ASSESSMENT-BASED ECO-EFFICIENCY ESTIMATION OF COMPOSITE AND HYBRID STRUCTURES IN COMMERCIAL AIRCRAFT

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ABSTRACT

In the early development stage, decision-makers select the product specifications. These demand-oriented specifications are achieved by configuring the associated processes. Such decision-making may be involved with various life-cycle stages and multiple development disciplines. Therefore, decision-support systems (DSSs) are essential to facilitate the decision-making process on strategic, tactical, and operational managerial levels. To consult the decision-makers, success factors are to be defined and evaluated. Success factors such as the sustainability aspects such as economic and ecological impacts may be evaluated on different levels starting from the global key-result indicators (KRIs). To serve different managerial levels by such DSSs, combining what are known as top-down and bottom-up evaluation approaches is crucial. In practice, a DSS provides the assistance regarding a specific selection of KRIs. In this work, economic as well as ecological KRIs are evaluated by the applied DSSs.

Therefore, two DSSs are discussed in this paper. The first DSS is the Eco-Efficiency Assessment Model (EEAM), which has been developed by the German Aerospace Center (DLR) as a bottom-up assessment tool for the production of composite and hybrid structures. In this work, EEAM is implemented to assess the economic and ecological KRIs of the "as-is" prototype manufacturing process at DLR laboratories. Based on EEAM, an Eco-Efficiency Estimation Model (E³M) is developed as the second DSS in this work. E³M evaluates the economic and ecological impacts of the "as-if" industrial scenarios by deriving a top-down estimation based on the bottom-up assessment. The advantage of this approach is the possibility of validating the data-based bottom-up assessment and consequently the assessment-based estimation.

As a case study, a novel design of a suction rib for a hybrid laminar flow control (HLFC) wing is selected in this work. While HLFC offers advanced performance during operation phase in the life-cycle of commercial aircraft, decision-makers need to investigate the performance of the selected KRIs such as direct cost and carbon footprint in the other life-cycle phases.

Despite the fact that all other phases are decisive, this work focusses on the manufacturing process. After performing a data-based eco-efficiency assessment of the "as-is" suction rib manufacturing, an estimation of "as-is" industrial manufacturing is derived. The results of both "as-is" and "as-if" scenarios show a reduction in the direct manufacturing cost of the suction rib from 4.9 k€/kg of the final structure to 0.395 k€/kg, in the carbon footprint from 313.9 $kgCO_2/kg$ to 93.7 $kgCO_2/kg$, as well as the by the product material waste from around 65% to 38% respectively.

1 INTRODUCTION

Especially in the early design phase, decision support systems (DSSs) assist decision-makers from different organization disciplines and levels in evaluating the product and process alternatives. For the selected success indicators, such evaluation is required for any sustainable development within the different life-cycle phases in general and the production in specific. While decision-makers may have diverse interests, the meaning of success indicators varies between their disciplines as well as their hierarchy levels. Therefore, this work reviews two DSSs that have been developed by the German Aerospace Center (DLR). These DSSs, which are the eco-efficiency estimation model (E^3M) and the eco-efficiency assessment model (EEAM), assist the decision-makers in evaluating selected economic and ecological impacts within the production of composite and hybrid structures [1].

In a comprehensive review, Hueber et al. classify the possible evaluation techniques into qualitative and quantitative ones. While qualitative techniques are split into intuitive and analogical, the quantitative techniques can be either parametric or analytical [2]. In a previous work, it has been concluded that data availability and decision maturity levels are decisive in selecting an evaluation technique and developing a proper DSS for it [3].

Generally, deriving the estimation results based on the knowledge generated from previous assessments is a known approach [2]. However, distinguishing the different knowledge stages and implementing them systematically to achieve an assessment-based estimation of virtual or non-assessable processes is novel. Whether it is an estimation or assessment, defining the targeted decision-makers, the studied product as a functional unit, as well as the process as a product system is essential for any evaluation [4]. In literature, evaluating the economic and ecological impacts in aircraft production has been studied in several works. A selection of these studies is reviewed briefly in Table 1.

Table 1. Brief literature review of associated studies.

