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Results of the Environmental Impact Balancing as a Restriction of Undercarriage Concepts

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Abstract: This research shows the quantitative determination of the environmental impact using an undercarriage. The necessity of circular value creation is demonstrated using application strategies from the 9R model. Two strategies and the combination of these are applied to the undercarriage and the Carbon Footprint is approximated during raw material production, manufacturing, and usage. The results show potential design variables to reduce CO_2 emissions. The quantitative determination forms the basis for further research to calculate the current CO_2 equivalent during multidisciplinary optimization.

Keywords: Sustainable Design, Optimization, Circular Economy

1 Introduction

In 2018, the European Commission presented a vision whose key elements are intended to pave the way to climate neutrality. One of these key elements is the circular economy, which is used to minimize greenhouse gases (GHG). By 2017, GHG emissions had been reduced by 22% and by 2030, they are to be reduced by at least 40% compared to 1990. As a result, there is a need to transform existing products and their production processes with the approach of the circular economy. (European Commission, 2019) According to Olivier and Peters (2020), CO_2, along with CH_4 and N_2O, is a direct driver and contributed 72% of GHG emissions in 2019. The highest contributions to the CO_2 emitted are caused by coal, oil and natural gas combustion and have a negative impact on the environment.

Car manufacturers have set themselves the goal of producing CO_2-neutral vehicles. This applies not only to the production but also to the usage and End-of-Life (EoL) phases. To achieve this goal, car manufacturers want to focus on electric vehicles. The electric drive will use electricity from renewable resources wherever possible. The supply chains and production should also be largely CO_2-neutral. Another important part of achieving the target is the recycling of batteries. A large proportion of the batteries and their raw materials are to be recovered and fed into a closed material loop. (Volkswagen, 2021; Mercedes Benz Group, 2023a) This research study is focused on the fundamentals of reduced environmental impacts, circular design and production. The application area is located in the mobility sector using passenger car undercarriages. The prospect of success in reducing the environmental impact is to be achieved through a design that minimizes CO_2 emissions during the various phases of the product life cycle (PLC).

The opportunity for new concepts of battery electric vehicles (BEV) is relevant here, as these are designed differently for combustion vehicles due to the battery. The structure of the undercarriages is mostly affected by the smaller motor, the power train and the battery system. In addition to its structural functions, the undercarriages have important safety functions that help to protect the occupants, e. g. preserving the intactness of the cabin in the event of a crash. The battery can account for 25% of the total vehicle weight. Therefore, it becomes necessary to focus on the surrounding structure. The aim is to design a light and rigid frame and ensure the integrity of the passenger cell. (Belingardi and Scattina, 2023)

As Reimer (2021) summarizes, the mass contributes a high percentage to the energy consumption of a vehicle and the environmental impact during the use phase.

Lightweight design has the potential to increase the efficiency of vehicles but does not necessarily reduce the environmental impact on the overall balance. GHG emissions are reduced during usage, but material production, manufacturing and the EoL process are more energy-intensive. Therefore, lightweight materials and methods are used where weight reduction leads to significant advantages during the usage. Potting et al. (2017) describe a 9R-Model in the field of mechanical engineering. It deals with different methods in the circular economy, the so-called Design for ReX (DfReX) strategies to increase circularity at the product level. The DfReX strategies are about smarter product use and manufacturing, lifetime extension of products and recycling of materials.

In addition to structural integrity, it is therefore expedient to implement the DfReX methods before the production phase to reduce the environmental impact of the concepts as early as possible. The structural-mechanical design of an undercarriage is a highly complex system consisting of a large number of design variables, such as material properties, shape and positioning of the parts. As a result, it is already a challenge to find a good compromise between the different design variables which lead to different structural properties. Therefore, this study aims at the derivation of the main influence factors of the Carbon Footprint in different PLC phases for an automotive undercarriage. In the future, these are to be included in the early phases of product design, such as the optimization of components in the concept and design phase. As mentioned by Cantzler et al. (2020), most studies assume emission savings related to the application of DfReX strategies but do not include proof of their reduction potential.

This publication shows an application for an existing evaluation of the environmental impact of different concepts of undercarriages of electric vehicles. First, the basis and background are presented by highlighting the application strategies of circular value creation and the associated need for innovation. Chapter 2 shows applications of these strategies. In the next step, the environmental impacts that arise during the physical life cycle of a product will be assessed, followed by the assessment of GHG emissions. In Chapter 3, different industrial approaches in the automotive sector for life cycle assessment (LCA) are presented. The aim of Chapter 4 is to quantify the influence of preselected key factors that influence GHG emissions. Therefore, different design concepts for an undercarriage will be derived based on different application strategies for circular value creation to determine which of these causes the lowest GHG emissions. Therefore, the environmental impacts of the different undercarriage concepts are assessed and compared. This enables the proof of the efficiency of the application strategies. Finally, in Chapter 5, the results of the LCA of the undercarriage will be used to identify the main influence factors concerning the CO_2 emissions and the need for the integration of sustainability aspects in the early design phase is discussed. A brief outlook for the future is given.

