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Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry

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ABSTRACT

Carbon fiber reinforced polymers (CFRP) are frequently used in aerospace industry. However, the manufacturing carbon footprint and direct cost are obstacles in the way of adopting CFRP in further aerospace structures. Therefore, the development of a combined ecological and economic assessment model for CFRP manufacturing is demonstrated in this paper. This model illuminates the proper developments for the decision-makers.

In this work, the eco-efficiency assessment model (EEAM) is developed based on life cycle assessment (LCA) and life cycle cost analysis (LCCA). EEAM is an activity-based bottom-up decision support tool for the manufacturing process of fiber reinforced polymer (FRP). This paper discuses a case study of manufacturing CFRP wing ribs for a modern commercial aircraft as a part of the project LOCOMACHS.

Ecological results of EEAM conclude that the carbon footprint of manufacturing wing rib made of CFRP thermoset by the technique of in-autoclave single-line-injection (SLI) is around 109 kg CO_2-equivalent for each kg of CFRP. Moreover, fiber material is the main contributor in this carbon footprint. On the other hand, the economic assessment shows that the studied rib has a direct manufacturing cost of about 584 €/kg. In these results, labor work dominates the direct cost with 49%, while fiber and matrix compensate about 35%.

As an activity-based assessment model, EEAM guides the decision-makers toward sustainable direct applications. It is concluded that direct applications for fiber waste reduction are beneficial for both eco-efficiency aspects. Energy consumption reduction is ecologically beneficial, while labor work reduction on the other hand is cost relevant. In aerospace industry, there is a clear potential for eco-efficient direct applications that satisfy both aspects.

1. Introduction

In both ecological and economic aspects of sustainability, there is a significant potential for developing the eco-efficiency of aerospace manufacturing process. An eco-efficiency benefit is crucial for enhancing further implementation of carbon fiber reinforced polymers (CFRP) in modern commercial aircrafts. However, this promising implementation of CFRP is confronted by the lack of associated studies that discuss the eco-efficiency of their manufacturing process.

The increasing demand for structures made of CFRP in aerospace industry is enhancing the development of more eco-efficient manufacturing [1]. Within eco-efficiency enhancement, both ecological and economic aspects are involved [2]. Practically, eco-efficiency represents a major development concern in aerospace industry [3,4]. On the one hand, global warming and the phenomenon of climate change has been associated with the carbon dioxide (CO_2) as the primarily emitted greenhouse gas [5]. In Aerospace industry, structures made of CFRP can lead to a significant reduction in aircraft empty weight [6]. This weight reduction can decrease the CO_2 emissions up to 20% during operations [7]. On the other hand, the economic aspect is crucial in shaping the future of CFRP implementation in aerospace industry, whereas cost reduction is a main market driver [1]. In this work, the eco-efficiency for a case study of wing rib manufacturing made of CFRP is assessed. According to an internal investigation within the LOCOMACHS project, this rib offers up to 50% weight reduction compared to the conventional aluminum rib.

Considering CFRPs, there are several studies where eco-efficiency is discussed in the different life cycle stages of these materials. A selection of associated studies is briefly reviewed in this paper. The review illuminates the intersection areas between this work

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and the reviewed studies. It also discusses the differences between these studies and this one in terms of the industries and manufacturing techniques.

For automotive industry, many studies about the eco-efficiency of CFRP have been published. For instance, Dhingra et al. study has compared the ecological impacts of several materials including CFRP for a “cradle-to-grave” vehicle life cycle. However, neither manufacturing techniques nor unit processes within them are illustrated in that work [8]. Considering the same industry, Kasai paper provides also a comparison between several materials, such as steel, aluminum and fiber reinforced polymer (FRP). Kasai results show the benefit of implementing FRP. However, as a consequential LCA the exact impact value is undetermined. Moreover, Kasai work covers only the ecological impact [9]. Considering economic aspect, Das study describes the cost drivers for the manufacturing process of CFRP precisely. However, his work discusses only the economic impact of liquid compression molding (LCM) in automotive industry [10].

The eco-efficiency of CFRP manufacturing in aerospace industry has been studied as well. In their work, Shehab et al. have assessed the cost of aircraft CFRP structures. Their paper covers different cost categories for a selection of unit processes including manual layup (ML), vacuum bagging, in-autoclave curing, and quality assurance. Hence, this work discusses a very similar case study. Even though, the results of Shehab et al. work are incomparable to the results of this work, while the structure geometries are different and no cost values are provided by their work [11]. For ML and assembly, Choi et al. work studies the issue of design-to-cost (DTC) based on existing weight and cost estimation tools. Nonetheless, Choi et al. provide no activity-based assessment for the manufacturing process but rather an estimation model for DTC and weight-to-cost. Moreover, structure specifications in their study differ from the wing rib studied in this work [12]. Therefore, the direct comparison between Choi et al. and this work results is insufficient. However, input data such as material costs and work durations can be considered. Moreover, Haffner thesis provides an activity-based technical cost assessment of selected manufacturing techniques for various aerospace structures. Nonetheless, his thesis doesn’t study the techniques of in-autoclave liquid resin infusion (LRI) such as single-line-injection (SLI) [13].