Literature	Approach	Product system and functional unit
Al-Lami et al. [1]	Bottom-up direct cost and carbon footprint assessment based on collected data from laboratories	In autoclave manufacturing of wing ribs made of carbon fiber-reinforced polymers (CFRP) by manual layup and single-line infusion
Al-Lami [3]	Bottom-up direct cost and carbon footprint assessment based on real-time collected data from industry-close production	Selection of unit processes (UPs) in manufacturing wing ribs made of CFRP by automated layup
Gutowski et al. [5]	Cost estimation model focusing mainly on labor time estimation	Selection of manufacturing UPs in the production of various composite components
Haffner [6]	Activity-based technical cost assessment based on collected data	Selected manufacturing techniques for various aerospace structures
Hagnell et al. [7]	Cost estimation based on design complexity	Production of aircraft wing-box made of CFRP
Shehab et al. [8]	Knowledge based model validated by a bottom-up cost assessment based on laboratory collected data	Selection of UPs of manual layup (ML), in-autoclave manufacturing of aircraft pre-impregnated fiber (prepreg) structures
Wicke and Pohya [9]	Top-down economic estimation based on design configurations and aircraft specifications	Entire life-cycle of a commercial aircraft with natural laminar flow (NLF)

From Table 1, it is concluded that a comprehensive understanding of the evaluation aspects is required to classify the implemented DSSs based on unified criteria such as the data availability and its maturity level, the evaluated success indicators, the associated organization level, as well as the model complexity of the DSS. Other process characteristics such as technology readiness level (TRL), degrees-of-automation (DoA), and process maturity should be also clearly defined in such evaluation.

2 METHODS

2.1 Goal and scope definition

"Who are the decision-makers that a DSS aims to assist?" is an essential question to be answered prior to any evaluation approach [4]. Generally, decision-making is carried out on strategic, tactical, and operational management levels. In practice, these levels may also exist in each discipline within a multidisciplinary product development. For decision-making, the so-called knowledge pyramid starts from initial data, that is converted into data, through information, then knowledge and finally end by gaining the aimed wisdom. In practice, data collection and processing are known to be effortful and costly in the bottom-up eco-efficiency evaluation [3]. Therefore, decision-makers prefer to depend on available information, knowledge, or wisdom to avoid data collection. S such top-down estimation hinders the capability of results validation.

By correlating the maturity stages in the knowledge pyramid with decision-making processes, decision-makers can describe multileveled indicators. Such success indicators can be classified based on their impact comprehensiveness to descend from the global key result indicators (KRIs), result indicators (RIs), performance indicators (PIs), until the key performance indicators (KPIs) [3]. Practically, in aircraft development the economic and ecological aspects play a decisive role. Ideally, direct cost and carbon footprint can be evaluated as KRIs by the same DSS.

In a DSS, different modeling transparency levels may be adopted including the white-box, grey-box, and the black-box models [3]. The first type depends on the bottom-up data in establishing a thorough transparent description of the system. In a black-box model, the relation of cause-and-effect is hidden from the decision-makers. While the conclusions of a black-box model can be difficult to trace, white-box models are associated with costly data collection and processing.

2.2 The Evaluated Functional Unit and Product System

According to Wortmann, an aircraft producer is considered as a product-oriented original equipment manufacturer (OEM), that invests in order to offer pre-request products to its customers. It is also defined as an engineer-to-order OEM, while customers may still modify some of the aircraft features [10]. While the aircraft or parts from it may be evaluated as a functional unit, product systems such as the production processes may be evaluated regardless of their functional unit as well [3]. Therefore, for any evaluation it is essential to define the scope, which may be associated with a product concept, a process scenario, a technique within a UP, or a technology in activity, as they are illustrated in Figure 1.

The illustration in Figure 1 is adopting in developing EEAM as a white-box model that describes the different indicator levels from the KPIs up to the KRIs. As Figure 1 shows, evaluation scopes may vary based on the evaluated objects. In practice, the eco-efficiency evaluation can be either attributional or consequential. On the one hand, the attributional approach focuses on describing the exact impact value of a product or process. On the other hand, the consequential one describes the change in selected UPs as a response to applied developments.

