Aerospace Science and Technology 79 (2018) 669–678

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

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

Ali Al-Lami [a,*], Philipp Hilmer [a], Michael Sinapius [b]

[a] Institute of Composite Structures and Adaptive Systems, German Aerospace Center (DLR), Braunschweig, Germany
[b] Institute of Adaptronic and Functional Integration (iAF), Technische Universität Braunschweig, Braunschweig, Germany

ARTICLE INFO

Article history:
Received 10 January 2018
Received in revised form 2 May 2018
Accepted 18 June 2018
Available online 19 June 2018

Keywords:
Aerospace structure manufacturing
Gate-to-gate eco-efficiency assessment
Carbon fiber reinforced polymers (CFRP)

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

* Corresponding author.
E-mail address: ali.al-lami@dlr.de (A. Al-Lami).

https://doi.org/10.1016/j.ast.2018.06.020
1270-9638/

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

Table 1
Comparison of LCA and LCCA, based on [17] and [18].

Framework phases	Comparison	
	LCA	LCCA
Goal and scope definition	Evaluating and/or comparing the life cycle of functional unit(s) from environmental perspectives	Evaluating and/or comparing the life cycle of functional unit(s) from economic perspectives
Life cycle inventory analysis (LCI)	Measuring process parameters as elementary and intermediate flows (in physical units) and identifying the characterization factors (in CO_2-equivalent per unit)	Measuring process parameters as elementary and intermediate flows (in physical units) and identifying the characterization factors (in monetary value like Euro (€) per units)
Life cycle impact assessment (LCIA)	Determining and/or comparing ecological impacts such as carbon footprint, and identifying the category endpoints	Determining and/or comparing economic impacts such as cost impact
Direct applications	Adopting environmentally friendly sustainable development	Adopting cost efficient sustainable development
Interpretation	Evaluating results and framework within environmental norms	Evaluating results and framework within economic norms

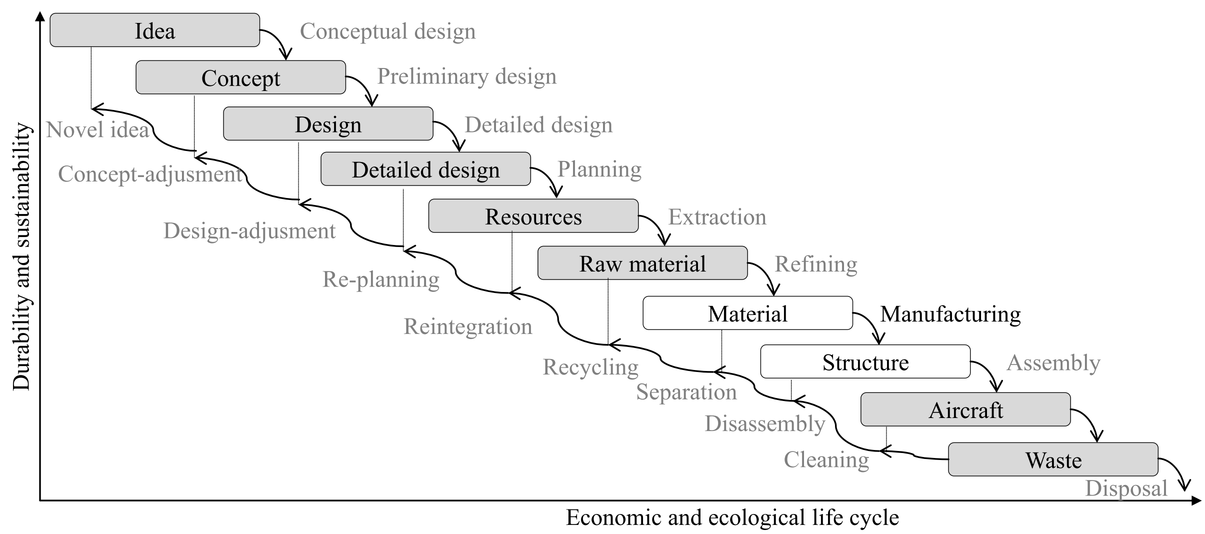

Fig. 1. Eco-efficiency durability and sustainability in product life cycle, based on [21].

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, while in this study we consider labor work as a form of energy. On the other hand, intermediate flows include any product, material, or energy that flows between the unit processes within the same system [17].

Considering the cost assessment, there are several other models which might be implemented in undertaking LCCA, such as material flow cost accounting (MFCA) [19] and activity-based costing (ABC) [2]. These models have a common bottom-up approach. Technically, LCA guides the decision-makers to select the suitable direct applications and comparing different scenarios. It can be used to provide comparable non-absolute values within what is called consequential LCA as well [18]. On the other hand, cost models are mainly implemented to determine exact values within what can be considered as attributional LCCA [20].

Generally, in LCA a product life cycle includes all product stages from raw material to final disposal. This physical life cycle, which is also known as cradle-to-grave, can be split into several gate-to-gate stages [17]. Even though, the definition of life cycle stages differs from economic and ecological perspectives. Considering the durability and sustainability, a holistic eco-efficiency life cycle has been established. This eco-efficiency life cycle is illustrated in Fig. 1.

In Fig. 1, activities of both sustainability and durability are associated with the defined stages. Hence, this paper demonstrates the assessment of structure manufacturing from refined materials as a gate-to-gate simplified LCA, as it is unshaded within Fig. 1.

In this work, the ecological impact category of climate change is assessed by determining the carbon footprint [5]. Beside carbon footprint, manufacturing direct cost is assessed for the economic aspect. Generally, bottom-up models are implemented in realizing a gate-to-gate assessment of economic or combined eco-efficiency impacts [19]. For such activity-based assessment, sufficient process modeling method and framework are crucial. In practice, the correlation between LCA as well as LCCA on the one side and the process modeling on the other side already exists. However, it has been concluded that a clear framework for process modeling that covers both visualization and parametrization is decisive for the eco-efficiency assessment [18].