2 Application Strategies for Circular Economy

This research study aims to contribute to achieving the climate goals of using the resources used in a passenger car for as long as possible and contributing to decarbonization through the usage of design concepts for circular economy. The term "circular economy" was examined by Kirchherr et al. (2017), among others. They point out that the term has not been standardized and cannot be understood identically in every publication. The conclusion is drawn based on a systematic literature research, where a large number of publications are analyzed. These publications deal exclusively with reduce, reuse and recycle. On this basis, the publication shows that the term CE must be extended by the EoL phase to include reuse, alternatively reducing, recycling and the recovery of materials in production/distribution and consumption processes. Therefore, this publication focuses on the 9R model, including the resulting DfReX strategies.

Linear, traditional economy includes the production, use and final disposal of products. However, not only the price of natural resources is rising, but value creation is becoming increasingly difficult. The linear economy is therefore no longer viable due to increasingly scarce resources. In the interest of reducing the environmental impact, existing products and materials should therefore be returned to production and used to minimize the amount of waste that ultimately has to be disposed of. (Circular Tayside, 2017)A so-called "closing the loop" strategy is applied, under which the strategies to be used, such as DfReX, are to be classified. As illustrated in Figure 1, the targeted DfReX strategies at the product level are very different in terms of their level of circularity and their need for innovation. Design for reusability, for example, aims to increase the service life of a product and its parts as much as possible. The part should continue to be used by other users in its original function. The level of circularity and the need for innovation are proportional. If the circularity level increases, as is the case with design for reusability, this also requires a greater need for innovation for the product. Design for Recycling is aimed at the useful reuse of the materials, in which the materials can be processed in such a way that the same or lower quality is achieved, but the need for innovation is lower overall. (Potting et al., 2017)

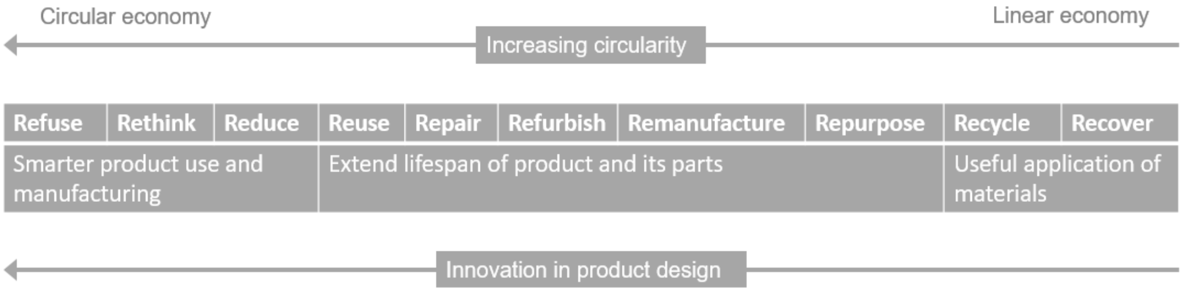

Figure 1. 9R-Framework, adapted from (Potting et al., 2017)

Some of these R-Strategies are already being implemented and applied in the industry. Mercedes-Benz Group (2023a) has set itself the goal of making all new vehicles electric and CO_2-neutral over their entire life cycle by 2039. Overall, more than 70% of the energy required at the Mercedes-Benz production plants is to be sourced from renewable sources by 2030. Suppliers should also minimize or exclude possible effects on the environment. The focus will be on materials and components that produce particularly high levels of CO_2 during production, such as steel, aluminium and battery cells. Among other things, it is possible to use secondary materials and conserve primary resources. The approaches described mainly fall under Design for Refuse and Design for Reduce and represent a high degree of innovation in product design, which results in a higher demand for new concepts and costs.

One example of Design for Reuse is reusable packaging. Possible reusable transit packaging can include pallets, but also containers and tanks. The main task involves the transportation of raw materials or goods to distribution centers or warehouses. There is now a large marketplace for reusable packaging in a wide range of industries, such as the automotive and food sectors. (Reusable Packaging Association, 2021)

Prendeville et al. (2016) present various case studies for the application of design for remanufacturing in industry. In one case study, for example, the bearings of an electric motor are replaced with higher quality bearings at the end of its first service life, thus extending the service life of the overall product. Another manufacturer has developed ways to remanufacture gearbox housings and turbos, as most parts can be machined.

Recycling in the automotive sector was already established in 2000 with Directive 2000/53/EC. Among other things, it defines that vehicles must be at least 80% recycled by 2006. (Official Journal of the European Communities, 2000)

The examples from the industry presented here show that the application of circular value-creation strategies is already being used. Newer approaches focus more on strategies that require a higher degree of circularity. It can be concluded that there is a need for research on high circularity to keep products and raw materials in the cycle as long as possible.