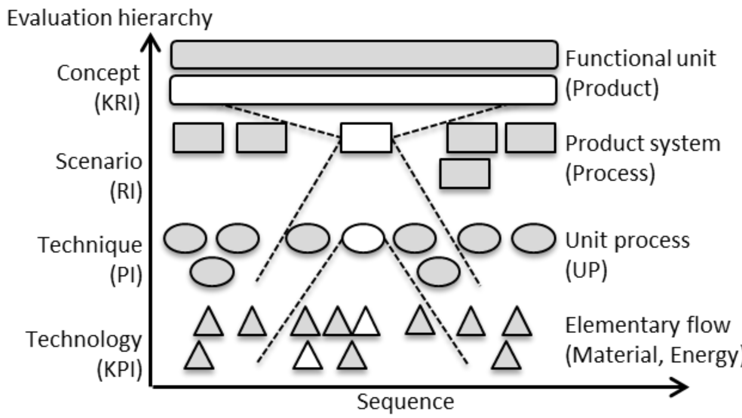

Figure 1. Evaluation objective and scope.

In this work, a technology is defined as the technical solution to realize an activity, while technique is defined as the result of combining all technologies within a process, a UP, or several UPs [3]. While a detailed generic description of aircraft life-cycle has been introduced in a previous work [1], this paper focuses on evaluation, the interaction between development activities of aircraft structures, and its production.

2.3 Eco-Efficiency Estimation Model (E³M) based on the Eco-Efficiency Assessment Model (EEAM)

Developed by DLR, E³M is a DSS that enables the estimation of production KRIs for novel structure designs and process techniques. E³M is a bottom-up-based top-down eco-efficiency white-box model. With the availability of default parametrization from historical prototype production scenarios as well as industry projects, the estimation effort is significantly reduced. After assessing the "as-is" prototype production by the EEAM in this work, the E³M is applied to anticipate and estimate the direct cost and carbon footprint of the industrial "as-if" production scenario. Despite the usefulness of it for various organization levels, the results of E³M aim to serve the production management mainly.

Theoretically, production cost, specifically, and Life-cycle cost (LCC), in general, can be classified under a set of intersectional cost categories to include direct, indirect, recurring, nonrecurring, fixed, as well as variable costs. In this work, the evaluation aims to quantify the direct cost including its recurring, nonrecurring, fixed, and variable portions, while this approach is also applied to the carbon footprint [3].

For a selected product system, EEAM is calculating the direct cost δ_j of all elementary flows from each type j. It also evaluates its carbon footprint β_j. Based on this bottom-up calculation, the impacts of different hierarchy levels from Figure 1 can be realized. In the developed DSSs, the direct cost assessment is carried out through Equation (1).

$$\delta = \sum_{i=1}^{m} \sum_{j=1}^{n} \gamma_j \alpha_{ij} \tag{1}$$

These elementary flows α_{ij} are measured in the "as-is" prototype production, while their values are specific for their type j as well as the UP i in which they occur. On the other hand, the economic characterization factors γ_j are only correlated with the elementary flow type j. Similar to Equation (1), Equation (2) provides the calculation for the carbon footprint assessment on different levels.

$$\beta = \sum_{i=1}^{m} \sum_{j=1}^{n} \varepsilon_j \alpha_{ij} \tag{2}$$

In EEAM, both economic and ecological characterization factors, which are represented by γ_j and ε_j respectively, are based on literatures, internal projects, data from suppliers, internal calculations, and assumptions. In EEAM, a data base has been established to provide these factors for around 840 elementary flows in composite production. These elementary flows can be clustered in this case study into categories that include; labor, facility, energy, molds and jigs, fiber, matrix, fiber waste, matrix waste, ancillaries and equipment.

All materials including the reinforcement, which is carbon fiber in this case study, matrix, ancillaries, as well as fiber and matrix waste can be assessed by multiplying their masses with their factors in Equation (1) and Equation (2). Similarly, the energy impact is calculated by the magnitude of consumed electricity multiplied by the factors of the local electricity mix. The impacts of labor and equipment are calculated by the work duration multiplied by the factor per time. Still, equipment characterization factors are calculated in details for specific life-spans, maintenance and repair scenarios, as well as working shifts. Equipment utilization is considered to have universal usage. For instance, autoclave can be implemented for a wide range of scenarios and it is not product or project specific. The facility impact has a very similar calculation approach to both labor and equipment. However, facility impact is not only calculated by the equipping time but also the equipped area. On the other hand, molds and jigs are product and project specific. Therefore, they have a unique calculation functionality in EEAM, in which the total production cycles, maintenance, and repair rates are considered. The impact of each mold or jig is distributed equally on the associated produced functional units throughout its life-span.

