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Computer-Aided Design and Applications

Sustainability Engineering Support for Automotive Development

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Abstract. The development of sustainable products requires an integration of new methods and tools, which are able to support decision makers and developers throughout product creation processes effectively. In this context, the paper introduces a holistic approach to the provision of sustainability-related information to different sequences of product development and offers selected examples of applications from the automotive industry. The approach for effective evaluation of product design solutions is supported by an integration of life-cycle assessment under consideration of product characteristics, manufacturing, usage, and end-of-life treatment, facilitating the creation of optimized products with reduced environmental impact.

Keywords: product development, sustainability, life cycle assessment
DOI: https://doi.org/10.14733/cadaps.2025.947-957

1. INTRODUCTION

Product development is increasingly challenged by societal, environmental, and market-related boundary conditions that target more sustainable solutions to reduce environmental impact. This includes changes in technologies for energy provision and usage, as well as the application of materials, production technologies, and recycling processes to reduce resource demand and environmental pollution. The dependencies and interactions of factors related to design decisions are complex, as aspects of the entire product life cycle have to be considered. This includes the selection of materials, related manufacturing processes, different effects of the product's use phase, and recycling and disposal. In this way, the layout and design processes are influenced not only by technological and economic aspects but also by factors that indicate sustainability in a holistic view.

In this context, the present paper introduces an approach of sustainability engineering support, which provides comprehensive information about influencing factors of sustainability to engineers and decision makers throughout the entire product development. In this way, experts are able to make design decisions based on a broader data basis, considering technical, economic, and sustainability-related aspects. The approach is based on the provision of relevant information in parallel to the different steps of product development. This covers requirements engineering, concept development, manufacturing development, testing, and verification. Information is supplied by processing the desired data and material to the corresponding experts in the different sequences of product development. The introduced approach is applicable to all types of consumer products in general, whereas the article focuses on the development of complex products to discuss the potential on a broad basis. The introduced sustainability engineering support has been developed for the automotive industry, which is under great pressure this time to reduce its environmental impact. From this basis of relatively complex products, as represented by cars, several findings can be transferred to general product development. In any case, the efforts for the application of the approach should be adjusted according to the actual complexity and characteristics of the product under consideration.

1.1 Analysis of the State of the Art

The integration of sustainability-related parameters into product development has been and still is a relevant factor in research to improve design processes and to reduce environmental impact. In this way, several works have contributed to the enhancement of product development in recent years. AcAloone [12] introduced a guide for environmental improvement through product development, which provides a stepwise approach to integrating positive environmental effects into design and product development processes. Rio [14] developed a framework for eco-design for the effective integration of life-cycle assessment into design processes. The integration of environmental criteria into co-design processes was investigated by Michelin [13] and applied in a case study for a specific application. An approach for the integration of eco-design into computer-aided design processes was introduced by Gaha, [5]. In this context, Stadler [17] developed a knowledge-based framework for the effective integration of specific supporting processes into computer-aided design. Tao, [18], used a feature-based approach to integrate life cycle assessment and computer-aided product development and Bratec [2] conducted a study targeting to the integration of feasibility into eco-design processes based on a linkage of design criteria and environmental parameters. Salvador investigated life cycle assessment as a relevant basis for decision-making in product development [15] and Hirz [8], who applied extensive life-cycle assessment for the evaluation of products in the automotive context.

1.2 Research Demand and Challenges

The automotive industry is significantly influenced by legislative, market-related, and societal demands and boundary conditions. Besides traditional factors of costs, safety, convenience and comfort, aspects of environmental impacts are increasingly influencing the development of new cars. This includes the effective use of resources and materials and the avoidance of harmful impacts on the environment but also focuses intensively on the reduction of greenhouse gas emissions. In this way, design decisions are affected by a number of environmental impact-related parameters, which leads to highly complex processes in the development of new cars. Especially during vehicle conception and initial development phases, which are characterized by a high degree of freedom for the definition of product characteristics, the provision of fundamental data and information is crucial.