3 Balancing the Environmental Impact

The physical life cycle of a product can be understood as the path of the product, which begins with the extraction of primary resources for the product and ends with the thermal utilization or disposal of waste, see Figure 2. The physical life cycle of a product is thus linked by a material flow. (Kaltschmitt and Schebek, 2015)
As indicated in the previous chapter, one objective is to keep the material flow circulating in the technosphere for as long as possible. The need to move away from the linear economy and the application of the closing-the-loop strategies described above provide the base to reach a circular economy. Different ReX strategies can be assigned to the different stages of the PLC shown. (Circular Tayside, 2017)

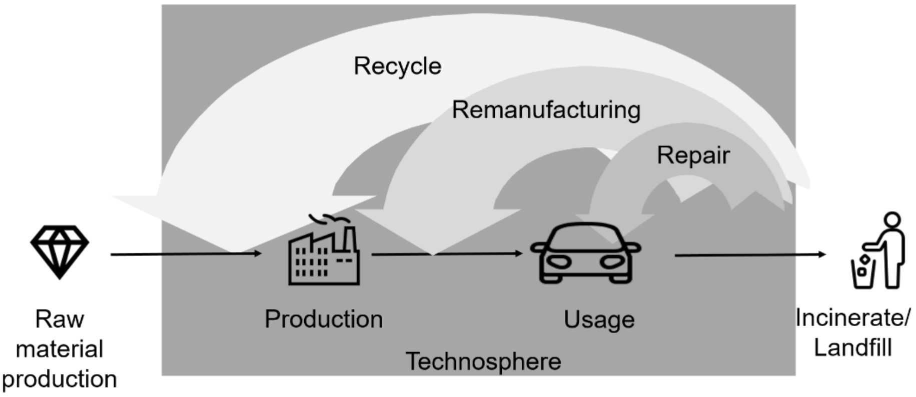

Figure 2. PLC merged (Kaltschmitt and Schebek, 2015; Circular Tayside, 2017)

Le Dan et al. (2020) have made several proposals to contribute to decarbonization through product design, the production process, consumption and waste management. These proposals therefore concern all phases of the PLC, include different DfReX strategies and contribute to the tackling of climate issues.

To take the environmental impact of the DfReX strategies into account as a design restriction or objective, it must be quantified. In future research, the overall focus will be on CO_2 balancing considering other structural criteria. The battery pack of the undercarriage must be designed in such a way that it supports the battery cells without impairing their functionality. (Belingardi and Scattina, 2023) This focus should enable the simple evaluation of designs in terms of suitability and environmental impact. It makes sense to predict the environmental impact of a product before it is launched, which requires a high level of knowledge about the PLC. To determine the success of the applicable DfReX strategies, environmental impact assessment approaches must be implemented in the early concept phase.

Evaluating the environmental impact of a product requires the most influencing criteria to make the modelling as accurate as possible. It must be clarified which factors are systemically relevant, which simplifying assumptions may be made, which effects should be taken into account and where the system boundaries are. One option for assessing and quantifying environmental impacts is the LCA. The entire PLC is considered, from resource extraction to thermal recycling and waste disposal. The LCA including all subsequent analyses and is based on a functional unit that determines what is to be examined. In the first phase of the LCA, the objectives and scope of the analysis are therefore defined. The second phase involves determining all material and energy flows that cross the system boundary by flowing into and out of the system. In the subsequent impact assessment, the environmental impacts of the material flows are to be recorded. The final evaluation includes the derivation of conclusions and recommendations. (DIN EN ISO, 2021; Kaltschmitt and Schebek, 2015)

As stated by Stölzle et al. (2023), most DfReX strategies affect the late phases of the product development process. The strategies primarily affect the product structure and are only implemented late. The most commonly used strategy relates to repair, while strategies for reuse are the least frequently covered. Zomer et al. (2022) highlight the need for research to investigate approaches to quantify the impact of individual DfReX strategies on emissions reduction. This should contribute to a deeper understanding of the effectiveness of the different DfReX strategies.

Design decisions in the early product development phase define important influencing factors about environmental impact. Changing these at a later stage is costly and time-consuming. The influence of the environment should therefore be incorporated into the design process at an early stage. To carry out a LCA, a high level of information about the product is required, which is not available in the early phases of the product development process. The quantification of carbon provides a descriptive value between different products. (Trimingham and Garcia-Noriega, 2011)

A special form of the LCA is known as the Carbon Footprint Method. This method is used to record climate-damaging effects and products and describes a key figure that includes all GHG emitted about their environmental impact. The unit of the Carbon Footprint is the so-called CO_2 equivalent (CO_2e), in which all factors affecting the environment are converted into this equivalent. (Kaltschmitt and Schebek, 2015)

The Carbon Footprint Method must also include the 4 phases of LCA, to quantify the environmental impact in the course of the PLC (DIN EN ISO, 2021). One possible simplified approach is to use tables containing CO_2-Factors. An example can be found in the information sheet for CO_2-Factors from the Bundesamt für Wirtschaft und Ausfuhrkontrolle (2023), an excerpt of which is shown in Table 1. Different CO_2-Factors in t*CO_2 equiv./t of raw material are given here, which enable the calculation of CO_2 emissions for different resources, for example. These factors can be used to obtain initial indications of the CO_2e from the mass of the resource. In addition, the information sheet offers the possibility of using a CO_2-Factor to determine the CO_2 emissions emitted from an energy source.