Practically, the accuracy of the result depends highly on validating the elementary flows and characterization factors. However, it is challenging to validate the characterization factors even with available commercial databases. The lack of studies about composites and their raw materials as well as the lack of clarity of assessment system boundaries require collaborative work between the decision-makers throughout the entire life-cycle of the studied functional unit. Based on Equation (1) and Equation (2), the estimation of “as-if” industrial process is carried out by alternating the characterization factors as well as the elementary flows if required. That is, whenever a difference regarding the elementary flow is noticed between these laboratory and industrial scenarios. Although both ecological and economic aspects may be assessed similarly [3], there is a lack of reliable data for the required ecological characterization factors of several categories including; fiber, labor, equipment, and facilities. Therefore, assumptions are adopted for the characterization factors of these categories.

3 CASE STUDY: PRODUCTION OF SUCTION RIB

3.1 System boundary definition

The definition of temporal and geographical horizons is essential for any evaluation. These horizons have a direct impact on the characterization factors. On the other hand, technical boundaries describe the techniques and technologies implemented in realizing the product systems. For aircraft production, the process scenarios should be precisely defined to have a clear description of what is evaluated.

To understand the case study in this work, Figure 2 gives an overview of the individual parts of the developed HLFC wing. The core of this HLFC system is the suction rib, which is a hollow structural rib that contains the compressor. This CFRP made rib has also the functionality of distributing the vacuum to the chambers beneath the microperforated skin. The hollow chamber of the suction rib is enclosed by a CFRP substructure. Together they make up the load carrying structure which is directly mounted to the structural parts at the front spar of the wing box. The aerodynamic surface consists of a microperforated titanium skin, which is fitted around the CFRP substructure. CFRP Spacers provide a dedicated distance between these two structures and keep the skin at its desired position.

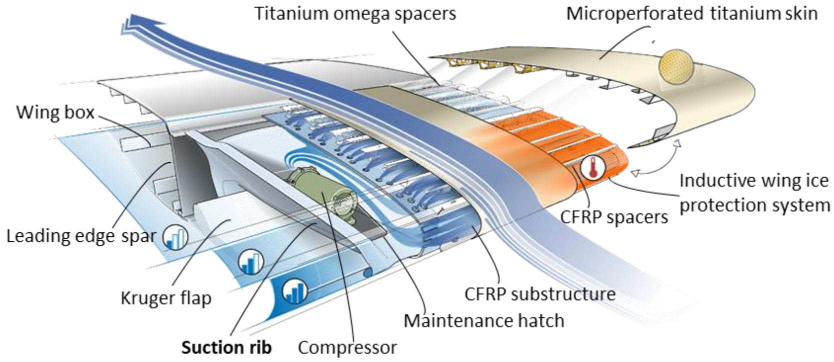

Figure 2. HLFC concept – structural and functional overview.

The space in between functions as a spanwise chamber for vacuum distribution. The rib in this case study is manufactured for the ground-based demonstrator (GBD) with a TRL4.

3.2 Modeling and parametrization of the manufacturing process

The visualization of each UP is an effective modeling and communication solution. As shown in Figure 3, in this case study 8 different input elementary flow categories are considered. Waste outputs are also assessed separately in this work due to the significance of determining them. In addition, the product maturity evolution is shown as an intermediate flow between the UPs and ended by the output of CFRP suction rib.

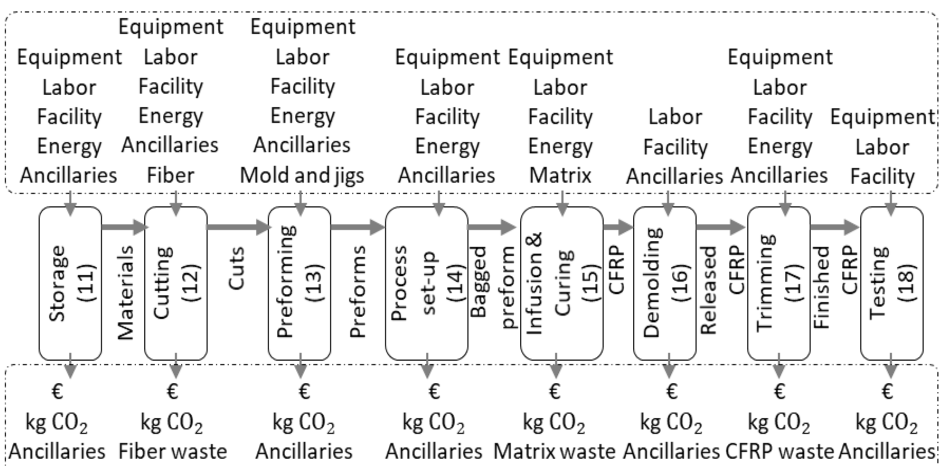

Figure 3. Manufacturing process model for scenario (1): hand lay-up, single-line infusion, and autoclave.