Costs play a major role in the development of products. In relation to the discussed boundary conditions, potential technologies to be integrated into a new car model are evaluated in view of their cost impact. As an example, lightweight technology has the potential to reduce fuel and energy consumption, which reduces CO2 emissions while driving. On the other hand, lightweight solutions might lead to higher production costs and to increased CO_2 impact during production. In this way, a trade-off between a potential reduction of CO_2 emissions and increasing costs has to be done. Another example includes the selection of technologies, e.g., powertrain systems. Here, battery-electric drivetrain systems seem to be a promising approach to reducing greenhouse gas emissions in comparison to traditional combustion engine-based propulsion technology. However, the production of battery systems comes with a high demand for resources and energy, which leads to higher costs as well as increased environmental impact of the production phase.

Life-cycle assessment is one approach to providing valuable information based on a holistic consideration of the product characteristics. As a state-of-the-art, life-cycle assessment is conducted in parallel or subsequential processes to product design, especially during early phases.

This procedure comes with the weakness that main decisions regarding product design are made with insufficient information about the actual impact on environmental-related parameters. In this context, the present paper contributes to improved development by introducing an effective approach for the integration of life-cycle assessment and product design to support design decisions, especially in the early phases of product development.

1.3 Research Approach

The research approach of the present paper includes four main steps:

1. Identification of sustainability-related parameters and influencing factors: Section 3 investigates sustainability-related factors with a focus on the automotive industry and discusses their impact on design- and development processes.
2. Finding an approach to integrate relevant parameters into (automotive) product development processes: Section 2 discusses the sequences of product development and section 4 introduces to life-cycle assessment with relation to the automotive industry.
3. Exemplarily implementation of a sustainability engineering support: Section 5 introduces the approach of integrating a supporting tool into in CAD environment with the target to assist engineers and decision makers instantaneously during their work.
4. The potential of the introduced approach is discussed based on an example of application of lightweight design in automotive bodywork in section 6.

2. ASPECTS OF PRODUCT DEVELOPMENT

Typically, product development starts with the definition phase in which the specifications of the product to be developed are elaborated. This includes a detailed investigation of user demands and a study of existing products and of (potential) competition in the target markets. As a result, use-cases, product-specific characteristics and technical requirements are determined as a basis for subsequently performed development processes. In addition, costs and life-time-related efforts, e.g., regarding product upgrades, maintenance and service are defined. In the following concept phase, the elaborated specifications are converted to technical solutions and realized in first drafts. This includes conceptual layout of functionalities, styling and packaging, as well as the integration of technical solutions on system- and module level. Besides the involvement of traditional engineering disciplines, these initial phases require detailed consideration of sustainability-related aspects to provide a fundamental basis for later development sections. This step especially comprises the careful definition of product characteristics and behavior in view of production and recycling, but also with respect to the use-phase. In this way, parameters describing applied materials, components and functionalities that support economical use have to be defined and determined in the requirements specification. During subsequent manufacturing development, the conceptual product design is advanced in detail to production-ready maturity. This includes system development as well as detailed development of modules and components by use of computer-aided design and simulation tools. In the manufacturing development phase, a main focus is put on production- and manufacturing processes by intensive integration of the corresponding supplier. Throughout these development phases, numerous product-defining decisions are made, including geometrical shape, materials, connection technologies, etc. These design decisions influence production technologies and costs, but of course have a great impact on the product regarding sustainability-related aspects. Due to the fact that especially in the early phases of development the degree of freedom for finding optimal solutions is largest and the number of unknown internal and external influencing factors is not yet clearly defined, there is a relevant demand to integrate sustainability-related information in a holistic way here.