Table 1. List of resources, extracted from (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2023)

Name	Category	CO_2-Factor [t* CO_2 equiv./ t]
Steel (primary)	metal	2,18
Steel (secondary)	metal	3,4*10-2
Aluminium (primary)	metal	10
Aluminium (secondary)	metal	0,52

The LCA results of the Renault Kadjar show, that an LCA requires a high level of knowledge of the environmental impacts of all parts of the product. Renault has therefore limited the LCA to a total of five impacts. One of these, the Global Warming Potential (GWP), shows that the main shares of the kg CO_2e occur during vehicle production (24.8%) and usage (25.96%). Around 60% of the GWP is caused by metals during vehicle production and a further 15% by plastics. The main CO_2e emissions of around 90% occur during usage. The remaining emissions in the use phase are caused by maintenance and well-tank. The EoL phase, including recycling, is used to generate a negative environmental impact and thus contribute to climate neutrality. (Renault, 2017)

The results of the LCA refer to an existing complete vehicle to which the method was applied. In future developments, LCA is to be taken into account in the early product development stages and thus quantified. As the Carbon Footprint Method offers an approach that takes into account one of the most relevant factors influencing the environment and therefore has good initial significance, it is used in the following concept evaluations.

4 Balancing the Environmental Impact on the Example of an Undercarriage

The requirements for an undercarriage are extensive and offer scope for conflicting objectives. In general, the requirements can be divided into customer-relevant and production-relevant criteria. For customers, important criteria include a high level of comfort with maximum safety and minimum fuel consumption. On the production side, a low variety of parts, minimum use of materials and existing production equipment are important. (Bubb et al., 2016) In addition, there are also environmental requirements to meet the new standards.

In this section, undercarriage concepts for the bodies in white of passenger cars will be developed, focusing on the implementation of one DfReX method. The requirements for the undercarriage in terms of geometry, ergonomics, use and maintenance are assumed to be given. Only the undercarriage is taken into account in the following calculations. In the calculations, the estimated masses of the used parts, the main energy consumers during production and the fuel consumption during usage for a mileage of 200000 km are taken into account (see chapter 4.1). The aim here is to determine the main factors influencing the CO_2e for the undercarriage and to compare the potential for reducing CO_2 emissions of different DfReX strategies. For this reason, a case study is carried out in which different DfReX strategies are applied to the reference undercarriage and the resulting CO_2e and their main influencing factors are determined. The basis is an undercarriage concept in the SUV sector (see Figure 3), in which the geometry and the basic materials used were estimated and defined based on market research. It is assumed that the reference concept is compatible with both combustion engines and battery-electric vehicles.

4.1 Reference Concept

For the reference undercarriage, it is assumed that no steps have yet been taken to reduce CO_2 emissions. Therefore, only primary resources are used for raw material extraction in this variant. To calculate the CO_2e of the raw materials, the proportional masses of the individual materials are required. Material waste is not taken into account here. For this reason, the actual CO_2e of the raw materials are expected to be higher. As the concept in Figure 3 is purely a concept for visualizing the external dimensions, the mass can only be estimated roughly. In a real vehicle, the individual beams shown would be hollow structures. Consequently, a study by Alumobility is used to determine the weight of the individual materials of the reference undercarriage. The vehicle dimensions here are comparable and relate to an Audi e-tron. A weight of around 287 kg can be derived from this study for the undercarriage with doors and flaps. (Alumobility, 2021) Other add-on parts, such as tailgates and doors, which do not have to be taken into account for the reference undercarriage, can be deducted based on spare parts catalogues. This results in a total weight of approximately 210 kg for the undercarriage.

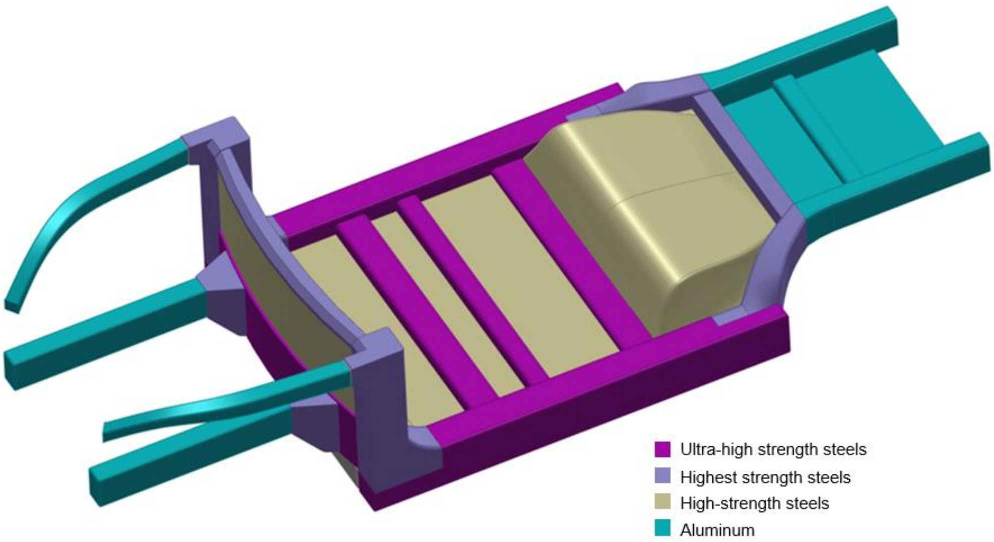

Figure 3. Base concept for the undercarriage

The weight of the aluminium and steel quantities is estimated proportionally to the undercarriage. This results in 35 kg for the aluminium and 175 kg for the steel. This mass can now be multiplied by the CO_2-Factor for the primary materials and the CO_2e of the individual materials added together. This results in 731,5 kg*CO_2 equiv. for the raw materials. All calculated results of the Carbon Footprint are also summarized again in Figure 4.