In Figure 3, standard definition of the manufacturing UPs is selected based on the output of the on-going *SAUBER4.0* project. To serve the decision-makers, all definitions, their associated visualizations, the data collection sheets of every UP, the visualized results, as well as the summary of global results that are compared to validation studies are all integrated in a new standardized EEAM-communication format. In this UPs definition, the manufacturing process is to be distinguished in assessable UPs. With a standardized definition of each, a UP should be adaptable for different techniques and scenarios. This offers a fair comparison that enables carrying on a consequential assessment of the different scenarios. Still, a flexibility in the definition must be considered, while not all scenarios can be fit in such standardization. For instance, preparing the process set-up is a UP that represents several activities. These activities may be carried out in different work stations and in separated time slots. Generally, the numbering of these UPs is applied as a unique identification of each one, while these UP are not necessarily performed in this sequence [3]. For the “as-is” laboratory manufacturing scenario (1) of the suction rib, the technologies of manual preform, single-line infusion, and autoclave curing are implemented. This scenario (1) requires specific input and output elementary flow categories as well as intermediate flows.

Similar to Figure 3, in Figure 4 the “as-if” industrial scenario (2) of the resin transfer molding in the Endkonturnahe Volumenbauteile (EVo)-platform is modeled [3]. This highly automated platform has not only unique elementary flow categories and intermediate flows, but also specified characterization factors.

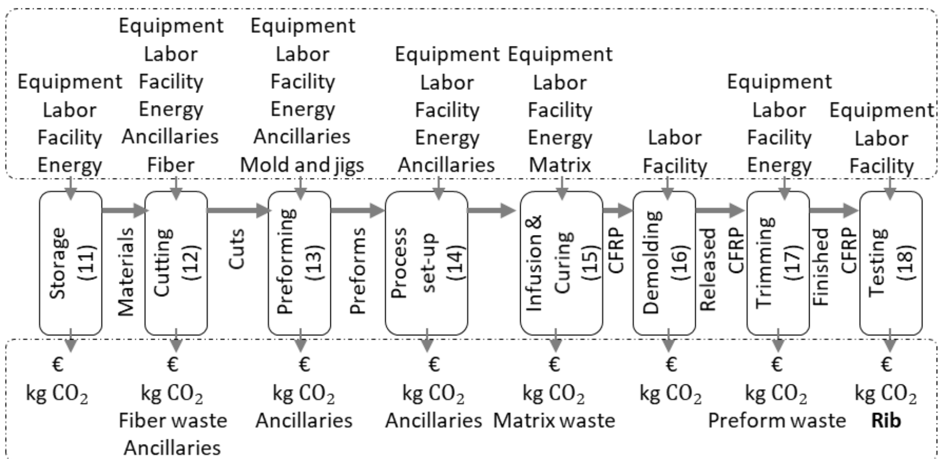

Figure 4. Manufacturing process model for scenario (2): hand lay-up and autoclave.

As Figure 4 shows, the industrial process has a unique configuration that impacts the definition of elementary flow categories. For instance, ancillaries are implemented only in three UPs in this industrial process. As a technical example, preforming vacuum foils are replaced by more expensive but also more sustainable preforming membranes as a part of the press device. Despite the high DoA in the EVo-platform, man power is assumed for controlling in this “as-if” scenario (2) to fulfil the aerospace production and certification regulations. Unlike scenario (1), in scenario (2) the Evo-platform offers the final net-shape before infusion. This early trimming produces preform waste instead of CFRP waste, which may be significant for circularity solutions. Unlike scenario (1), which implements the single-line infusion after vacuum-bagging, the resin-transfer molding in scenario (2) generates no bagged-preform.

