' is the second largest contributor of greenhouse gasses with freight and logistics being responsible for a quarter of this amount [7].

Table 1. Carbon emissions for different powertrains and life cycle phases [tCO_{2eq}]

	Production	Use	End of Life	Total	Production	Use	End of Life	Total
	ICEV				**PHEV**			
MEAN	6,13	30,35	-0,24	36,60	7,53	22,57	0,45	32,03
MEDIAN	5,78	27,75	0,50	35,72	7,38	21,30	0,41	29,16
STANDARD DEVIATION	1,82	14,57	1,28	14,60	1,92	13,14	0,05	13,64
Min	3,08	2,10	-2,63	8,45	5,33	6,33	0,40	11,66
Max	11,25	63,35	1,17	70,95	11,24	43,05	0,50	52,90
N	82	79	38	80	18	15	7	15
	BEV				**FCEV**			
MEAN	11,08	14,57	0,11	24,49	11,45	14,12	0,65	24,68
MEDIAN	9,79	12,22	0,58	24,15	11,40	15,05	0,50	27,48
STANDARD DEVIATION	4,13	10,58	0,88	11,65	2,35	10,23	1,81	9,80
Min	3,99	0,00	-3,95	3,00	7,17	0,30	-4,61	9,88
Max	19,80	49,27	1,40	62,27	15,28	32,16	0,80	45,00
N	92	83	45	83	16	13	7	12

Table 1 shows the wide range of carbon footprint results of LCAs where "N" stands for the number of studies analyzed and compared. For example the ICEV was analyzed by 82 studies, of those, 79 studies determined the use-phase emissions, but only 38 the end-of-life emissions, and 80 studies gave a total emission figure. Examples of examined studies can be found in [8], [5] and [1]. The complete list of evaluated LCAs may be forwarded on request. As for the production phase, a complete and part specific analysis, which broke down every single component of the vehicle, could not be found. In comparison of LCAs from BEVs, FCEVs and ICEVs the ICEV was less detailed seeing as the others evaluated most of the major components rather than taking the complete powertrain as a single unit. Also, the analysis rarely considered where the components and resources were produced. One of the main contributors of the resulting deviation between all the studies derives from the assumptions made in the use-phase such as e.g. fuel consumption, or vehicle lifetime. Most of the BEV LCAs assumed that the energy demand in the use-phase was supplied by an EU-28 energy-mix but some also assumed, that the energy was completely "carbon neutral", therefore resulting in use-phase emissions of zero CO_2, not considering the carbon footprint of energy production. Another aspect of the use-phase of ICEVs is the fact, that the carbon emissions of this phase are mainly defined in a Tank-To-Wheel (TTW) perspective whereas the other propulsion systems are determined with a Well-To-Wheel (WTW) evaluation. The end-of-life phase also needs further investigation, as this phase depends on the recycling technology used, the amount of material reused and remanufactured and the necessary energy-input for each process-step. All in all, there are multiple aspects that need consideration in an LCA, and these aspects can therefore lead to different total values.

The absolute and relative contribution of the three main lifecycle phases (production, use-phase, end-of-life) to the overall lifecycle carbon emissions depends significantly on the powertrain concept. In the traditional ICEV drivetrain more than 80% of the entire lifecycle emissions (mean values) derive from the use-phase, when fossil fuel is burned, whereas in electrified powertrains around 40% of emissions derive from the production phase (see Fig. 3). This figure can vary significantly (see Table 1), as currently large-scale production processes for new powertrain concepts like BEVs or FCEVs are rather limited and considerable technological progress is constantly being made. In the study performed, literature data gave a value of 1 – 3.5 t of CO_{2eq} for the production of the fuel cell stack, and 1.2 – 4 t CO_{2eq} for the hydrogen tank. Despite the existing differences in materials for these components, the major deviations result from the system boundaries chosen, and the assumptions made, due to lack of information on manufacturing processes.