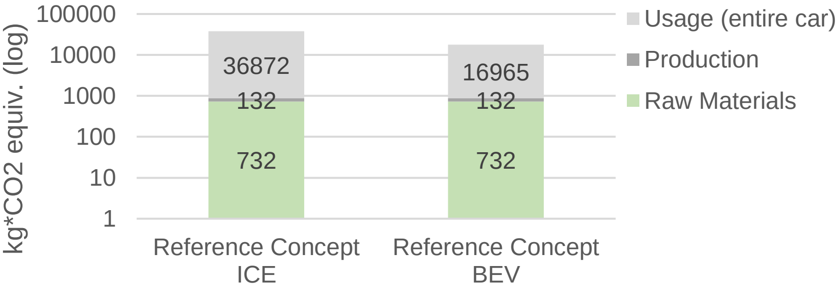

Figure 4. Results of the Carbon Footprint Analysis of the Reference Concept

In the next step, the CO_2 emissions in the production of the undercarriage in Germany must be analyzed. For this purpose, only the energy consumption in the press shop and body shop are considered below, as these contribute significantly to the production of the undercarriage due to the forming and joining processes used. According to a study by the European Automobile Manufacturers' Association (ACEA), an average of 2,82 MWh of energy was consumed per vehicle produced in 2021. The proportional, percentage energy consumption of the various trades for an entire vehicle is known from Bornschlegl et al. (2016). These are used to calculate the proportionate energy consumption in the body shop and press shop. In addition, the percentage production proportion of an undercarriage unit is used, which results from the mass proportion of the undercarriage about the body in white. These assumptions are used to determine the energy consumption of the individual trades for the undercarriage. This results in a value of 95 kWh for the press shop and 209 kWh for the body shop. As the resource consumption is not a material but electricity, these values can be added together and multiplied by the factor for electricity, 0.435 t*CO_2 /MWh (cf. Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2023). This results in a total CO_2e of 132 kg*CO_2 equiv. During the usage, there are two options for the drive system: It can be a BEV or an internal combustion engine vehicle (ICE). According to the Office of Energy and Renewable Energy (2021), a vehicle with an internal combustion engine consumes an average of 0.078 l/km of petrol. With a CO_2-Factor of 2.37 kg*CO_2 equiv./l petrol (Deutscher Bundestag, 2019) and mileage of 200000 km, this results in a CO_2e of 36972 kg*CO_2 equiv. for the total service life and 0,18 kg*CO_2 equiv./km. If this calculation is carried out analogously for a BEV with an average consumption of 0,195 kWh/km (Electric Vehicle Database, 2024), the result is a CO_2e of 16965 kg*CO_2 equiv. for the entire service life and 0,08 kg*CO_2 equiv./km. The EoL phase is defined by 2000/53/EC with recycling in the automotive sector. Furthermore, car manufacturers such as the BMW Group (2021) show that recycling in the EoL only has a very small share of the GWP. The EoL process is therefore neglected in these calculations.

Additionally, three concepts of this undercarriage are presented in this publication. The first variant is conceived with the Design for Recycling strategy, the second variant with Design for Reduce and the last variant a combination of both. As the three variants have different circularity levels, it is necessary to compare the potential success for reducing the environmental impact, in this case, the Carbon Footprint of the different strategies. The similarities and differences of the undercarriage can be seen in Figure 4, where a life cycle scenario for the first life cycle is shown for each DfReX method.