As a transparent DSS, the characterization factors are provided in EEAM, while the significant ones are shown in a visualized process model for each UP. The definitions of these UPs have been studied thoroughly in previous works [3] [1]. Based on the suggestions from industrial partners such as AIRBUS in the project *SAUBER4.0*, every UP is modeled, parametrized, and evaluated in the standardized EEAM-communication format. This format includes the inputs and outputs of each evaluated scenario with facilitated visualization for the decision-makers.

After collecting the data from the “as-is” manufacturing of suction rib prototypes, this scenario (1) in Figure 3 is assessed by the EEAM. Based on that assessment, the elementary flows in the data collection sheets of the evaluated UPs are alternated to match the industrial scenario (2). In addition, the characterization factors of the assessment are modified to carry out the estimation of the "as-if" scenario (2) in Figure 4 by the E³M.

4 RESULTS

4.1 Economic Results

The results from both "as-is" laboratory scenario (1) in EEAM and the "as-if" industrial scenario (2) in E³M may be distinguished into the main studied KRIs, which are the direct cost as an economic impact as well as the carbon footprint as an ecological one. In both evaluations, the calculated investments are around 1 million € in scenario (1) and around 4.6 million € in scenario (2), while equipment utilization is universal and not project specific. The total direct cost of scenario (1) is around 14.4 k€ for the 2.95 kg suction rib prototype, which is equal to 4.9 k€/kg with 63% recurring costs.

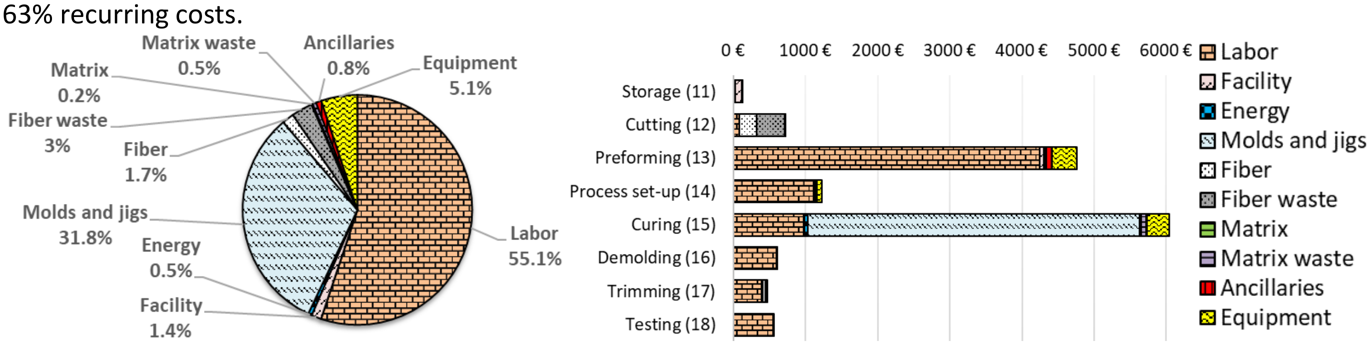

Figure 5. Direct cost of scenario (1): percentage per category (left) and absolute results per UP and category (right)

In Figure 5, the labor and mold direct costs are significant. This is a result of low process maturity and its early stage in the learning curve as well as the low volume of five produced prototypes per mold.

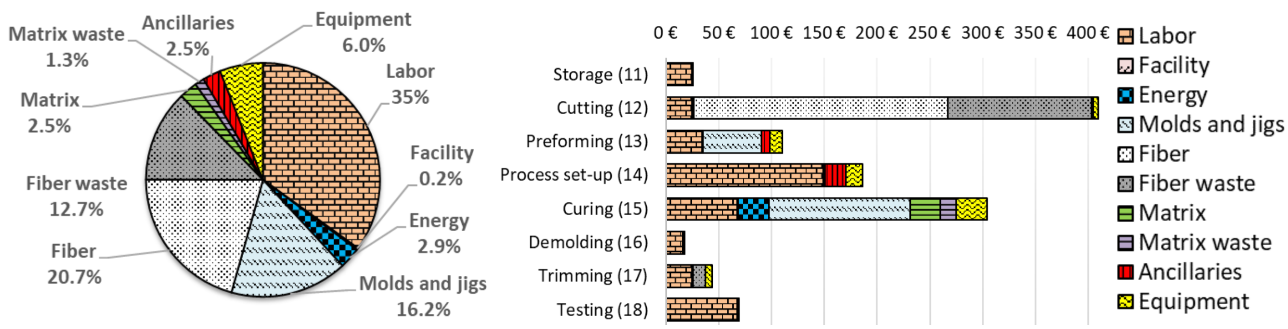

Figure 6. Direct cost of scenario (2): percentage per category (left) and absolute results per UP and category (right)

Despite the significant reduction in the total direct cost of more than 15 times, both labor and mold categories still dominate the total direct cost. Preforming in scenario (2) has relatively lower impact, while testing has higher contribution in this "as-if" scenario.