3. SUSTAINABILITY-RELATED FACTORS

Besides technically and economically driven aspects, the consideration of ecological factors plays an increasingly important role in product development. This includes the reduction of emissions to decrease pollution and climate warming, but also the consideration of land-, energy-, water- and other resources demand Zapf, [20]. It is relevant that these aspects have to be considered for the entire product life cycle, including conception, development, production engineering, manufacturing, the use phase, and finally, recycling and disposal. Global climate change, resource scarcity, and growing pressure from relevant stakeholders have stimulated the industry to integrate sustainability considerations into their business activities. These reflections have to start already in the early sections of product development since, in these phases, a main share of product characteristics, costs, and the majority of environmental impacts are determined. Sustainable product development refers to a number of directives to ensure compliance with material prohibitions and environmental regulations in manufacturing and end-of-life phases. One example of legal conditions includes the ELV directive of the European Union, which addresses end-of-life treatment [4]. Another focus of the legislation lies in the reduction of greenhouse gas emissions and pollutants during operation. A selection of related legal conditions in this context is described in [19].

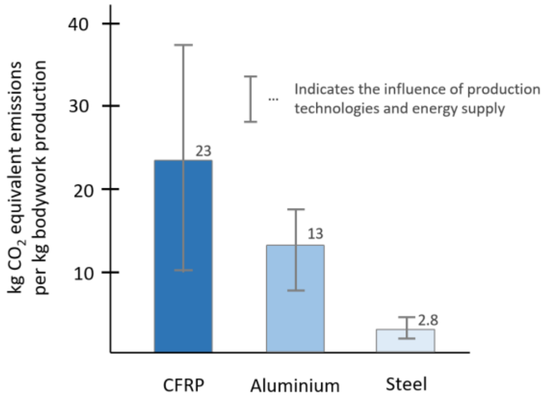

Figure 1: Production-based CO_2 equivalent emissions of selected automotive bodywork materials.

The application of lightweight materials is often discussed in the development of complex products. For example, in the automotive industry lightweight design can reduce driving resistances and thus lower fuel-, respectively energy demand during driving. Here, different lightweight materials come to use, e.g., high-strength alloys, light metal, fiber-reinforced plastics, multi-material construction, but the resources and energy demand of materials production, processing and vehicle manufacturing might be increased for certain technologies. In the example of automotive body design, the use of aluminum material has potential to reduce the body mass about 30% in comparison to steel-made car bodies. Moreover, the use of carbon-fiber reinforced plastic (CFRP) material has a weight reduction potential of about 50%. But the efforts for production of these lightweight materials is significantly higher than for steel. Figure 1 shows results of a study that analyzed the impact of different body materials and their production technologies on the CO_2 equivalents of bodywork production. The study is based on [16], who investigated the greenhouse gas emission impact of different influencing factors on CFRP production, and is enhanced with data from an actual study for investigation of body materials for a midsize class car. Remark: The relatively large variation of CO_2 impact for CFRP is based on the fact, that different production technologies are taken under account. The lower limits indicate future technologies and the use of electric energy with a low CO_2 impact. The upper limits indicate today's production technologies and the use of average CO_2 footprint of electricity production in industrial countries. It has to be stated, that a relevant impact on the greenhouse gas emissions is also caused by the different suitability of the technologies for recycling. Steel and aluminum can be supplied to recycling processes in an efficient way on industrial scale, whereby CFRP is very difficult to recycle. As a result of the study, the diagram shows that a reduction of body weight by technology change is connected to significantly higher greenhouse gas impact in production. In this way it is highlighted that the entire lifecycle of the product must be considered when selecting a specific technology in product development.

Besides body weight and production-related greenhouse gas impact, economic and technological factors are also to be considered in decision making processes. In view of the selection of car body materials, this includes investments costs for production facilities and variable costs for raw materials, body panels and parts manufacturing, joining technology, corrosion protection and paining. Considering these factors, steel bodies show economic advantages in case of larger production sizes, typically above about 100.000 pieces per year. Aluminum space frame design enables the introduction of relatively simple components, which reduces investment costs, but increases costs for assembly and joining techniques. Carbon fiber provides advantageous physical behavior, but this technology is the most expensive one for automotive body design by far (and has the highest CO_2-impact of production). As a consequence, it has to be investigated in detail, if a lightweight technology is advantageous in view of total life cycle footprint and economic viewpoints.