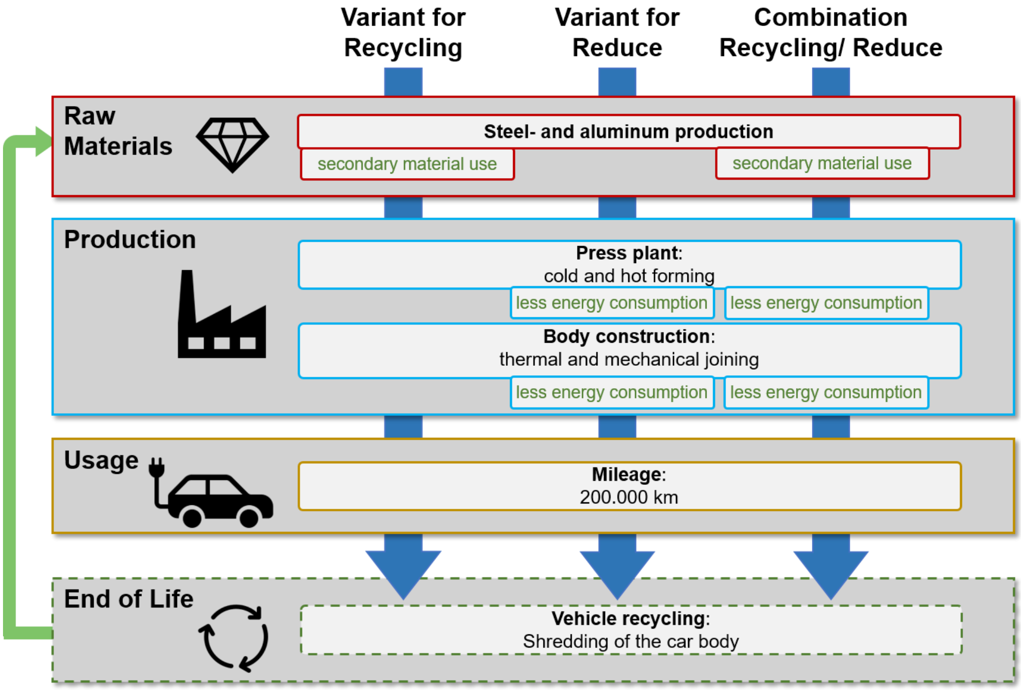

Figure 5. Similarities and differences between the concept variants

4.2 Variant 1: Design for Recycling

This strategy requires a small amount of circularity, which is why it is recommended that this strategy should always be considered in future developments. Alsaadi and Franchetti (2016) illustrate the recycling of the EoL vehicle for different car manufacturers, which includes that usable marketable parts are removed and the vehicle is then drained. During draining, all operating fluids, batteries and pyrotechnic components are removed. Other components suitable as spare parts can then be removed. Usable materials such as aluminium, scrap metal, glass and plastic parts can be separated. The remaining body in white should be shredded and reused as secondary material after sorting the different shredder fractions. This facilitates recycling in the EoL process and should be carried out following Directive 2000/53/EC.

For the recycling variant, it is assumed that the main changes in the Carbon Footprint occur in the production of raw materials. In this variant, at the first 50% and second 100% secondary materials are used. Production is assumed to be identical to the basic variant. There are also no changes within the usage, as the type of drive depends on the application scenario and tends to play a subordinate role here. If the calculation described in Chapter 3.1 is carried out with the reference undercarriage with the CO_2-Factors for 50%, this results in a CO_2e of 378 kg*CO_2 equiv.. Similarly, a CO_2e of kg*CO_2 equiv. can be calculated for the undercarriage made from 100% recycled metals. All results of the calculations for all variants are also summarized once again in Figure 6.

4.3 Variant 2: Design for Reduce

In contrast to the first variants, the Reduce-Variant Strategy is not created to start at the end of a product's life cycle, but before the product is realized. The aim is to increase material efficiency by reducing primary resources at an early stage and using secondary materials of equivalent quality. One possibility is to use high-strength steel by adapting the design, thereby reducing the wall thickness of the beams. This offers the additional advantage of saving weight. However, as the materials have already been specified in the basic concept, the efficiency of the process in the production phase is optimized here along the product creation process in terms of energy and resource consumption. Minimizing parts waste, shortening process chains and closing resource cycles through energy recovery or conversion can achieve a possible increase in efficiency in the manufacturing process according to Fraunhofer Gesellschaft e.V. (2008), for example. These points will be considered in the Reduce-Variant for the undercarriage and are taken into account in the calculation of the Carbon Footprint. More in detail, the authors of Fraunhofer Gesellschaft e.V. (2008) have assumed, that these actions, which have been partially implemented, have an energy-saving potential of a maximum of 30%. If this 30% is included in the production, the efficiency actions result in a CO_2e of 92 kg*CO_2 equiv.. At this point, it should be mentioned that if only renewable energies are used, the CO_2-Factor for electricity is 0 (cf. Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2023). Based on the selected approach, no CO_2e is emitted.

4.4 Variant 3: Combination of Design for Recycling and Design for Reduce

The third variant deals with the combination of Design for Recycling and Design for Reduce strategies. This is intended to show the possible potential when several DfReX strategies are applied to a reference. By using both strategies, measures are taken that influence both the raw material production and the production phase and thus have an impact on the resulting CO_2 emissions. In the first step, it is assumed that 50% of secondary materials are used in the concept and efficiency actions are implemented in production in such a way, that the energy saving amounts to 15%. The calculation is analogous to the procedure described in the previous chapters. This results in CO_2e of 378 kg* CO_2 equiv. in raw material extraction and 112 kg* CO_2 equiv. in production for this variant.

4.5 Results of the Carbon Footprint Analysis

When analysing the results of the Carbon Footprint, only the usage of the different drive types should be compared in the first step. The drive type of a vehicle is determined at the beginning of the design phase and is initially assumed to be transferable to all variants of the undercarriage with the different DfReX strategies. For this reason, this publication only analyses the Carbon Footprint in the usage for the reference concept. If the CO_2e of the usage of the reference concept with the integrated ICE and those of the BEV are compared directly with each other, it is noticeable that those of the combustion engine are up to 117% higher. In the case of the ICE, the usage accounts for around 98% of the total CO_2e of the first three product life phases. For the BEV, this is 95%. It should be mentioned at this point that the utilisation phase, in this case, refers to the complete vehicle and not just the undercarriage, so the actual proportion of the usage of the vehicle as a whole is lower. If results from Del Pero et al. (2018), for example, are used for comparison, it can be seen from the CO_2e that they show only slight deviations in the utilisation phase. If the results shown for the ICE are related to one kilometre driven, the CO_2e is 0.14 kg* CO_2 equiv./km. The CO_2e for the ICE determined in this publication is 0.18 kg* CO_2 equiv./km. The deviations are categorised as minor, as they depend on the vehicle type and its average consumption. Even compared to the results of Del Pero et al. (2018), the CO_2e of the ICE are 105% higher if the assumption is made that the electricity provided per kilometre also emits CO_2 through its provision.