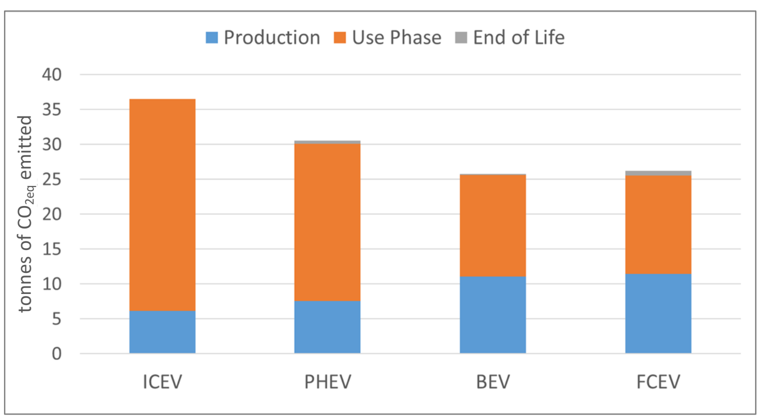

Fig. 3. Mean carbon emissions [tCO_{2eq}] from over 80 LCA studies for different powertrains

As shown in Fig. 3, the carbon emissions from the production of electrified powertrains is twice as high compared to conventional ones. The main influencing factors are the materials used and the energy intensive production processes of batteries, fuel cell stack and hydrogen tank, and – for both powertrain concepts - the energy source used for the production of components. Again, as for all other powertrain concepts, the influence by OEMs on the use-phase are limited (apart from developing a highly efficient powertrain to limit the energy consumption in this phase). Due to the change of ownership at the end of the production phase, as happens in most cases, the vehicle producers have no influence on how a vehicle is used, and how the energy carrier – be it fossil fuel, electric energy or hydrogen – is produced and how it is supplied to the vehicle's tank.

3 Relevant Data for Carbon Footprint Calculation of Powertrain Production

As discussed in section 2 and depicted in Fig. 3, the distribution of the emissions of alternative powertrain concepts across their lifecycle phases is different to classic powertrain concepts. A shift from emissions in the use phase to emissions in the production phase appears. To reach a low-carbon design of future powertrains it is necessary to reduce the carbon emissions of the production processes. Various data is required to calculate the carbon footprint of powertrain production. In this section, the production process, displayed in Fig. 2 with its material flows and energy flows provides guidance for a comprehensive overview of the required data.

Raw Material Extraction and Fabrication Data
The carbon emissions of the raw materials themselves, be it ore mining for raw metal production and crude oil or natural gas extraction for the production of plastics and chemicals must be considered from the very start. In addition to the extraction of the raw materials, the processing of pre-products is also often very energy consuming and has therefore to be considered. Examples of raw material production processes are the production of steel or aluminum profiles or sheet material. The area of production also plays an important role. That is because the energy mix and used production processes strongly depend on the location of production. For example, steel produced in India or China shows higher carbon emissions than steel produced in Austria. Also the amount of recycled material, which is used for the production of the material, has an significant influence on the carbon footprint, especially if the extraction of the raw material is very energy intensive like the production of raw aluminum or the mining of noble metals.

Manufacturing Process Data
Depending on the type of powertrain, the carbon emissions of the manufacturing steps can have a huge share of the total lifecycle carbon emissions. As explained in section 2, particularly the manufacturing process of electric powertrains leads to increased carbon emissions in the manufacturing phase. That is because the production of the battery requires a high amount of energy.
Because of the required robustness or because of other technical requirements, powertrain components are often made of metals like steel, cast iron or alu-

minum. Typical manufacturing processes for primary shaping of metal parts in powertrain manufacturing are casting and forging. The smelting of the raw material for the casting process requires thermal energy, which is either electric energy or fossil fuels. Typical cast parts in powertrains are pistons, casings, engine blocks and cylinder heads. Typical forged powertrain parts are connecting rods, crankshafts and gearbox components.
Other common manufacturing processes in powertrain production are all kinds of cutting processes like turning, milling, cutting, grinding and honing. The electric energy consumption of these processes is dependent on factors such as material parameters, processing time and size of the manufacturing machine. The same part can be processed by hand in a small machine or fully automated in a machining center. In addition to the manufacturing processes, emissions from intralogistics might also have to be considered for the full carbon footprint calculation.