This example demonstrates the essential importance of an overall consideration of life-cycle-related aspects in the product development process. The integration of eco-design approaches and strategies for sustainable product development can contribute significantly to the reduction of resource demand and increase the efficiency of material cycles facing future challenges in sustainable production. In the conception- and design process, several aspects have to be considered: Careful use of resources plays a crucial role for reaching sustainability goals. This includes recycling-related product development that forces the use of recycled materials. If possible, renewable (e.g., plant-based) materials should be taken into account. Consideration of guidelines of materials marking and disassembling processes can support recycling, not only for complex components, but also for simple parts. Heavy metals should be reduced as far as possible to reduce environmental impact and to increase the re-usability of recycled metals.

4. LIFE-CYCLE ASSESSMENT

Comprehensive consideration of sustainability-related factors requires detailed investigation of corresponding boundary conditions and influencing parameters. For this purpose, the method of life-cycle assessment (LCA) is deeply integrated in the approach of sustainable engineering support. In this way, LCA is applied to evaluate and compare different design variants regarding their behavior in view of specific key parameters under consideration of the entire product life-cycle, including manufacturing, use-phase and end-of-life. The application of LCA is standardized, e.g., according to the ISO 14040 [10] and the ISO 14044 [11] and is characterized by a pre-defined sequence of process steps, Figure 2. Representative key parameters include energy and resources demand as well as environmental pollution.

An important parameter for evaluation of product characteristics represents the life-cycle-based carbon footprint, calculated as carbon dioxide equivalent emissions (CO_2 equivalents). Equivalent emissions mean the consideration of different impacting factors (e.g., provision of resources and energy, manufacturing and recycling processes, as well as various gases and pollutants) by conversion and computation to one representative parameter. In this way, CO_2 equivalents are often taken as relevant parameter to support design-related decisions in product development. Relevant for successful LCA is the provision of comprehensive and correct data of materials sourcing and processing. There are different commercial software tools available, supporting LCA with the corresponding information, e.g., [1], [6], [7]. These tools are integrated in the present approach of sustainability engineering support.

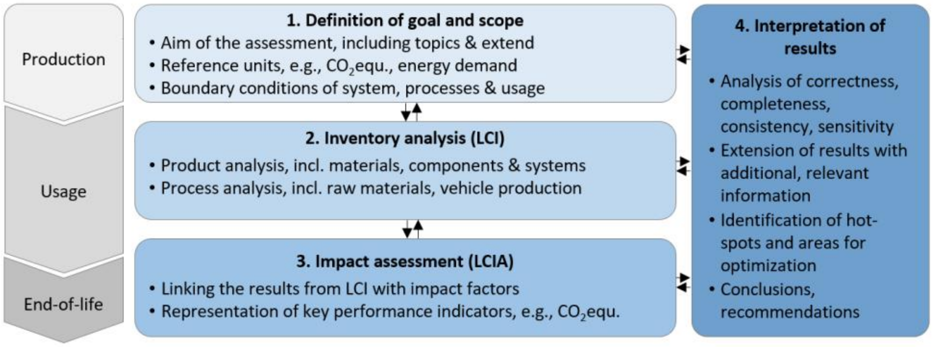

Figure 2: Standardized process of life-cycle assessment, [9].

Figure 3 introduces the general procedure of an LCA for complex products using the example of automotive development and highlights relevant factors that are included in the sustainability engineering support. The assessment is split into four main sections: Materials production, product manufacturing, product usage, and end-of-life treatment. Materials production includes the provision of raw materials, materials refinement, and alloying, as well as logistics. Product manufacturing includes the production of components, modules, and systems, as well as assembly. Relevant are the applied production technologies and processes at the corresponding suppliers and manufacturer locations, as well as logistics and transportation. In addition, the resources and technologies used to supply energy for production are of high importance. The use phase includes the expected carbon footprint during product usage. This comprises energy demand during use, efforts for maintenance and service, and potential exchange of components, e.g., spare parts. The end-of-life phase comprises dismantling, reusing components and materials, recycling, and disposing of waste.