4.2 Ecological Results

In this section, the ecological impacts from both scenario (1) and scenario (2) are evaluated in Figure 7 and Figure 8, respectively. On the one hand, the total carbon footprint of scenario (1) is assessed to be around 925 kg CO_2. On the other hand, scenario (2) is estimated to have a total carbon footprint of around 276 kg CO_2. In scenario (1), facility has a significant ecological impact. This is similar to the result from a previous work with similar system boundary and assumptions [3]. Energy and fiber-waste follow facility respectively with the highest carbon footprint.

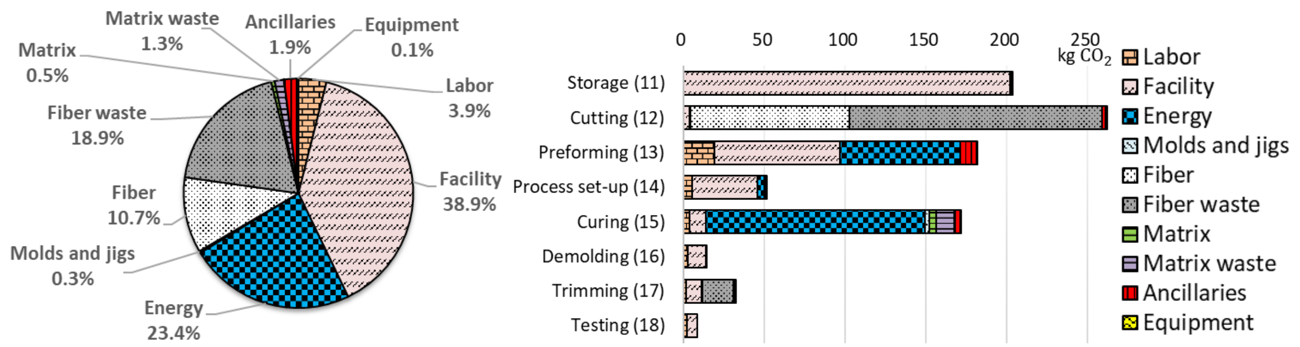

Figure 7. Ecological results of scenario (1): percentage per category (left) and absolute results per UP and category (right)

In scenario (2), fiber and its waste are the leading ecological contributors, followed by energy use. This describes the common drivers of carbon footprint in an industrial process [1]. However, the adopted fiber ecological characterization factor of around 46.8 kg CO_2/kg is crucial here, while it is reletivly high in comparison to all other materials. Nonetheless, a sensitivity analyses of alternating this factor has been discussed in a previous work [3].

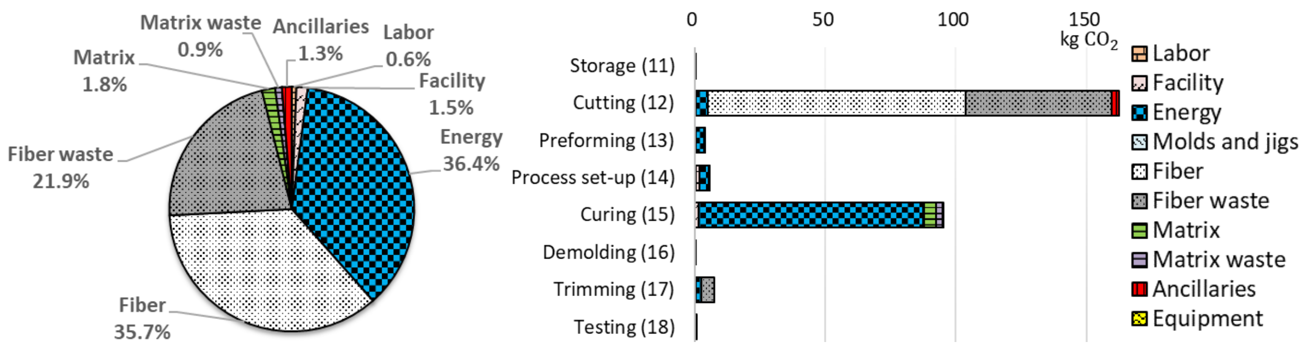

Figure 8. Ecological results of scenario (2): percentage per category (left) and absolute results per UP and category (right)

4.3 Validation

For the validation as a multilevel approach, comparible results are required [3]. In literature, there are two main challenges for the realization of such validation, which are the lack of clarity of adopted system boundaries in exisiting studies and the lack of publications regarding these studied KRIs in composite production.