2.2. Process modeling

For activity-based eco-efficiency assessment, a modeling framework is required. This framework should enable the development of a computer-based model. In its framework, LCA contains only general guidelines for the calculation procedures and system boundary modeling [17]. LCA framework needs to be integrated with a suitable modeling framework such as the BPR. According to Champy and Cohen, BPR is defined as a fundamental redesign and rethinking of a business process. It aims to achieve the required development by measuring the performance including cost, quality, and time [22]. Practically, process modeling is a core dimension of LCA [17]. Furthermore, implementing BPR facilitates the combination of both eco-efficiency aspects in one comprehensive process model. It also enables the process modification and redesign to evaluate the direct applications.

In this paper, the realization of eco-efficiency model for the manufacturing process is carried out through the BPR within LCA framework. Therefore, an integrated framework that includes LCA, BPR, and manufacturing decision support has been developed, as it is shown in Fig. 2. This framework aims to facilitate handling the eco-efficiency assessment models particularly in manufacturing.

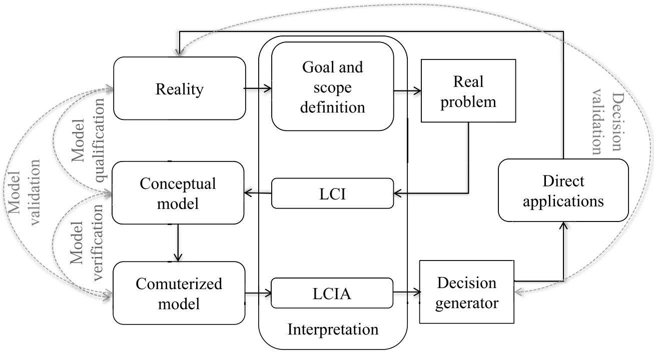

Fig. 2. Integrated LCA and BPR for decision support in manufacturing, based on [17] and [23].

This integrated framework starts from defining the assessment goal and scope based on the reality [23]. Then the real problems are clearly defined [17]. These real problems are analyzed through the LCI to build a conceptual model that represents them virtually [24]. From this conceptual model a computerized model is to be formulated by representative mathematical algorithms [23]. For the selected impact categories, these mathematical algorithms realizes the LCIA and computes its results [17]. For each elementary flow, its impact can be represented by the following simplified equation:

$$\text{Process parameters}(x) \times \text{Characterization factors}(x) = \text{Impact}(x)$$

From these results, decisions for sustainable development are to be generated. These decisions can be implemented in reality as direct applications [17].

In its framework, LCA includes an iterative interpretation and evaluation phase. This integrated framework consists of validation stages as they are shown with dashed lines in Fig. 2. The generated computerized model is validated through the qualification of conceptual model to reality as well as verification between both conceptual and computerized models [24]. Furthermore, the generated decision can be validated with reality as well [23]. Similar to the conventional frameworks, this decision support framework is applied as a continuous iterative development loop.

2.3. Eco-efficiency assessment model (EEAM)

In practice, decision support tools can be realized in the form of software based on LCA framework [25]. Ganzheitliche Bilanz (GaBi) for instance, which is a German term that means holistic balance, is decision support software that is developed by the University of Stuttgart in Germany. This tool provides ecological assessment for the entire life cycle of a product. Another example is Umberto software that assesses both ecological and economic impacts. Within Umberto, manufacturing processes can be modeled and the associated elementary flows can be allocated [26]. System for integrated environmental assessment of products (SimaPro) is another worldwide known LCA software that covers the entire life cycle [27]. These assessment software packages depend on universal ecological databases. These databases are continuously updated based on the results of associated assessments [28]. These tools are able to cover the entire life cycle as well as a wide range of ecological impact categories such as climate change, human health, resources, and ecosystem quality [5].

This paper presents the results generated by the eco-efficiency assessment model (EEAM). Based on the integrated framework, EEAM is developed by the German Aerospace Center (DLR). EEAM is a bottom-up and activity-based carbon footprint and direct cost assessment model. It assesses only the manufacturing process as simplified gate-to-gate LCA [17]. On the one side, EEAM is similar to other existing tools as an eco-efficiency decision support model that covers both ecological and economic impacts. This model is designed to handle the manufacturing of FRP in specific. EEAM has the advantage of offering detailed assessment. It is also adaptive for various manufacturing techniques of numerous FRP structures.

3. Case study: eco-efficiency assessment of CFRP wing rib manufacturing

By EEAM, the eco-efficiency of wing rib manufacturing is assessed in this work. After defining the wing rib as a functional unit and the manufacturing unit processes within a clear system boundary, the included elementary and intermediate flows are determined. Then, the manufacturing process is modeled and visualized. LCI is performed to collect the data for the parametrization. As a part of LCIA, EEAM results facilitates the detection of the manufacturing bottlenecks. This assists the decision-makers in identifying the proper development as direct applications.

3.1. System boundary definition

In aerospace industry, load transmitting structures such as wing ribs are considered as complex composite structures [1]. In this paper, an aircraft wing rib made of CFRP is studied. As it is shown in Fig. 3, this rib has the configurations of about 1.35 m length, 0.29 m height, 0.05 m depth, 3.2 kg mass, and 0.008 m skin thickness. The CFRP rib is manufactured by the technique of in-autoclave SLI and a ML preforming process. Within the LOCOMACHS project, the application possibilities of such ribs are studied for a modern commercial aircraft [29].