In the evaluation of the design for the recycling variant, a proportion of secondary materials of 50% was assumed in the first step compared to the reference undercarriage. The effects of the Design for Recycling strategies here relate purely to the raw materials and their production. As already described, it is assumed for all concepts that the EoL is carried out by Directive 2000/53/EC. It is therefore assumed that the recycled materials have no different impact on CO_2 emissions in the EoL phase than primary resources. The partial use of secondary materials can reduce CO_2 emissions in raw material production by 48%. If theoretically 100% recycled metals are used for the undercarriage, the CO_2 emissions can be reduced by 97% in this case. This is not always possible in real applications.

One challenge arises from the fluctuating costs of recycled materials, as these are dependent on availability. To obtain recycled metals, they have to be collected and transported. Some metals require a high amount of energy for recycling, while others harbour risks, such as the release of contaminated materials into the environment. (AG Metals, 2023) It must be possible to separate the elements from each other during recycling. With aluminium alloys in particular, the addition of alloying elements often results in impurities that make recycling unattractive. The alloying elements cannot be melted out, as is the case with iron (Soo et al., 2018). Nevertheless, car manufacturers have set themselves the goal of using more and more recycled materials in their fleets. BMW, for example, uses monomaterials with detachable joints to separate materials (BMW Group, 2023). The car manufacturer Mercedes also wants to increase the proportion of secondary raw materials in its vehicles to up to 40% by 2030 (Mercedes-Benz Group, 2023b). Even if it is currently not possible to use 100% recycled materials in a vehicle, the choice of material plays a decisive role in CO_2 emissions. The right choice of material and their quantity (see Chapter 4.1) not only influences the structural integrity and weight of the underbody but also has a significant impact on the CO_2 emissions of a vehicle via the CO_2e.

If the Design for Reduce Variant is analysed, the effects over the entire PLC are classified as relatively low. The energy savings achieved by Fraunhofer Gesellschaft e.V. (2008) reduce CO_2 emissions in production by 30% compared to the reference undercarriage. With a share of 40 kg* CO_2 equiv., the savings are not decisive, as the use of 50% recycled materials, for example, can reduce the CO_2 emissions of the undercarriage by 354 kg* CO_2 equiv.. It should be mentioned at this point that only the main trades involved in the production of the undercarriage were taken into account in these calculations. In a real application case, in particular by considering the supply chains, the CO_2 emissions are higher. The main dependency of the production phase results from the energy sources and their CO_2-Factors (see Chapter 4.3). Nevertheless, consideration should always be given to reducing energy consumption. In addition to the energy-saving measures of Fraunhofer Gesellschaft e.V. (2008), energy-saving measures in production can also be achieved through product design (Soew et al., 2016).