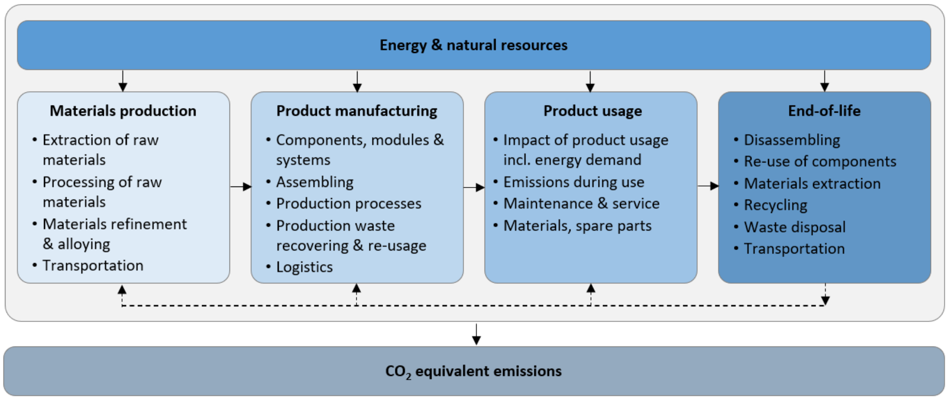

Figure 3: Main phases and influencing factors of a CO_2 equivalent-emissions oriented LCA.

5. SUSTAINABILITY ENGINEERING SUPPORT

The introduced method, capable of effectively supporting design engineers and decision-makers in their work, is based on direct integration of a data-based tool into the design process. In this way, experts are supplied with fundamental and comprehensive information about sustainability-related characteristics of their design decisions, and that in real-time. The method supports holistic evaluation of solutions, which not only covers the traditional technological and economical aspects, but also involves relevant data of environmental impact. Figure 4 shows the architecture of the approach on the example of automotive bodywork development, but the methodology can of course be applied for different other products, too. In the exemplarily shown bodywork development process, the computer-aided design (CAD) model plays a central role because the CAD process defines geometrical shapes and materials as well as manufacturing-related aspects. Thereby, the CAD process is closely interlinked with parallel engineering processes, e.g., packaging and ergonomics, body structure development and crash simulation, aerodynamics optimization, and manufacturing-related investigations [8], [17]. In the course of the design process, the CAD model serves to generate and supply geometrical data and characteristic parameters to adjacent processes and receive information from engineering processes for the enhancement of the model in the course of circular, recursive processes. In this way, the sustainability engineering support is connected to the CAD process because of its central role in product development. This strategy enables processing of information via the design stage to other connected development processes.

The sustainability engineering support is composed of four main modules, plus operational process management and interfaces to product lifecycle management (PLM) and different databases. The four main modules include an interface for data definition, a so-called input data module, a comprehensive section for life-cycle assessment-based analysis and investigation, a section that enables variant studies and optimization by parameter variation, and finally, a section for representation of the results. The tool can be applied throughout product development by integrating sustainable engineering support into the different phases of product development to provide tailored information for each step of product creation. This covers the elaboration of product characteristics during requirements definition and the concept phase, but also detailed module- and component development as well as production development and supplier integration.

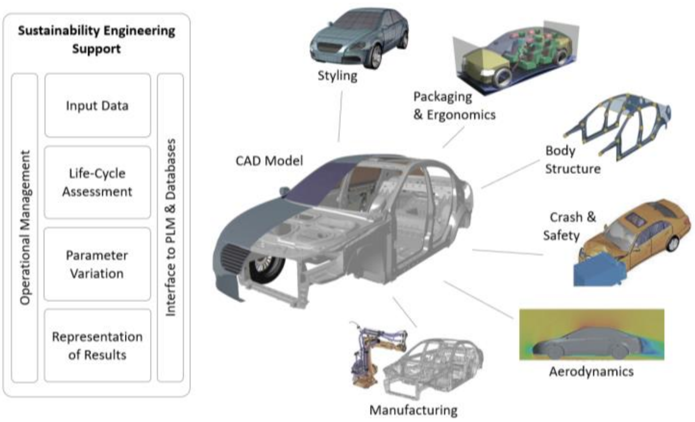

Figure 4: Architecture of the sustainability engineering support on the example of bodywork development.