Assembly Data
The assembly of the individual components to produce the final powertrain also leads to carbon emissions. Emissions occur from handling processes where components are moved and from joining processes where components or sub-systems are connected to larger units. Typical handling processes in the industry are carried out either manually by a worker or automated by a robot. Common joining methods for powertrain components are pressing, welding, riveting and screwing.

Logistics Data
The required raw material and vendor parts are often produced all around the globe. Therefore, the transport to the specific production facility also has an impact on the carbon footprint which should not be neglected. Finally, the distribution of the finished product to the customer has to be considered.

Additionally, raw data proprieties such as source reliability, velocity and variety should be provided for all previously mentioned data categories to estimate the data variability impact on the carbon footprint calculation.

4 Data Structure and Data Sources

In this chapter a data structure, which can be filled with required information for the carbon footprint calculation of production processes, is developed. This data structure should provide guidance for the data collection process. It should enable developers to set up a well-formed data model of the production process, which contains all required information for the calculation of the carbon footprint. In this work, the carbon emissions of the production process are assigned to four categories, which are displayed in Fig. 4. These are direct on-site emissions, energy supply emissions, emissions from raw material extraction and emissions from logistics processes. The four categories origin from the observation of typical production processes in powertrain production.

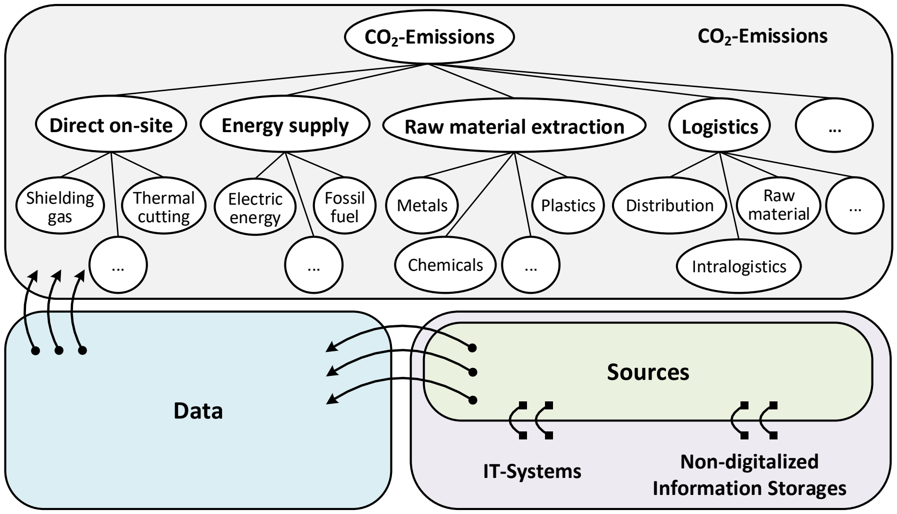

Fig. 4. Data flow and emission categories for carbon footprint calculation

To calculate the carbon emissions, various data from different sources is required. Fortunately, much of the required data is already available in companies. Especially product related data and data of production processes is often digital available. Other required data can be taken from external databases, has to be measured on site or is available in non-digitized form such as handwritten documents or employee knowledge.

4.1 Production Process Data

A possible way to sort the required data of the production process is displayed in Fig. 5. Guidance for the development of a suitable data structure can be found in [10], [12] and [11]. Data for the description of the manufacturing process can be assigned to the part, to the manufacturing activity or to the machine. Additional data from resource extraction, logistics and general data is required to calculate the full carbon footprint of the product. Typical data of the manufactured part is the raw material, design parameters like surface roughness and functional requirements. Examples of machine data, which have an influence on the carbon emissions, are the power consumption of the machine, the tools required and substances for operation and maintenance. Such substances are e.g. lubricoolant for chipping processes and welding wire for inert gas welding. Activity data is needed to assign the emissions from the machine to the single part. To calculate the carbon emission value, data of resources like electricity generation and raw material extraction is needed. If the production facilities of a company or suppliers are distributed over different countries, emissions from logistics have to be considered for the carbon emission calculation as well.