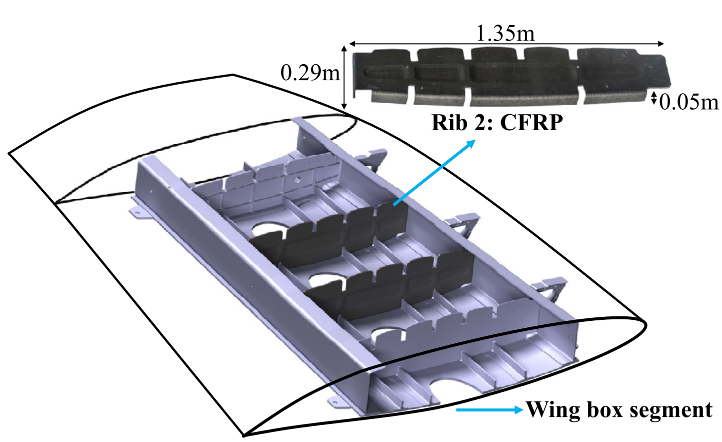

Fig. 3. Studied application of CFRP wing ribs in modern aircraft within LOCOMACHS.

Technical system boundary is summarized by defining the assessed manufacturing technique. From the discrete open mold techniques of LRI, SLI is used in manufacturing the aircraft wing rib in this case study. In this process, a microwave autoclave with about 8.04 m^3 capacity, computer-numerical control (CNC) cutter, and a double ribs mold are implemented. Furthermore, other equipment such as air blowers, matrix vessel, and single vacuum pump with 8.5 m^3/h performance are utilized. The materials implemented include non-crimp fabrics (NCF), thermoset epoxy resin as matrix, and other ancillary materials such as tacky-tape, vacuum bags, adhesive tapes, acetone, release agents, and different types of gloves. In this paper energy is defined to be the energy mix that is used in electricity form. In practice, wing ribs have been manufactured in DLR laboratories within very low production volume. However, the equipment utilization is calculated for industrial scale with consideration of affiliated maintenance costs. Mold cost distribution has been adjusted to match industrial series production as well.

Beside the technical boundary, the definition of system boundary describes the geographical and temporal boundaries of the studied process [17]. After defining the technical, geographical, and temporal boundaries, the manufacturing process is visualized.

3.2. Process visualization

Within the simplified LCA, manufacturing process of CFRP is defined as a product system that consists of several unit processes. These unit processes have quantifiable input parameters as elementary and intermediate flows [17]. Process outputs on the other hand represent the assembly-ready CFRP structure and process eco-efficiency impact. Ecological and economic inputs as well as outputs are generically categorized and described, as it is shown in Fig. 4.

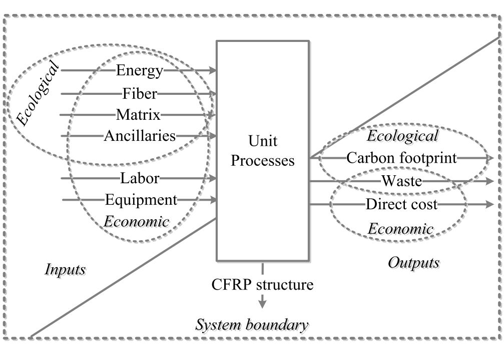

Fig. 4. Product system of CFRP manufacturing, based on [25].

Ecological elementary and intermediate flows include either materials or energy [17]. However, in this case study, these flows are considered for both eco-efficiency aspects. Hence, the material flow is split into three categories that consist of fiber, matrix as well as ancillaries. The ancillaries have been defined to be materials that are utilized to perform the process without being an element of the final structure [17]. To cover LCCA, labor and equipment inputs have been taken into account as well. Beside the CFRP structure, the product system outputs comprehend the carbon footprint, direct cost as well as material waste. Material waste consists of the wasted fiber and matrix materials.

Generally, the manufacturing cost composes of direct and indirect costs [30]. In this study, only the direct manufacturing cost is assessed. Direct cost includes fiber and matrix materials, labor work, equipment operation, ancillaries, and energy. However, due to the minor impact it shows in previous studies, facility rent cost is neglected in this work. Although the total carbon footprint and direct cost include the waste impact, waste is displayed separately for the decision-makers.

In this case study, the in-autoclave SLI and ML manufacturing technique of CFRP is split into a chain of discrete unit processes, as Fig. 5 shows. This separation between the studied unit processes facilitates an independent assessment of each unit process. It also enables the development of proper direct applications for them. As it is demonstrated in Fig. 5, these unit processes are correlated with each other through intermediate flows [17].

Within this visualization, allocation rules have been defined and implemented as Fig. 5 shows. These rules specify in which unit process each elementary or intermediate flow is to be considered. CFRP manufacturing model illustrates the unit processes from fiber cutting by CNC cutter all the way to the wing rib finishing. In preforming, the fiber cuts are draped on mold and formed by applying heat and pressure. Preparing unit process meant to include the preparation of mold, infusion system, autoclave as well as vacuum bagging. Infusion consists only of the infiltration process where the matrix material is allocated. In curing, autoclave is implemented to consolidate the impregnated preform. While the unfinished structure is released within demolding, finishing includes the machining, trimming, and cleaning to produce an assembly-ready CFRP structure. Based on the process visualization, the associated process parameters are collected within LCI.