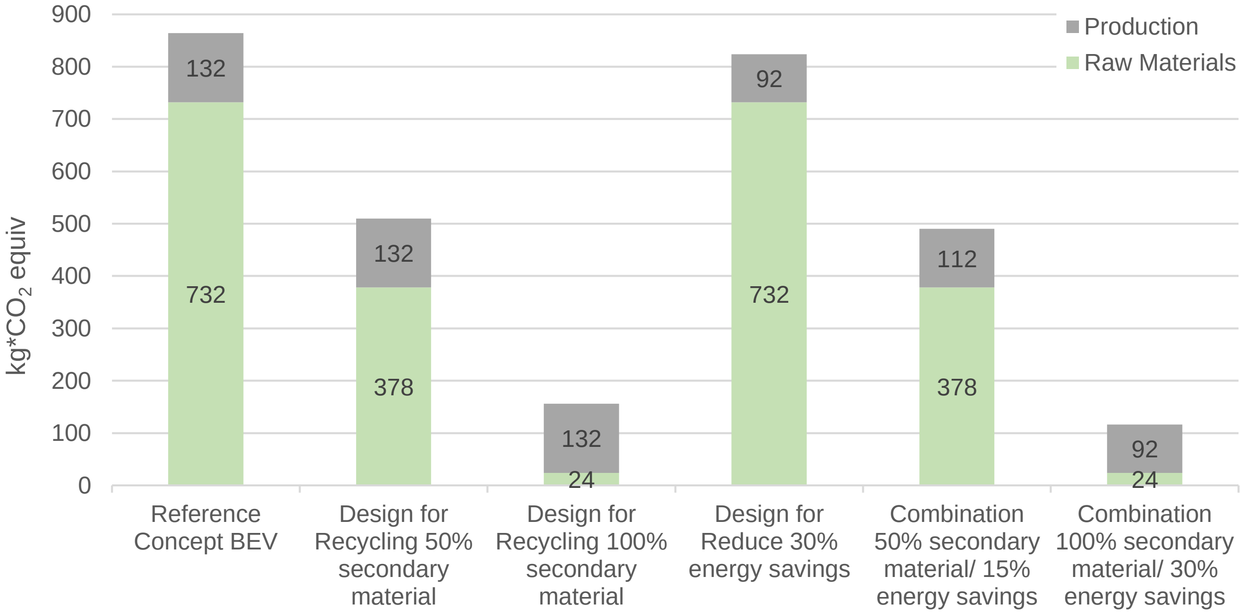

Figure 6. Results of the Carbon Footprint Analysis of the raw material production and utilisation phase of the concept variants

As shown in this publication, the choice of material and energy source, including their CO_2-Factors, have the main influence on the CO_2 emissions of the undercarriage. During usage, the type of propulsion plays a decisive role. If CO_2 emissions are to be minimized as an objective function, the material of the undercarriage, the energy sources in production and the type of drive must be varied and are thus identified as potential design variable. Since the choice of material has a high influence on both the structural integrity and the Carbon Footprint, this results in a complex problem with various design variables that can be varied. The problem presented can be transferred to other technical products with different degrees of complexity, and the number of design variables varies depending on the phases of the PLC under consideration.

5 Conclusions and Outlook

This publication shows a comparison of the efficiency of DfReX methods using the example of an undercarriage. The Carbon Footprint Method is used for the environmental impact balancing. To derive this approach, the application strategies of circular value creation and their already utilized and future potentials are first shown. In the next step, the environmental impacts are balanced to obtain quantitative values as a comparison for later concepts. To this end, the LCA is presented first. However, the aim is to enable a simple assessment of designs in terms of suitability and environmental impact, which is why the LCA are limited to the Carbon Footprint Method. This describes a key figure that includes the GHG emitted about their environmental impact, for example by converting the mass of raw materials using a CO_2-Factor. As it was previously unclear which variables have a main influence in the different phases of the PLC on the CO_2e, a preliminary study is carried out using the example of a passenger car undercarriage. Three concept variants for a passenger car undercarriage are presented, all of them refer to a reference concept of an undercarriage. The geometry and the base materials used are predefined. By applying the strategies of circular value creation, three concepts (Design for Reduce, Recycle and a combination of both) are developed.

In addition to the CO_2-Factors of the energy sources and materials, the main factors influencing Carbon Footprint are the quantities of material used, the quantities of energy required in the production and the kind of propulsion in the usage. The material, the type of energy source and the kind of propulsion can be adapted as design variables. The amount of energy required to manufacture the materials and production and the mass of the material result from these. The aim should be to estimate CO_2 emissions at an early stage of product development and include them in the development process to minimize them. The Carbon Footprint Method described here offers a possible solution. According to Cantzler et al. (2020), more research is needed to move from the assumption to proof that the use of DfReX strategies is associated with a reduction in the Carbon Footprint and to quantify this potential. Most existing studies assume emission savings through the use of DfReX strategies but do not provide evidence for the reduction. The case study presented in this publication contributes to providing evidence of the potential of applying DfReX strategies to an undercarriage.

The challenges for the undercarriage are to enable a sustainable design result from the large number of requirements and materials and the high complexity of the undercarriage. As Werner et al. (2020) describe crash and stiffness requirements in the bodywork area are often in conflict with the geometric requirements. This is why optimization procedures can be useful here. Sustainability aspects should also be included in future systems, for example, to predict and influence positively the potential environmental impact of an assembly at an early stage. As described by Keoleian and Sullivan (2012), the vehicle life cycle and its influences, such as material, use and recovery as well as design decisions, is a multi-criteria optimization problem. The circular economy and the associated circular design are playing an increasingly important role in the industry and must therefore be incorporated. If an assessment of the environmental impact is also to be taken into account, this must be quantified. If this value of each optimization algorithm is known and calculated automatically, this can be used as a restriction. (Werner et al., 2020; Duddeck, 2007) As shown by Sadollah et al. (2020), there are various approaches to combining optimization algorithms and environmental impact. Only a few of the approaches shown address CO_2 emissions and are used only for sustainable buildings. Ortner et al. (2022) provide a possible procedure for implementing the various DfReX strategies and relate specifically to product design. The authors implemented for example the Reduce Strategy in an optimization routine in such a way that the weight of the overall design and the volume were reduced via the use of different materials. Thus, the optimization process works with the choice of materials for the component. In the case of the Design for Recycling strategies, only recyclable materials that are as environmentally friendly as possible should be used during the optimization. The effectiveness of the optimization procedures can be demonstrated based on the case study carried out.

It is currently unclear which variables need to be known to determine the Carbon Footprint for the PLC as a design variable or objective function. Knowing the required design variables is an important step in setting up an optimization procedure, in addition to formulating the optimization objectives and restrictions and selecting suitable analysis models. For this reason, a preliminary study is first carried out manually in this publication using the example of different concepts for an undercarriage to determine the objective functions and design variables for the Carbon Footprint.

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