In an exemplarily realization of the approach, it has been integrated into a commercial CAD software, [3]. Figure 5 shows this integration by use of specified toolbars that provide the different functions. So, the design engineers have easy access to the tool directly in the used CAD software and can perform sustainability evaluation during their design work. In Figure 5, the application of the tool is exemplarily shown for the development of a sheet metal part, which represents one component of an automotive bodywork section. The part is made of standard steel with specific material characteristics, that influence geometrical shape, mass and joining technologies. As an alternative, high-strength steel might be an option, which allows lightweight design, but that comes with higher effort in materials provision and processing, and consequently higher energy demand and CO_2 equivalent emissions in production. In this example, the sustainability engineering support provides a bunch of information to the design engineer, which includes product characteristics as well as environmentally-related footprint of production and during the use phase, e.g., a reduced energy consumption of the car because of less vehicle mass. Based on this information, the expert can select the optimal variant for the specific use case.

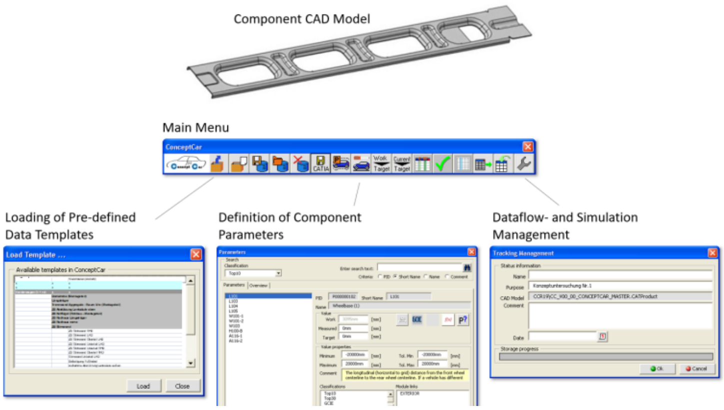

Figure 5: Exemplary application of the sustainability engineering support for the development of a sheet metal part.

The example of application based on a single sheet metal part is focused on the material selection within tight boundary conditions, because an overall decision for a steel bodywork has been made in a previous process step. Of course, the approach of sustainability engineering support can also be applied on system level, e.g., in course of concept development. In that case, the entire vehicle bodywork would be assessed in view of potential design solutions and material selections. In case of a full-aluminum body, the exemplarily shown component might have a very different geometrical shape, which has to be assessed accordingly in view of its impact under consideration of sustainability criteria. In another option, the bodywork could be made of CFRP, which would lead to an even more different design solution that could make the exemplary component obsolete. In that case, the sustainability-related consideration would be conducted for the entire car body design and compared with different other car body solutions, e.g., steel body and aluminum body.

6. EXAMPLE OF APPLICATION

To point to the relevance of sustainability-related consideration during product development, an exemplary application of the introduced method is shown in Figure 6. Here, the impact of different car body materials on the life-cycle CO_2 equivalent emission impact is indicated on the example of a typical midsize class car bodywork. Three different body technologies are considered: A traditional steel bodywork with a mass of 380 kg, an aluminum body structure with a mass of 270 kg and a CFRP body with a mass of 200 kg. The impact of production is calculated with average values of each technology, see Figure 1. The impact of the reduced vehicle mass in the use-phase of the car is considered by a reduction of fuel consumption based on lowered vehicle weight for the aluminum and the CFRP bodyworks: The standard car has a fuel consumption of 5 liters gasoline per 100 km, the car with aluminum body a fuel consumption of 4.7 liters per 100 km and the car with CFRP bodywork a fuel consumption of 4.5 liters per 100 km. In this way, the car variants equipped with lightweight bodies show a considerably lower CO_2 impact in the use phase. Remark: for the presented study, only the different body materials (and different body masses) are considered. All other technologies, e.g., propulsion, safety and comfort equipment are kept the same for the three variants. Figure 6 shows the impact of CO_2 equivalent emissions for the production of the three bodywork variants. It is visible that the steel body has the lowest factor with about 1 ton of CO_2 emissions produced. The alternative materials show considerable higher emission impacts with 3.5 tons for the aluminum body and 4.6 tons for the carbon-fiber body, because of the more complex processes of material sourcing and bodywork production. In the use-phase of the car, the lighter materials lead to lower driving resistances and thus a reduced fuel consumption, which reduces the CO_2 impact considerably in comparison to the variant with steel body. But considering the total balance of CO_2 emissions, it is visible that the higher influence of production of lightweight materials cannot be compensated during the use phase. In a total consideration for a driving distance of 200000 km, the car with steel body has a greenhouse gas impact of 24.2 tons, the car with aluminum body an impact of 25.3 tons (plus 4.5 %) and the car with CFRP body an impact of 24.4 tons (plus 4.9 %). In this way, the steel body represents the optimal solution under consideration of the life-cycle carbon footprint. This information is of great value especially in the early phase of vehicle conception to support the right decisions for subsequently performed development steps.

