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Concurrent design & life cycle engineering in automotive lightweight component development

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Abstract

Lightweight design is a major trend in automotive component development. This is induced by regulatory requirements targeting the use phase of vehicles. The predominant approach is the introduction of new materials, either in single- or multi-material designs. Taking an environmental life cycle perspective, new materials typically cause increased burdens from raw materials provision that need to be compensated by energy savings from the vehicles use phase. Interfaces between life cycle engineering, component design and manufacturing of automotive lightweight components are elaborated. A redesign process for a roof structure serves as an exemplary case. Based on these activities, research demands in data acquisition, methods and tools in design and life cycle evaluation are presented. A special focus is set on the conceptual design stage, as emerging materials and manufacturing processes routes lead to a broadening of the concept variety.

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1. Motivation

The weight of mass-produced automobiles has been increasing steadily. An important reason for this development are rising customer demands. Customers expect new vehicle generations to outperform their predecessors. This leads to vehicles with improved safety, comfort and entertainment features. Nonetheless, vehicles ought to have low environmental impacts to fulfill legal restrictions, e.g. greenhouse gas emission targets according to e.g. EU directive 443/2009 [1].

One approach to meet the described requirements is the application of lightweight design especially for vehicle bodies. The weight decrease serves as an efficiency measure for the vehicle use phase, leading to lower environmental impacts. There are different strategies to achieve a lightweight design. Introducing new materials, often in combination with new or adapted manufacturing processes, is the predominant approach in nowadays' vehicle development. The extensive introduction of high strength steels in automotive mass production is widespread in the current vehicle generation. As conventional material substitutions are reaching their limits, new approaches are considered. This encompasses multi-material designs combining different materials on a component level with a special focus on the introduction of fibre-reinforced plastics [2].

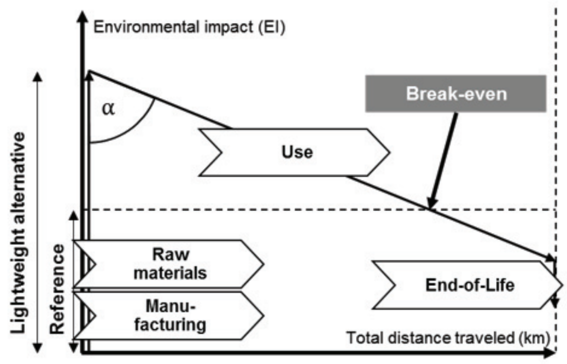

Fig. 1. Life-cycle perspective of the influence of lightweight designs on vehicle environmental impacts

In comparison to vehicle designs that apply steel alloys, the introduction of new materials leads to increased environmental impacts from raw materials provision and component manufacturing. These effects are i.e. caused by different sourc-

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ing routes, higher efforts for raw materials extraction or less efficient production processes. Additional impacts need to be compensated over the use phase of the vehicle, e.g. through decreased fuel consumption. In addition, potential efforts in the end-of-life need to be regarded. Figure 1 schematically shows the influence of a lightweight design alternative on the environmental impacts of a vehicle. Based on impacts originating from raw materials provision and manufacturing, the slope (angle alpha) represents benefits due to a decreased energy consumption within the use phase. The break-even point points out the driving distance required to achieve an environmentally benign alternative. The end-of-life covers the effort to recover material, the avoided landfill and avoided primary material consumption due to the availability of secondary material.

2. Design and Life Cycle Engineering for automotive lightweight structures

2.1. Lightweight design in automotive engineering

Lightweight design in general is a strategy intending to reduce a product's weight without downgrading its performance. From a mechanics point of view, the intention of lightweight design is to improve the load-bearing capacity without increasing weight [3].

