Life cycle analysis results for engine blisk LCA

Kilian Fricke, Thomas Bergs, Philipp Ganser and Martin Seimann
Fraunhofer Institute for Production Technology IPT, Aachen, Germany

Abstract

Purpose – The aviation industry has seen consistent growth over the past few decades. To maintain its sustainability and competitiveness, it is important to have a comprehensive understanding of the environmental impacts across the entire life cycle of the industry, including materials, processes and resources; manufacturing and production; lifetime services; reuse; end-of-life; and recycling. One important component of aircraft engines, integral rotors known as Blisks, are made of high-value metallic alloys that require complex and resource-intensive manufacturing processes. The purpose of this paper is to assess the ecological and economical impacts generated through Blisk production and thereby identify significant 'hot-spots'.

Design/methodology/approach – This paper focuses on the methodology and approach for conducting a full-scale Blisk life cycle assessment (LCA) based on ISO 14040/44. Unlike previous papers in the European Aerospace Science Network series, which focused on the first two stages of LCA, this publication delves into the "life cycle impact assessment" and "interpretation" stages, providing an overview of the life cycle inventory modeling, impact category selection and presenting preliminary LCA results for the Blisk manufacturing process chain.

Findings – The result shows that the milled titanium Blisk has a lower CO_2 footprint than the milled nickel Blisk, which is less than half of the global warming potential (GWP) of the milled nickel Blisk. A main contributor to GWP arises from raw material production. However, no recycling scenarios were included in the analysis, which will be the topic of further investigations.

Originality/value – The originality of this work lies in the detailed ecological assessment of the manufacturing for complex engine components and the derivation of hot spots as well as potential improvements in terms of eco-footprint reduction throughout the products cradle-to-gate cycle. The LCA results serve as a basis for future approaches of process chain optimisation, use of "greener" materials and individual process improvements.

Keywords ecoDESIGN, Sustainability, Productivity, Manufacturing, Production, Blisk, Engine, Life cycle assessment, LCA, Life cycle impact assessment, LCIA, Clean sky

Paper type Research paper

Nomenclature

3D = three-dimensional;
CML = Centrum voor Millikunde Leiden;
CMM = coordinate measuring machine;
CO_2 = carbon dioxide;
DALYs = disability-adjusted life years;
DTU = Danmarks tekniske universitet;
ECM = Electro chemical machining;
EBC = environmental barrier coatings;
Eq. = equivalent;
FPI = fluorescent penetrant inspection;
GEO = geographical correlation;
IBR = integrally bladed rotor;
K_A = imputed depreciation;
K_E = energy costs;
K_F = manufacturing costs;
K_I = maintenance costs;
K_{LH} = labour costs per hour;
K_M = machine costs;
K_{MH} = machine hour rate;
K_R = room costs;
K_W = tool costs;
K_Z = imputed interest;
LCA = life cycle assessment;
LCI = life cycle inventory;
LCIA = life cycle impact assessment;
Ni = nickel; and
Ti = titanium.

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/1748-8842.htm**

Aircraft Engineering and Aerospace Technology
96/1 (2024) 2–13
Emerald Publishing Limited [ISSN 1748-8842]
[DOI 10.1108/AEAT-04-2023-0108]

This paper forms part of a special section "Innovation in Aviation & Space for Opening New Horizons (12th EASN International Conference)", guest edited by Spiros Pantelakis, Andreas Strohmayer and Jordi Pons Prats.

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreements No807085, 945541 and 945549. Special acknowledgement to the industry partners represented in workshops of this project.

Ethics statement: This work has not been subject to studies on human subjects, human data or tissue, or animals.

This work is part of the Clean Sky 2 ecoDESIGN Transversal activity and Engines ITD.

Received 24 April 2023
Revised 18 September 2023
Accepted 25 September 2023

Introduction

Global air traffic has doubled approximately every 15–20 years and is expected to continue, albeit with some limitations because of the COVID-19 pandemic (Pearce, 2020). The European Union's Flightpath 2050 roadmap and the Clean Sky program (Clean Sky 2 JU, 2015; Clean Sky 2 Joint Undertaking, 2017) are currently driving technological advancements in the aviation sector. Resource-efficient manufacturing beyond the operational phase is crucial for the overall ecological evaluation, and the construction of aeroengine components is of great significance as engine design affects the entire life cycle. Integrally manufactured compressor rotors, also known as Blisks/integrally bladed rotors (IBRs), are one of the most demanding components to manufacture in aeroengines. Complex shapes, tight tolerances and tough materials like titanium and nickel-based alloys require intricate manufacturing process chains. The environmental impact of such process chains can be analysed through life cycle assessment (LCA) according to ISO 14040/14044, the scientific standard for evaluating the environmental impact of product systems. LCA outlines a process for "compiling and assessing the input and output flows and the potential environmental impacts of a product system during its life cycle" [International Organization for Standardization (ISO), 2020]. The procedure comprises the phases (Figure 1):