3.3. LCI

After visualizing the process and defining the associated parameters, these process parameters are collected within the LCI. In Table 2, examples of such collected data from manufacturing wing rib at DLR are shown. For the discussed unit processes, these input parameters include the main elementary flows for both eco-

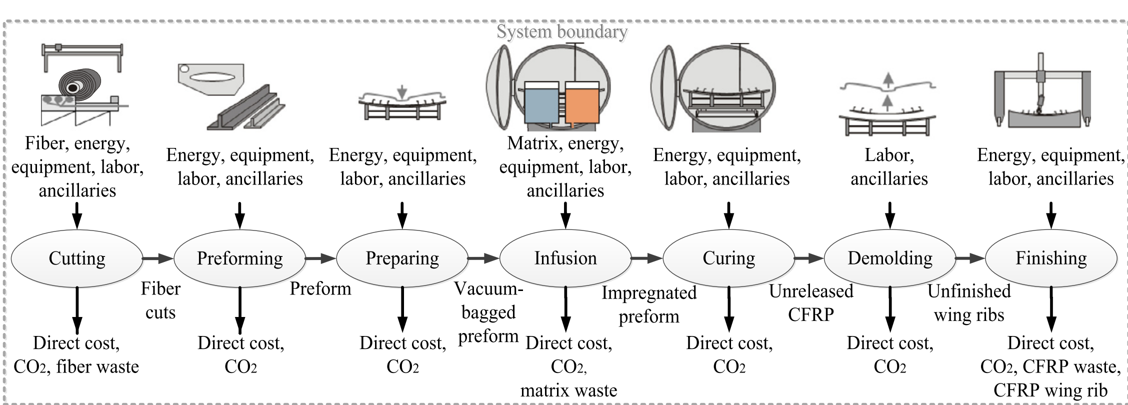

Fig. 5. Unit processes of in-autoclave SLI and ML technique and their flows.

Table 2
Selection of process parameters per kg of finished CFRP wing rib.

Description	Input	Elementary flow	Unit process
Electricity	29 kW/kg	Energy mix	All
NCF	1.6 kg/kg (±0,01 kg)	Fiber + Fiber waste	Cutting + Finishing
Epoxy resin + Hardener	0.5 kg/kg (±0,01 kg)	Matrix + Matrix waste	Infusion + Finishing
Autoclave operation	1.4 h/kg	Equipment	Curing
CNC cutter operation	0.7 h/kg	Equipment	Cutting
Man hours	3.5 h/kg	Labor	All

efficiency aspects. The process parameters are collected from CFRP manufacturing as primary data within the LCI between 2014 and 2016 at DLR laboratories in Germany.

In Table 2, the demonstrated parameters include the used electricity, fiber, matrix, and their wastes. Table 2 also shows the operation duration of autoclave and CNC cutter as well as the labor work hours. The electricity amount represents the summation of all electrical energy used throughout the manufacturing of a rib divided by the rib mass. Similar to that approach, fiber, fiber waste, matrix, and matrix waste are measured from the entire manufacturing. In Table 2, equipment operation and labor work time are also measured and calculated for each kg of wing rib.

Characterization factors are collected within the LCI according to the system boundaries. Selections of ecological and economic characterization factors are illustrated within Table 3 and Table 4 respectively. A selection of ecological characterization factors, their CO_2-equivalents, their orientation within elementary flows, as well as their temporal boundaries are shown in Table 3.

Table 3
Selection of ecological characterization factors, based on [2] and [31].

Input parameter	Description	CO_2-equivalent	Temporal boundary
Energy mix	Electricity	0.631 kg/kWh	2014
NCF	Carbon fiber	46.8 kg/kg	2011
Epoxy resin	Matrix	2.6 kg/kg	2011

On the other hand, a selection of cost associated parameters based on DLR internal EEAM-database from 2015 is shown in Table 4.

Table 4
Selection of economic characterization factors.

Input parameter	Description	Cost
Energy mix	Electricity	0.08 €/kWh
NCF	Carbon fiber	54 €
Epoxy resin	Matrix	52.5 €/kg
Labor	Man hour	82 €/h
Autoclave	Equipment	500 k€
CNC cutter	Equipment	177 k€

As it is mentioned previously in the simplified equation, LCIA is performed to assess the eco-efficiency impact. LCIA is based on these process parameters and characterization factors which are gathered within the LCI. To accomplish an eco-efficiency assessment in this study, the carbon footprint and direct cost are computed by EEAM.

3.4. Computer-based EEAM

As a LCIA tool, EEAM communicates with the different data sources required to calculate the carbon footprint and direct cost. Besides assessing the total impact, EEAM assesses the carbon footprint and direct cost of each unit process and elementary flow. Based on the integrated framework, the functionality of EEAM is summarized within Fig. 6.

From LCI, the collected process parameters are categorized within generic structure of input data. Due to the scope definition of FRP manufacturing process as a set of unit processes, data from each unit process are collected in separated Excel-spreadsheets.

As user friendly model, EEAM user has confined tasks that include distributing the Excel-spreadsheet on each unit process. As