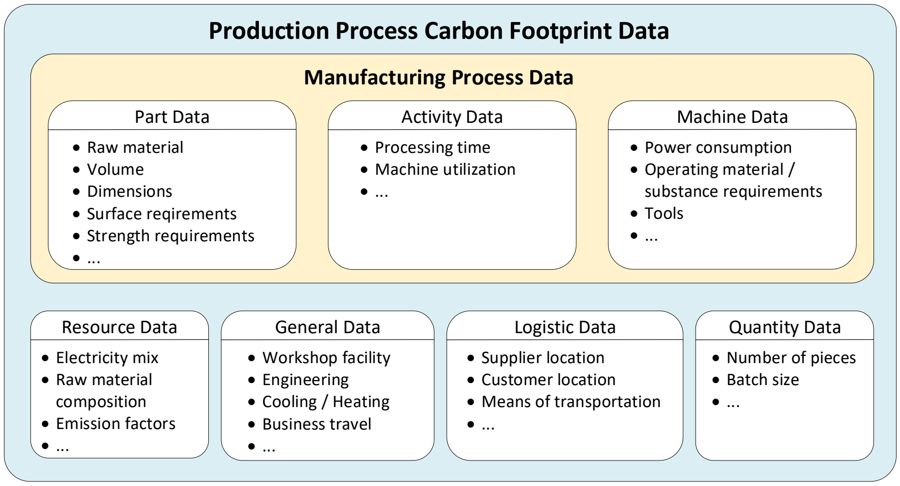

Fig. 5. Data structure for carbon footprint calculation

Finally, quantity data is required to assign the total carbon emissions of the production process to the single product. The data structure in Fig. 5 provides an overview of possibly required data for carbon footprint calculation. It aims to support designers in the data collection process. Another possible classification found in literature is the differentiation between activity data from the production process and emission factors from databases. Here a further fragmentation in primary data, which is measured inside the company, and secondary data from other sources, such as databases and scientific literature, is possible [2]. The data can also be classified according to the location where the emission takes place.

4.2 Data Sources

Depending on the aspect under consideration of the production process, suitable data sources have to be identified. An overview about possible data sources for the different data categories is shown in Fig. 6. In companies, IT-systems like PLM-Systems and ERP-Systems already contain a large number of relevant data sources for the carbon footprint calculation. These sources can be used to speed up the data collection process. In [9], opportunities and limitations of connecting CAD software and PLM systems with ecodesign software tools are assessed and in [13], a methodology to connect a simplified LCA tool with PLM and ERP systems is proposed. If the carbon footprint of a new product should be calculated in the development phase, data from similar products could also be used for a first carbon footprint estimation. To demonstrate the data collection process for carbon footprint calculation, an illustrative case study of a typical powertrain component is presented.