Similar to previous results, the ecological impact of traditionally neglected facility is significant in scenario (1). It is essential to mention, that the impact of 1 m² area is assumed to be around 71 kg CO_2/ year [11]. Still, there is a lack of studies about the impact of industrial facilities in Germany. The high economic and ecological impacts of the "as-is" protytype manufacturing may be associated with the high structure complexity and low process maturity. Compared to previous studies, the estimated impacts of around 0.395 k€/kg and 93.7 kgCO2/kg in scenario (2) are lower than all these previous works [3] [1]. More efficient material utilization in scenario (1) is impacting both eco-efficiency aspects positively. Faster automated processes in the industrial scenario reduce the direct labor cost, and reduces the ecological impact of facility per manufactured product.

4.4 Discussion and Outlook

In this work, two main subjects are discussed: the method of assessment-based estimation within the E³M as a DSS for the early design phase, and the results of the selected case study that aim to validate the applicability of this new DSS and investigate the possible further developments. Within the assessment of the "as-is" laboratory prototype manufacturing, the laborious data collection and processing necessitate the implementation of suitable automated solutions such as the concept of Smart-Work-Station (SWS) [3]. In general, E³M enables the simulation of various "as-if" scenarios by alternating not only the elementary flows, but also the characterization factors. In future works, it is essential to assess a comparable industrial process of similar structure by EEAM in order to validate the estimation results of scenario (2) in E³M. This may be realized by collaboration projects with industry partners that implement the EEAM and E³M directly in evaluating their processes.

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5 REFERENCES

[1] A. Al-Lami, P. Hilmer and M. Sinapius, "Eco-efficiency assessment of manu facturing carbon fiber reinforced polymers (CFRP) in aerospace industry," *Aerospace Science and Technology,* vol. 79, pp. 669-678, 2015.

[2] C. Hueber, K. Horejsi and R. Schledjewski, "Review of cost estimation: methods and models for aerospace composite manufacturing," *Advanced Manufacturing: Polymer & Composites Science 2,* pp. 1-13, 2016.

[3] A. Al-Lami, Time-Dependent Eco-Efficiency Assessment in the Production of Composite Structures Case study from manufacturing aircraft ribs, Braunschweig: Technische Universität Braunschweig, 2021.

[4] "ISO14044: Environmental management Life cycle assessment Requirements and guidelines," International Organization for Standardization (ISO), 2006.

[5] T. Gutowski, D. Hoult, G. Dillon, E.-T. Neoh, S. Muter, E. Kim and M. Tse, "Development of a theoretical cost model for advanced composite fabrication," *Composites Manufacturing ,* vol. 4, pp. 231-239, 1994.

[6] S. M. Haffner, Cost modeling and design for manufacturing guidelines for advanced composite fabrication, Massachusetts Institute of Technology (MIT), 2002.

[7] M. Hagnell and M. ˚Akermo, "A composite cost model for the aeronautical industry: Methodology and case study," *Composites Part B: Engineering,* vol. 79, p. 254{261, 2015.

[8] E. Shehab, W. Ma and A. Wasim, "Manufacturing Cost Modelling for Aerospace Composite Applications," in *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment* , London, 2013.

[9] K. Wicke and A. A. Pohya, "Operator and Manufacturer Life Cycle Cost-Benefit Analysis of Aircraft with Natural Laminar Flow Technology, in: 2018 AIAA Aerospace Sciences Meeting, 2018, p. 0270.," *AIAA Aerospace Sciences Meeting,* p. 0270, 2018.

[10] "Production management systems for one-of-a-kind products," *Computers in Industry 19,* vol. 1, pp. 79-88, 1992.

[11] W. K. Biswas, "Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia," *International Journal of Sustainable Built Environment,* vol. 3, pp. 179-186, 2014.