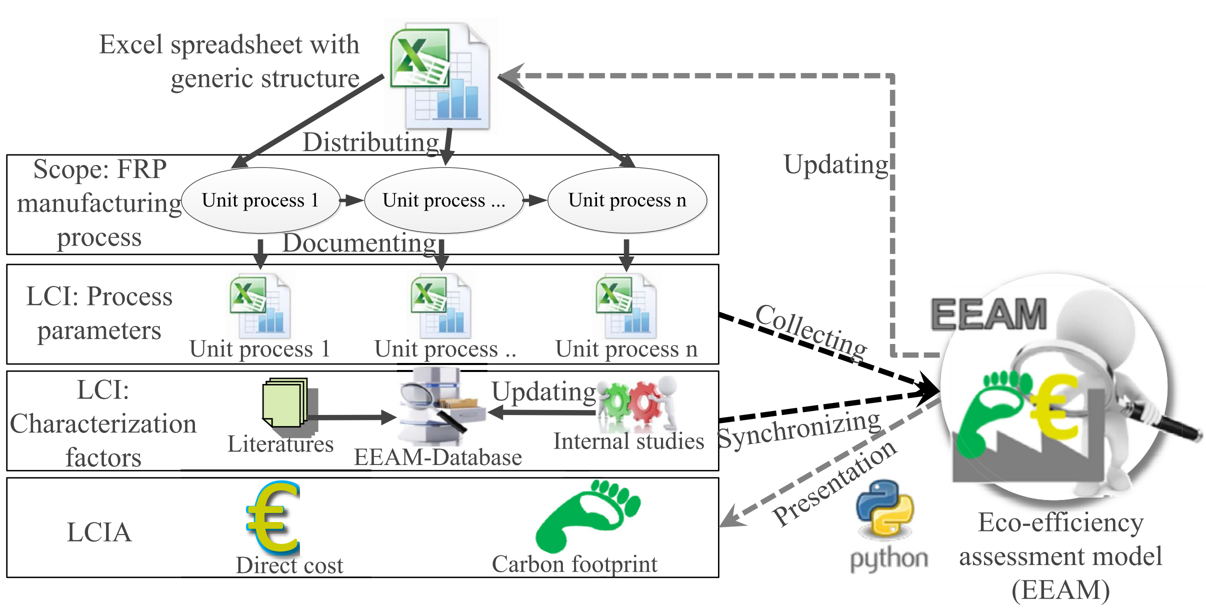

Fig. 6. Functionality of EEAM.

a part of LCI, the user documents the process parameters in these sheets based on the system boundary definition in Fig. 5. In practice, such Excel-spreadsheet facilitates the data collection task for the field workers. This spreadsheet is structured generically as a table of inputs from all unit processes. It is adaptable for various manufacturing techniques of different FRP structures. Finally, the user needs to activate EEAM, whereas no extra process modeling is required. Moreover, the user can optionally update the characterization factors. In Fig. 6, these user tasks are illustrated with solid arrows.

After filling the spreadsheets with data, EEAM collects these data under defined flow categories including materials, labor, equipment, ancillaries and energy. On the other hand, FRP associated ecological and economic characterization factors are gathered from literatures, suppliers, and internal studies. Examples of these characterization factors have been presented previously in Table 3 and Table 4. These characterization factors are automatically uploaded within EEAM-database and synchronized in each assessment to have up-to-date results. Based on previous studies, about 330 process parameters within clearly distinguished categories are listed in the EEAM-database and integrated in the spreadsheets. These studies include for example processes deduced from internally assessed manufacturing of FRP structures such as aircraft wing leading edge, L and T-shaped FRP structures, FRP pressure vessels, as well as wind rotor blades.

In EEAM the assessment is conducted through the correlation between the spreadsheets and the EEAM-database by a python-based tool. This tool connects the spreadsheets, collects the inputs from them, synchronizes these inputs with EEAM-database, and calculates the outputs. As a LCIA tool, EEAM reports the carbon footprint and direct cost results statistically and visually. In case of a new process parameter, EEAM adds this input to EEAM-database and integrates it into a new up-to-date version of the Excel-spreadsheet. As they are shown with dashed lines in Fig. 6, these computer-based activities are performed automatically whenever an assessment is activated in EEAM.

Based on EEAM results, developments can be suggested by decision-makers in the form of direct applications. Direct applications can include any eco-efficient management or technical developments. The impact of such direct applications can be estimated within EEAM as well. EEAM anticipates the benefit of such developments in both eco-efficiency aspects. Fig. 7 describes generically the possible impact behaviors of direct applications on eco-efficiency.

Fig. 7 illustrates the benefit of direct applications in two main fields. These benefit fields include the eco-efficiency field which serves both aspects and a single aspect dedicated field. To enable interchangeable generic illustration, (x) curve can represent the ecological aspect when (y) curve is the economic aspect and vice versa. For clarification, three generic imaginary direct applications are represented by (1), (2), and (3). These direct applications which have different eco-efficiency impacts can be applied as process modifications to a conventional process (A). Moreover, the benefits of these direct applications are shown for both aspects on the vertical axes. Generally, for aspect (x) in Fig. 7 the benefit is increasing by the direct applications (1), (2), and (3) respectively. However, regarding the benefit in aspect (y) these direct applications have different impact behaviors. While direct applications (1) has positive benefit impacts on both (x) and (y) aspects, it is considered in the eco-efficiency benefit field. Compared to direct application (1), the direct application (2) has an increasing benefit for (x) and no change in benefit on (y). The direct application (3) increases the benefit impact on aspect (x) but decreases the benefit impact on (y) compared to the prior (1) and (2) direct applications.

However, as generic illustration neither the value nor the correlation of the curves in Fig. 7 is relevant. Furthermore, examples for direct applications are selected based on the results from EEAM in this work and applied to this generic illustration. This illustration assists decision-makers in classifying possible direct applications based on their eco-efficiency impacts in order to enhance the proper applications.

4. Results

EEAM calculates both carbon footprint and direct cost results for the assessed process. For carbon footprint, results are calculated in CO_2-equivalent per each kg of CFRP wing rib [17]. On the other hand, direct cost impact is compiled in Euro (€) per each kg. In addition, fiber and matrix wastes are displayed in order to illuminate more eco-efficient developments [25]. Within a report, the exact values of carbon footprint and direct cost are presented to the decision-makers.

4.1. Ecological assessment in EEAM

From the ecological results it is concluded that the carbon footprint of manufacturing each kg of CFRP wing rib is around 109 kg CO_2-equivalent. It is also found that fiber and electricity are the main contributors in carbon footprint, as it is shown in Fig. 8.