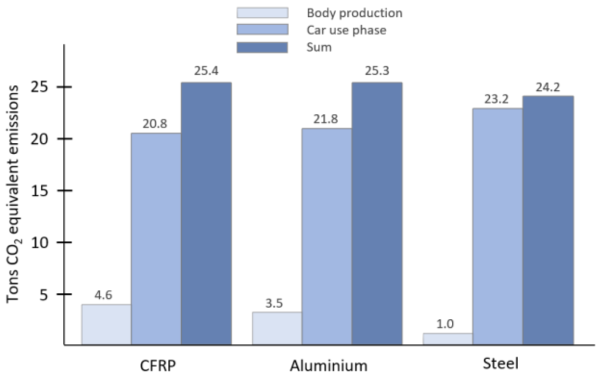

Figure 6: Life-cycle CO_2 equivalent emission of different car body technologies over a driving distance of 200000 km.

It has to be considered, that this exemplary study is focused on the greenhouse gas emission impact only and does not reflect other factors like production costs, which might be higher for aluminum and CFRP bodyworks. Not considered in this study, but of relevance, is the influence of vehicle mass on driving dynamics behavior, which will be advantageous for the car variants equipped with lightweight bodywork construction. In any case, a broad range of parameters has to be involved in the design process. One cluster of these influencing factors is related to sustainability characteristics, which must be provided from the beginning of product development to support experts and decision-makers in selecting the optimal configuration. This is of high importance, especially in the early phases of product development where main decisions are made, e.g., the selection of materials and the corresponding technologies, which cannot be changed with reasonable effort during later detailed product development phases. In this context, it is crucial to implement fundamental sustainability evaluation as a supplementing process to traditional economically and technically-driven development to provide a broad view on the various influencing factors in product development. In the present approach, the sustainability engineering support has been implemented into the CAD environment, because the CAD model represents a central role in product development. Here, a broad range of product characteristics is defined, including materials, geometrical shape, functional parameters and the interaction of the components and modules within the complete system.

7. CONCLUSIONS

Product development is increasingly influenced by sustainability-related factors, which requires the implementation of a comprehensive evaluation of design parameters. The deep integration of corresponding measures into product development comprises the definition of product specifications, covers early product layout and conception, and influences detailed product development, manufacturing engineering, and recycling. Such holistic consideration of different aspects of the product life cycle requires the involvement of life-cycle assessment and the definition of representative key parameters to effectively support decision-makers and engineers during product creation and optimization processes.

With the aim of fulfilling the high demands on data and knowledge provision throughout the entire product development, an approach of sustainability engineering support is introduced. The approach includes the sequences of data provision, data processing and the representation of results in parallel to different engineering workflows. A direct integration into computer-aided design software supports the intuitive handling of the tool and motivates involved engineers to make use of the tool in parallel to their development tasks. Effective assessment of design variants is supported by holistic life-cycle assessment under consideration of materials, manufacturing technologies, effects of usage, and recycling processes. In this way, experts and decision makers are supported in finding the optimal solution for product specification as well as for detailed product development, which supports the creation of new and more sustainable concepts and technologies.

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