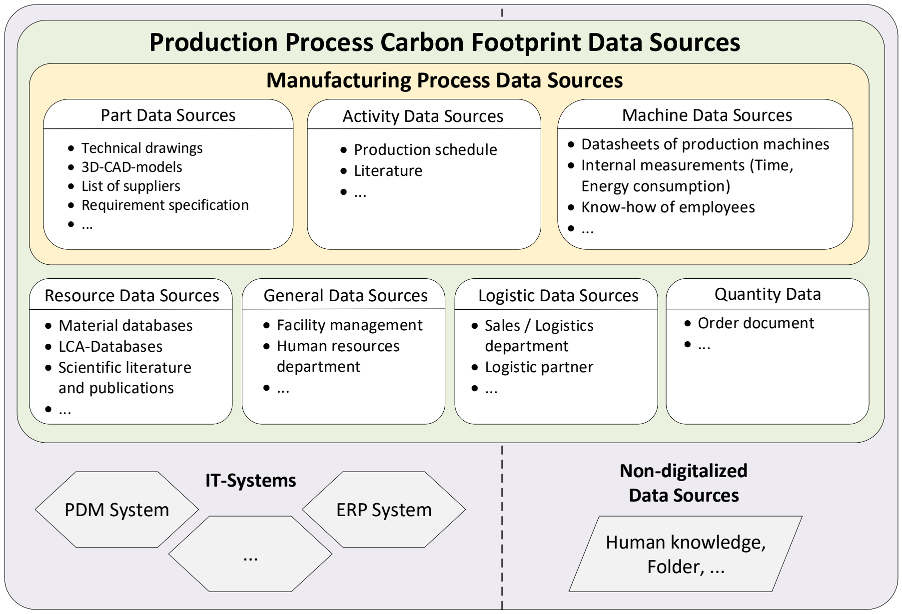

Fig. 6. Data source classification

As an example, the production process of a cast aluminum piston was chosen. A technical drawing of the piston and a 3D CAD model provide the basis for this case study. The technical drawing contains information about the raw material, heat treatment and surface requirements. The CAD model is used to calculate the amount of required raw material. If a PDM system is implemented in a company, this would be a good source for product related data. Possible sources for data related to the production processes are production plans, which can be found in an ERP system, and non-digitized information sources like knowledge of experienced engineers. For the case study of the piston, information for the calculation of the energy demand of manufacturing machines was found in machine datasheets or was measured like the processing times.

Data of the product and data of the manufacturing processes provide the basis for the carbon footprint calculation of the manufacturing phase. For the calculation of explicit carbon emission values, carbon emission factors are required. They can be found in free emission databases or databases subject to a charge. These databases provide e.g. values for carbon emissions per kg of raw material or carbon emissions per kWh of electric energy. General data can be obtained from facility management and the human resources department. For products with an energy intensive production process, the emissions from company processes which are not directly related to the manufacturing processes, might be neglected. All the previously mentioned data can then be used as input for the calculation of the product carbon footprint.

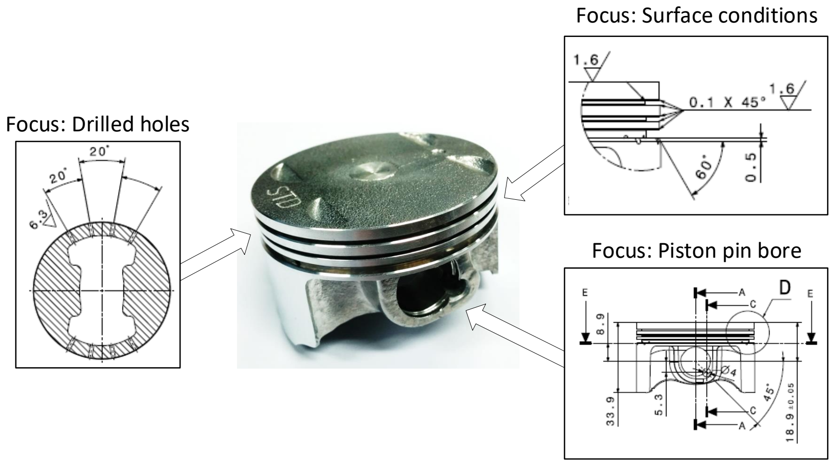

Fig. 7. Illustrative case study of cast aluminum piston

5 Conclusion

This paper points out the importance of the production phase for the total carbon emissions of powertrains. An analysis of 82 studies reveals that especially alternative powertrain concepts show a shift from the carbon emissions in the use phase to emissions in the production phase. With the increasing share of alternative powertrain concepts, the reduction of emissions in the production phase will become an important topic in the future. The calculation of the carbon footprint of production processes requires different types of data from various data sources. Important questions at the beginning of each carbon footprint calculation are, what data must be collected and what are possible sources for the required data? Therefore, in this publication two structures were developed to provide support for the data collection process. One contains the required data and the other one the corresponding data sources. This structures provides the basis for further research and development of a method framework, which can be used for the carbon emission calculation of powertrain component production.

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