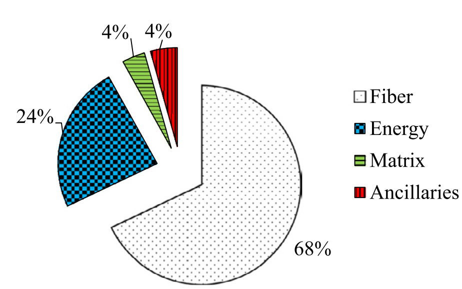

Fig. 8. Carbon footprint per elementary flow. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

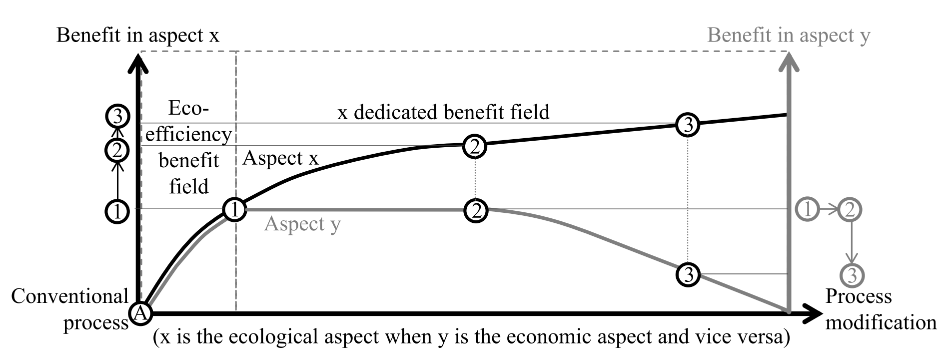

Fig. 7. Ecological, economic and eco-efficient direct applications.

Furthermore, the impact of these elementary and intermediate flows is reflected within the associated unit processes. As a result of the allocation of these flows, the highest impact appears in the unit processes where fiber and energy are allocated, as it is shown in Fig. 9.

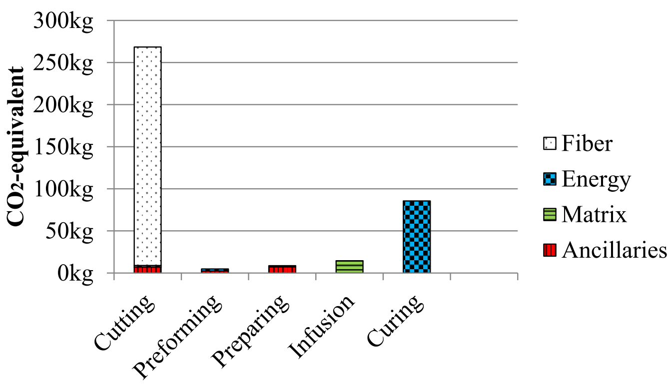

Fig. 9. Carbon footprint per flow in unit process.

It is obvious from Fig. 9 that the cutting has the highest impact, whereas the fiber is allocated in this unit process. This impact is mainly a result of the selected NCF type which has a high CO_2-equivalent, as it is shown in Table 3. As the highest energy consuming, curing represents the second unit process in producing carbon footprint. Due to the manual work, demolding and finishing have negligible ecological impact.

Considering wasted fiber and matrix, these wastes contribute in about 36% of the total carbon footprint. About 50% of the utilized fiber material is wasted in cutting due to the shape complexity of fiber cuts. Matrix waste represents about 23% of the used matrix in infusion.

4.2. Economic assessment in EEAM

The manufacturing direct cost of assembly-ready wing rib is about 584 € per kg. EEAM results show that labor cost constitutes with almost the half of the manufacturing direct cost, as it is shown in Fig. 10.

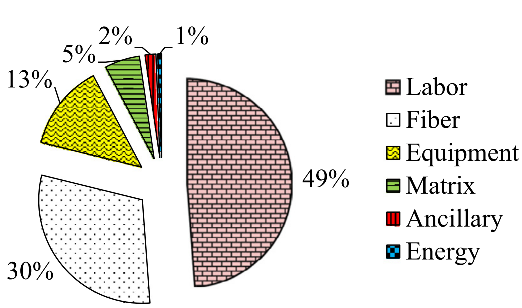

Fig. 10. Cost per elementary flow.

Fiber and matrix compensate about 35% of the cost impact. Moreover, Fig. 11 demonstrates the cost distribution among the manufacturing unit processes, whereas the allocation of elementary and intermediate flows plays again the main role in this distribution.

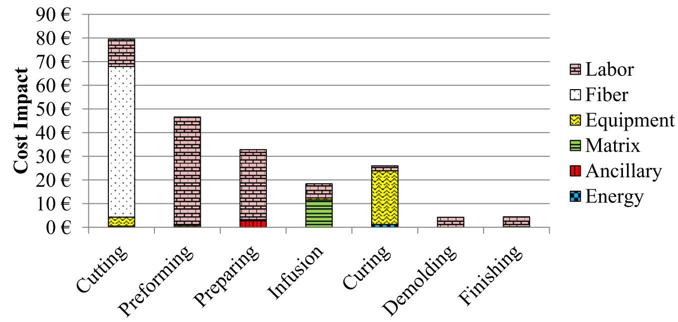

Fig. 11. Cost per unit process and elementary flow.

Again play fiber and fiber wastes a significant role in cutting cost, whereas half of fiber cuts are wasted. Labor cost is distributed unequally among all the unit processes. It has a significant cost impact on preforming and preparing due to the ML, vacuum bagging, as well as mold and autoclave preparation. Equipment cost is significant in curing due to the autoclave application. It has also a clear impact in cutting, while the CNC cutter is utilized.

From EEAM results, the eco-efficiency performance of the manufacturing process in general and the unit processes in specific is presented to the decision-makers. These results facilitate the identification of the process bottlenecks in order to develop suitable direct applications.

5. Discussion

Both ecological and economic aspects of EEAM results for CFRP wing rib manufacturing are reviewed here. Based on this revision, further suitable developments are suggested as direct applications. The impacts of these direct applications are anticipated for decision support purposes. Finally, the assessment results are evaluated by performing a set of validation activities.

