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Life cycle engineering of lightweight structures

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ABSTRACT

Lightweight structures are increasingly necessary to meet current engineering requirements. Weight reduction in diverse applications such as automobiles or machine tools is achieved either by using less material or by substituting material with a lighter one, which provides more functionality per unit of weight. To be an effective enabler for sustainability, lightweight structures should result in lower environmental impacts per functional unit when compared to conventional structures on a life cycle basis. However, applying new materials and manufacturing processes often leads to an increase in environmental impacts from the raw materials and production stage of the life cycle. Furthermore, end-of-life disassembly and recycling may become more difficult. In addition, the expected efficiency gains from the use of lightweight structures depend on how the overall market and technical systems respond to them. Consequently, the environmental evaluation of lightweight structures in engineering entails various methodological challenges. Organised around a life cycle engineering framework with a focus on eco-effectiveness, this paper provides a comprehensive review of lightweight structure applications and the challenges and opportunities they present in a life cycle engineering context.

1. Introduction

Lightweight structures are physical products or parts of products that enable a required technical functionality at lower weight than generally achievable by other means. This can be implemented by using less material or by providing more functionality or improved functionality through lighter structures [1]. The relationship between technical performance and weight can be described in a number of ways, including the stiffness-to-weight ratio, which is a central concept in engineering design.

Traditionally, two main drivers have motivated the introduction of lightweight structures. From a technical point of view, lighter products can enable better performance, such as in the case of higher acceleration of a vehicle (e.g. an airplane) or providing a competitive advantage in sporting equipment (e.g. a golf club). Lighter products can also reduce life cycle cost because of lower operation cost for many applications. Depending on the specific case, material and production cost could either decrease by using less material or increase due to higher embodied energies and innovative, comparably inefficient production technologies. Furthermore, lighter products can be a means to comply with regulation. For instance, lighter vehicles enable to reduce fuel consumption and lead to decreased penalty fees for vehicle manufacturers faced with corporate average fuel requirements.

The authors aim to provide a review on the status quo and to anticipate future research regarding lightweight structures from a life cycle engineering perspective. According to Hauschild et al., life cycle engineering (LCE) is part of a company's activity covering engineering methods to look "at products [. . .] over all stages of the life cycle(s)" [2]. As a result, LCE is concerned with all "the main activities and life cycle stages (product development, raw material extraction, manufacturing, after-sales service/engineering, reuse, remanufacturing, recycling and disposal)" [2].

Lightweight structures are typically a part of larger product systems, e.g. as a structural element of a vehicle or machine tool. Those products operate in a background system such as a certain region with a specific local electricity mix (see Fig. 1).

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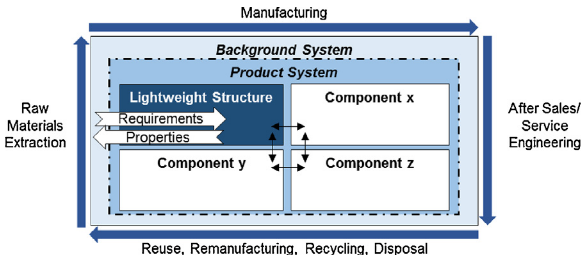

Fig. 1. Lightweight structures as part of product systems.

Thus, in addition to the different life cycle stages, on the one hand interdependencies between different sub-systems or components need to be considered when analysing potential burdens and benefits regarding the sustainability of lightweight structures. This way, properties of lightweight structures, such as their mass, are evaluated in context of a system perspective. On the other hand, both the product- and the background system set requirements for lightweight structures. The average lifetime of a product, for example, should align with technical capabilities of lightweight structures.

Hereafter, foundational concepts in life cycle engineering are presented and set into the context of lightweight structures in order to promote comprehension of specific challenges.

1.1. Evolution of life cycle engineering

An early definition of life cycle engineering was given by Alting: "Life cycle engineering is the art of designing the product life cycle through choices about product concept, structure, materials and processes, and life cycle assessment (LCA) is the tool that visualizes the environmental and resource consequences of these choices" [3]. In the CIRP Encyclopedia, Jeswiet broadens the scope to all three pillars of sustainability, defining life cycle engineering as: "[. . .] engineering activities, which include the application of technological and scientific principles to manufacturing products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability, while optimising the product life cycle and minimizing pollution and waste" [4].