Considering cost estimation based on complexity, the paper of Gutowski et al. provides cost estimation for a set of manufacturing unit processes. However, unlike our work the activity-based estimation in Gutowski et al. study is based only partially on data collection. Moreover, their study estimates mainly the time in a bottom-up approach, whereas no ecological estimation is considered [14]. For modern aircrafts, a similar approach with highly detailed complexity consideration has been adopted by Hagnell et al.. In their work, Hagnell et al. discuss the global production cost of the wing box to which the rib in our work belongs. However, in their work neither the ecological impact nor LRI technique is included [15].

A study that assesses manufacturing eco-efficiency has been performed by Witik et al.. Their study covers both eco-efficiency aspects for CFRP manufacturing using in-autoclave curing or oven tempering for LCM as well as prepreg. In their work, the manufacturing processes of a simple panel in different techniques are compared. Similar to this paper, their assessment illustrates the cost distribution over the following cost and carbon footprint drivers including materials, labor, equipment, ancillaries and energy [2]. However, several input parameters vary between Witik et al. study and this study.

Although CFRPs can be implemented in many industries the key behind their eco-efficiency impacts is affiliated with the holistic manufacturing process and not only the material itself. Therefore, it is concluded that eco-efficiency of aircraft wing rib manufacturing is only comparable with CFRP structures from other industries if the manufacturing processes are identical. Hence, the identification of these manufacturing processes, their input parameters, and their system boundaries is crucial for the assessment. This can be also clearly concluded from the significant cost differences of similar CFRP structures from different industries. For evaluation, the results of Hagnell et al., Das, Haffner, Gutowski et al., and Witik et al. are compared with the results of this paper.

2. Methods

In order to enhance the eco-efficiency, it is essential to investigate, develop, and implement suitable decision support tools that assess the ecological and economic performance of the studied process. Generally, there are several decision support tools that can be applied. LCA is adopted in this study due to its systematic framework. Furthermore, LCCA is integrated within the framework of LCA in order to have a comprehensive eco-efficiency decision support tool [16]. In order to have an adequate description of manufacturing process, a modeling method is required. Therefore, LCA and LCCA are performed within a representative process model that is developed by the application of business process reengineering (BPR). Thus, within this work an integrated framework of LCA and BPR is established.

2.1. LCA and LCCA

LCA is a support tool that provides decision-makers with ecological development guidelines. LCA aims to identify the associated ecological impact by a set of environmental performance indicators. This ecological impact can be assessed for a product as a functional unit or a process as a product system. The impact results should be gathered for defined ecological impact categories such as the climate change.

Both LCA and LCCA are key tools in promoting the eco-efficiency of a product system [18]. Based on LCA, LCCA analyzes the cost of a product system. It evaluates the economic performance within the product life cycle by a set of economic indicators. Performing LCCA guides the decision-makers to select the most cost effective alternatives and identify the required process modification [17]. Despite the fact that LCCA is based on LCA, they are considered as diverse decision support tools, due to their various goals and perspectives. These tools provide the support to solve completely different problems [18]. Thus, differences and similarities between these tools can be analyzed in a systematic comparison that is based on their common framework phases, as it is demonstrated in Table 1.

As it is shown in Table 1, LCA is performed through an iterative framework that consists of discrete phases. The first phase in this framework includes defining the goal and scope of the assessment as well as its system boundary. The second phase is the life cycle inventory analysis (LCI) in which the associated data from the assessed process are collected. Life cycle impact assessment (LCIA) is the third phase in this framework. LCIA is resulted from the assessment. The assessment results guide the decision-makers to the proper direct applications. However, the direct applications themselves are beyond the scope of the LCA. In the final interpretation phase, all previous phases are evaluated and the required modifications in each one are performed [17].

Table 1 explains the different goals and scopes of LCA and LCCA. It also illuminates the miscellaneous results which are compiled from the various indicators of both sides. Elementary and intermediate flows are the measurable parameters within the data collection in LCI. On the one hand, elementary flows are defined as the relevant inputs entering or outputs leaving the entire studied product system. Elementary flow can be either energy or material,

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