5.1. Results revision and possible direct applications

From analyzing the compiled results, it is concluded that fiber and energy dominate the carbon footprint. Due to the high CO_2-equivalent of the selected fiber for aerospace structures, fiber has the highest ecological impact. Energy is highly consumed by autoclave in curing. This consumption depends on the process duration and curing cycles. By implementing proper direct applications, eliminating fiber waste can avoid about 36% of the total carbon footprint and reduce about 17% from the total direct cost. The significant fiber waste is a result of the shape complexity of fiber cuts. This complexity disables an efficient cutting that is based on the correlation between the fiber cuts orientation and the CNC cutter capacity. Moreover, about 26% of the manufactured unfinished wing rib is wasted. This CFRP waste is produced in the machining and trimming work within the finishing unit process.

By EEAM, decision-makers can evaluate their direct applications. To achieve more eco-efficient process, decision-makers should enhance direct applications which are beneficial for both aspects. In aerospace industry there is still a significant potential for eco-efficiency developments such as direct application (1) in Fig. 7. Whereas, the maturity of manufacturing process is lower than other industries such as automotive industry.

As an example of direct application (1), waste reduction plays a decisive role in the future of CFRP implementation. For instance, eco-efficient cutting, infusion, and finishing solutions are required. Hence, the cost and carbon footprint can be simultaneously reduced by the waste reduction in these unit processes.

Other direct applications can serve a single aspect, which are generically represented by direct application (2) in Fig. 7. In practice, the impact on economic and ecological aspects differs when it comes to energy reduction. On the one hand, reducing the energy consumption leads to a minor cost reduction. On the other hand, this energy reduction decreases the carbon footprint significantly. Therefore, energy reduction can be represented by the direct application (2), when (x) is the ecological aspect. For economic aspect, labor work reduction represents a beneficial direct application. Practically, labor work reduction has no impact on the ecological aspect. In Fig. 7, labor work reduction can be also represented by the application (2), when (x) is the economic aspect.

Considering (x) as the ecological aspect, the in Fig. 7 showed direct application (3) represents the example of applying environmentally friendly fiber that has a higher direct cost. On the other side, direct application (3) can be the implementation of highly automated process as well. Such automated process can have a lower direct cost but a higher carbon footprint. In this case the curve (x) represents the economic aspect.

Based on the results of this work as well as the knowledge about aerospace industry, wide range of eco-efficient direct applications can be enhanced. They include not only eco-efficient technical but also management developments. Practically, decision-makers can still favor applications that are beneficial for one eco-efficiency aspect regardless of their impact on the other one based on the situation.

5.2. Results evaluation

In order to ensure the reliability of the compiled results, these results are validated. Based on the qualification of conceptual model, process model has been adjusted iteratively to reach a sufficient representation for the real manufacturing process. The second step is to check the holism of the report that is generated by the EEAM-python-tool based on the collected data.

In LCA, the evaluation includes completeness and sensitivity checks [17]. Completeness check examines the availability and entirety of the data. As it is shown previously in Fig. 6, the EEAM is based on field data collection, literatures, data from suppliers, as well as previous internal studies. Within LCI the data are collected from identical manufacturing events for ten wing ribs. For real field data, data unavailability within the system boundary represents a minor problem.

Furthermore, sensitivity check is performed by comparing the results of this work to the previously reviewed studies. Witik et al. results show similar economic behavior. However, comparing Das results from automotive industry with aerospace industry results illuminates significant differences between the manufacturing cycles time which leads to an enormous cost difference. Hagnell et al. have studied several assembly cases for the entire wing box. In these cases, the wing ribs are constantly handled, where the study focuses on the differences between assembly scenarios. For low production volume, Hagnell et al. work shows a close result.

The results of both Gutowski et al. and Haffner studies differ from the results of this work due to the variation in temporal, geographical, as well as technical system boundaries. The results of the majority of discussed literatures and this work vary remarkably. Therefore, this paper can contribute with its results in illuminating new detailed perspectives in assessing the eco-efficiency of manufacturing complex CFRP structures such as wing ribs in aerospace industry.

6. Conclusion

This paper presents the case study of assessing aircraft wing rib structure made of CFRP for a modern commercial aircraft. The assessment is performed within an integrated LCA and BPR framework for decision support in manufacturing. For FRP manufacturing processes, the computer-based EEAM is developed as a decision support tool. In this paper, EEAM assesses CFRP manufacturing performed by the in-autoclave SLI and ML technique at DLR. Considering existing associated literatures, the results of some literatures vary remarkably from this paper due to the distinction in manufacturing techniques and system boundaries. Other literatures conclude similar results which validate the results of this work.

The results of this work illuminate possible direct applications for the decision-makers. Lean manufacturing is an example of such management tools. On the other hand, advanced technologies for reducing the fiber waste during cutting are also needed. Moreover, energy consumption within curing can be significantly reduced. This might be achieved by more efficient autoclave utilization through reducing the curing cycle time and manufacturing multi ribs simultaneously in each cycle. Fiber and matrix waste can be also reduced by minimizing the machined part in finishing. Furthermore, implementing more automated processes can lead to a reduction in labor cost. In aerospace industry, certifications and regulations should be considered in such direct applications.

A gate-to-gate assessment of carbon footprint and direct cost of manufacturing process is a cornerstone in performing a cradle-to-grave assessment. Such a cradle-to-grave eco-efficiency assessment is crucial for the future of the CFRP implementations in aerospace structures. In practice, huge efforts are required for data collection in an activity-based eco-efficiency assessment. Moreover, precise system boundary, unit process definition, and elementary flow allocations are crucial and effortful. Therefore, data collection can be enhanced through the implementation of smart measurement systems that reduces the LCI efforts in eco-efficiency assessment.

7. Acknowledgments

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007–2013) under grant agreement n°314003.