This understanding has led to a significant eco-efficiency improvement in developing products and technologies. However, the benefits gained as a result of eco-efficiency improvements may have wiped out due to population and affluence increase and the associated environmental footprint. In the meantime, the concept of sustainability has shifted from relative to absolute sustainability due to the limited carrying capacity of the planet. As a result, Hauschild et al. propose a new life cycle engineering framework that combines a top-down with a bottom up perspective [2]. The framework enables a better understanding of the pressure that life cycle engineered products place on the earth's life support system. Sustainability constitutes an absolute constraint and is evaluated with regard to the time span of human civilisation. The top-down approach aligns with the different factors of the IPAT equation. The equation expresses the total environmental impact (I) as the product of population (P), affluence (A) and the environmental impact caused by technology (T). As global population and affluence have been steadily increasing and are expected to increase further, pressure mounts on the technological factor. The IPAT equation illustrates that, to use the example of climate change, greenhouse gas emissions (I) from the different life cycle stages of products (T) must decrease by almost a factor of 10 by the middle of this century compared to 2010 [2]. Focusing on the technology factor of the IPAT equation, impact mitigation options include reducing energy demand, improving energy efficiency and shifting towards renewable energy. Improving efficiency reduces resource consumption as well as emissions to water, air and land, all of which increase stress on humans and natural systems. Furthermore, materials entering production need to be taken into account, as the extraction and processing of resources also require energy and potentially result in various direct environmental impacts. Assembly methods and joining techniques employed in creating products also require consideration, as they often determine the viability of recycling and (re-)processing options which may reduce environmental impacts.

In line with this understanding, Hauschild et al. redefined life cycle engineering as "[. . .] sustainability-oriented product development activities within the scope of one to several product life cycles. The methods and tools used in life cycle engineering must support reducing the total environmental impact associated with technology change and volume increase from one product generation to another, in order to ensure that new product technologies stay within their environmental space as derived from the planetary boundaries" [2].

As already highlighted in Alting's early definition of LCE, the assessment tool that helps engineers to quantify the environmental impacts of engineering decisions is life cycle assessment (LCA). A set of international standards prescribe the fundamental principles and framework of LCA [5,6]. Fig. 2 shows an LCA-based framework of LCE rooted in the ISO 14040 norms. Reasons to use LCA and an LCA-based engineering approach for lightweight structures are:

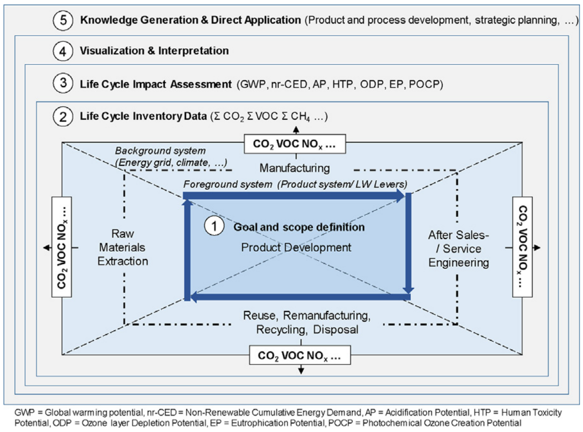

Fig. 2. Life cycle assessment methodology according to ISO 14040 as part of the bottom-up life cycle engineering methodology.

- **Identify hotspots:** Performing an LCA to support LCE allows for analysing the technosphere encompassing all life cycle stages and identifying the system elements with the most significant impacts on the ecosphere.
- **Avoid burden shifting:** Reducing the weight of a product is often motivated by a decrease in energy required to move it, thus decreasing its environmental impact (mostly during operation). However, this effect might be overcompensated by an increased impact of the raw material extraction, production and end-of-life stage.
- **Identify trade-offs:** Additional trade-offs may arise between different environmental impact categories. A reduction in climate change affecting emission during the use stage might be accompanied by substances with human toxicity potential being emitted in the raw materials extraction and manufacturing stage.
- **Gain system understanding and build knowledge:** Overall, LCE of lightweight structures fosters the understanding of cause-effect relationships and deepens knowledge on product- and process development. Thus, the most promising lightweight measures can be selected and options to reduce environmental impacts can be elaborated.