Lightweight design as a discipline is a combination of material science, product and process development, mathematics as well as mechanics. There are various approaches, which may set a focus on some of the mentioned disciplines. Lightweight design may be the application of lightweight materials such as aluminum, magnesium or composites. It may as well be a matter of product specification in terms of determining requirements and load cases for dimensioning purposes. Dimensioning structures is based on advanced mechanics theories and requires the application of higher mathematics. Existing approaches towards lightweight design highlight that material performance indicators can facilitate material selection [4,5].

Table 1. Material performance indicators (*Gütekennzahlen*) [4] & Impacts on climate change (GWP) [kg CO2eq/ kg material] [6–8]

Material	$\frac{E}{\rho g}$	$\frac{R_M}{\rho g}$	GWP
Aluminum (primary)	2,592.60	14.80	˜11
Steel (market)	2,675.16	8.92	˜4
Magnesium (pidgeon)	2,586.07	17.24	˜25
Carbon Fibre Reinforced Plastics (CFRP; PAN, PA6 30%)	8,155.88	115.53	˜26

Table 1 gives an overview of specific stiffness $\frac{E}{\rho g}$ and specific strength $\frac{R_M}{\rho g}$ of different materials [4]. Based on these material performance indicators, one might argue that a CFRP structure would be 3 times lighter than a steel structure if stiffness is the dominant design parameter or even 13 times lighter if strength is the dominant design parameter. The major drawback of these material performance indicators is that they assume large cross-sections and thin-walled structures without any space restrictions. This is why the theoretical weight reduction numbers are hard to achieve in practice.

Wanner considered the boundary condition of limited installation space [9]. He derived different material performance indicators assuming that the outer boundary condition is fixed, while the wall thickness is the free design parameter. Kaiser discusses Ashby's material selection in context with Wanner's work for the application in automotive lightweight design. He identifies fluctuating requirements and boundary conditions for automotive components as major drawbacks leading to a highly insecure material selection [10].

Besides material selection the conceptualization is a crucial step for lightweight design [11]. Material selection is always depending on the geometrical concept and vice versa. Additionally, automotive component development requires to strictly meet cost restrictions. Kleemann et al. discussed the dependencies of mechanical performance, weight and costs for an automotive roof structure [12]. Fröhlich et al. extended this analysis by a tool-supported conceptualisation of multi-material-components with concurring development goals [13].

2.2. Life Cycle Engineering in automotive engineering

Life Cycle Engineering (LCE) encompasses "engineering activities [...] to manufacturing products with the goal of protecting the environment [...], while optimizing the product life cycle and minimizing pollution and waste. [14] This definition stresses three important aspects of LCE. First the need for an evaluation method that enables to assess environmental impacts of products, second the incorporation of a life cycle perspective and third the engineering activities required to achieve this goal.

The methodology of Life Cycle Assessment (LCA) according to ISO14040 is a well established approach for a quantified environmental evaluation. LCA studies are common practice in the evaluation of market-ready vehicles (retrospective) and are increasingly applied during development activities (prospective) [15]. Among others, climate change, eutrophication, particulate matter and ozone depletion are relevant impact categories in automotive contexts.

As illustrated in Figure 1, the consideration of the full product life cycle is crucial towards generating results which can be used as a basis for decision making on environmental impacts. Towards increasing the life cycle system understanding, a distinction between characteristics which are influenced by decisions which result from activities in component design and those that are originating by the surrounding system is proposed. The first constitute the so-called foreground system, the latter the background system [16]. For example, the component weight is an inherent result of the design process. In contrast, the driving behavior is mainly independent from decisions in the component design process.

In the past years, numerous methods and tools to integrate life cycle engineering in product development have been presented. These are often referred to under the terms of EcoDesign or Design for Environment (DfE). The range reaches from qualitative tools to quantitative approaches that are based on LCA [17]. As identified in [11] the conceptual design stage is a major lever in automotive lightweight component development, which needs to be supported with appropriate methods and tools. Broch emphasizes the importance of robust LCE decisions in automotive product development which take into account different parameters originating from the foreground and background systems [15].