Conflict of interest statement

The authors declare no conflict of interest.

References

[1] M. Wiedemann, M. Sinapius, Adaptive, Tolerant and Efficient Composite Structures, Springer Science & Business Media, 2012.
[2] R. Witik, F. Gaille, R. Teuscher, H. Ringwald, V. Michaud, J.-A. Månson, Assessing the economic and environmental potential of out of autoclave processing, in: 18th ICCM, 2011.
[3] D.P. Raymer, Aircraft Design: A Conceptual Approach and Rds-Student, Software for Aircraft Design, Sizing, and Performance Set, AIAA Education, AIAA, 2006.
[4] W.J. Marx, D.N. Mavris, D.P. Schrage, A hierarchical aircraft life cycle cost analysis model, in: Aircraft Engineering, Technology, and Operations Congress, 1995.
[5] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, R. Rosenbaum, IMPACT 2002+: a new life cycle impact assessment methodology, J. Life Cycle Assess. 8 (6) (2003) 324.
[6] O. Dababneha, T. Kipouros, A review of aircraft wing mass estimation methods, Aerosp. Sci. Technol. (2017).
[7] A.J. Timmis, A. Hodzic, L. Koh, M. Bonner, C. Soutis, A.W. Schäfer, L. Dray, Environmental impact assessment of aviation emission reduction through the implementation of composite materials, J. Life Cycle Assess. 20 (2) (2015) 233–243.
[8] R. Dhingra, J.G. Overly, G.A. Davis, et al., Life-Cycle Environmental Evaluation of Aluminum and Composite Intensive Vehicles, CCP, 1999.
[9] J. Kasai, Life cycle assessment, evaluation method for sustainable development, JSAE Rev. 20 (3) (1999) 387–394.
[10] S. Das, The Cost of Automotive Polymer Composites: A Review and Assessment of DOE's Lightweight Materials Composites Research, National Laboratory Oak Ridge, Tennessee, USA, 2001.
[11] E. Shehab, W. Ma, A. Wasim, Manufacturing cost modelling for aerospace composite applications, in: Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment, 2013, pp. 425–433.

[12] J.-W. Choi, D. Kelly, J. Raju, A knowledge-based engineering tool to estimate cost and weight of composite aerospace structures at the conceptual stage of the design process, Aircr. Eng. Aerosp. Technol. 79 (5) (2007) 459–468.
[13] S.M. Haffner, Cost Modeling and Design for Manufacturing Guidelines for Advanced Composite Fabrication, MIT, 2002.
[14] T. Gutowski, D. Hoult, G. Dillon, E.-T. Neoh, S. Muter, E. Kim, M. Tse, Development of a theoretical cost model for advanced composite fabrication, Compos. Manuf. 5 (4) (1994) 231–239.
[15] M. Hagnell, B. Langbeck, M. Åkermo, Cost efficiency, integration and assembly of a generic composite aeronautical wing box, Compos. Struct. 152 (2016) 1014–1023.
[16] C.L. Simes, L.M.C. Pinto, R. Simoes, C. Bernardo, Integrating environmental and economic life cycle analysis in product development: a material selection case study, J. Life Cycle Assess. 18 (9) (2013) 1734–1746.
[17] ISO, ISO14040: Environmental Management – Life Cycle Assessment – Principles and Framework (ISO 14040:2006), vol. 14040, ISO, 2009.
[18] G.A. Norris, Integrating life cycle cost analysis and LCA, J. Life Cycle Assess. 6 (2) (2001) 118–120.
[19] M. Schmidt, M. Nakajima, Material flow cost accounting as an approach to improve resource efficiency in manufacturing companies, Resources 2 (3) (2013) 358–369.
[20] M. Brander, R. Tipper, C. Hutchison, G. Davis, Technical Paper: Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels, Econometrica Press, 2008.
[21] Y. Leterrier, Life cycle engineering of composites, Compr. Compos. Mater. (2001).
[22] J. Champy, L. Cohen, Reengineering Management, Dunod, 1995.
[23] H. Dyckhoff, T.S. Spengler, Produktionswirtschaft: Eine Einführung, Springer-Verlag, 2010.
[24] S. Schlesinger, R.E. Crosbie, R.E. Gagné, G.S. Innis, C.S. Lalwani, J. Loch, R.J. Sylvester, R.D. Wright, N. Kheir, D. Bartos, Terminology for model credibility, Simulation 32 (3) (1979) 103–104.
[25] B. Walter, Grahl Klöpffer, Ökobilanz (Lca): Ein Leitfaden für Ausbildung und Beruf, John Wiley & Sons, 2009.
[26] M. Schmidt, R. Keil, Stoffstromnetze und ihre Nutzung für mehr Kostentransparenz sowie die Analyse der Umweltwirkung betrieblicher Stoffströme, Hochschule Pforzheim, 2002.
[27] M. Goedkoop, A. De Schryver, M. Oele, S. Durksz, D. de Roest, Introduction to LCA with SimaPro 7, PRé Consultants, The Netherlands, 2008.
[28] M. Baitz, C.M. Colodel, T. Kupfer, J. Florin, M. Oliver, Kokborg Morten, Köhler Annette, Daniel Thylmann, Alexander Stoffregen, Steffen Schöll, Julia Görke, Rudolf Schuller, A. Liedke, GaBi Database & Modelling Principles 2014, PE-International, 2014.
[29] M. Weiland, LOCOMACHS: Demonstrators, Saab Aeronautics, 2015.
[30] S.M. Krolewski, Study of the Application of Automation to Composites Manufacture, DTIC Document, 1989.
[31] M. Großklos, Kumulierter Energieaufwand und CO_2-Emissionsfaktoren verschiedener Energieträger und -versorgungen, IIWU 09 (2014).