- *Goal and scope.*
  In this first step, the focus of the study and the regarded use-cases are described. This includes a definition of the component in scope, the processes that are being compared and analysed, as well as the functional unit.
- *Life cycle inventory.*
  The second step includes the acquisition of life cycle inventory (LCI) data. These resemble the input and output flows of each individual process step including mass and energy flows (electrical energy, tools used, etc.).
- *Life cycle impact assessment: (focus of this paper).*
  In the third step, the actual environmental impact of each process is calculated based on specific indicators, such as global warming potential (GWP), water pollution and toxicities. This step is conducted within software environments such as OpenLCA or GaBi (Ganzheitliche Bilanzierung, engl.: holistic balancing) (Lüdemann, 2014).
- *Interpretation: (focus of this paper).*
  This step is included in all three previous steps and requires domain-specific knowledge and technical expertise to transfer the findings and conclude overall results.

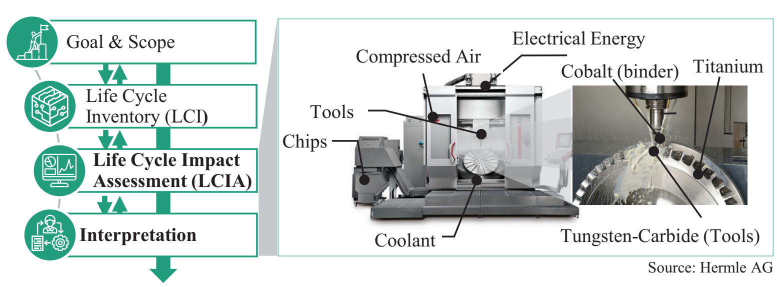
The following literature search provides an overview of existing LCA studies in the context of aviation. Several studies have dealt with the topic and carried out environmental impact assessments in a wide range of applications.

In 2013, Atılgan *et al.* conducted an environmental impact assessment for a turbo-prop engine using an exergo-analysis. The related environmental impact of each component of the engine was first calculated, and then an individual environmental performance was assigned to each component using the exergo rate. The study shows that the compressor, combustion chamber, gas generator turbine, power turbine and exhaust nozzle create different percentages of the total environmental impact of the engine. The exergy-based analysis is suggested as a valuable supplement to conventional analysis for getting more accurate results. However, no in-depth assessment of particular engine components was conducted here (Atılgan *et al.*, 2013).

Vinodh *et al.* published an LCA for a turbine blade. The article presents an LCA of a turbine blade used in aircraft engine systems to determine its environmental impact. The study uses the ISO 14040 standard and the Eco Indicator method to assess the environmental profile of the turbine blade. The results show that plating has the highest impact, followed by raw materials. Laser machining causes a high environmental impact, and efforts are being made to reduce this impact by adopting alternate eco-friendly machining processes. The article concludes that there is a vital need to perform environmental analysis of aircraft components to develop eco-friendly aircraft products, and more studies could be conducted on the LCA of complex aircraft products in the future (Vinodh *et al.*, 2017).

Musacchio *et al.* conducted a study to identify and define key environmental performance factors (KEPF) for gas turbine eco-design and production through LCA. The study aimed to develop a comprehensive framework for evaluating the environmental impact of gas turbine production and identifying opportunities for improving its sustainability. The article discusses the need for environmental impact assessment of new products, particularly in the oil and gas and power generation markets and emphasizes the importance of considering environmental impact aspects from the early stages of product development. The assessment is based on a Cradle-to-Gate LCA and is combined with case-specific qualitative and quantitative information such as material selection, manufacturing processes, mass quantity and coatings to provide environmental assessments. The authors present a case study of LCA applied to a heavy-duty gas turbine to outline the relative weight of each KEPF. The authors stress the

Figure 1 Four stages of an LCA study: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation (Hauschild *et al.*, 2018)



Source: Figure courtesy of Hermle AG 2017 and Fraunhofer IPT importance of reducing the carbon footprint (CF) of products while maintaining thermodynamic efficiency and highlight the potential for using upgraded biogas instead of fossil-origin natural gas to reduce CF (Musacchio *et al.*, 2020). Musacchio *et al.* also presented a comprehensive study on the LCA of gas turbine components, with a focus on the decarbonization of materials and machining processes. The authors conducted a general analysis of the environmental impacts of gas turbine components, from the extraction of raw materials to the end-of-life stage. The authors found that machining operations contribute to the CF of gas turbine components without, however, transparently outlining the impact of specific core engine parts like Blisks/IBRs or referencing any significant LCI data (Musacchio *et al.*, 2021).

Previous works on Blisk-LCA from our scientific working department focused on very basic preliminary results from small-scale Blisk by Bergs *et al.* (2021) and a collaboration with DTU Copenhagen analysed potential benefits of Ti-Blisk recycling without going into technical detail and in-depth analysis (Rupcic *et al.*, 2022). An in-depth assessment of full-size Blisk manufacturing is the focus of this study.

2. Method – life cycle assessment goal and scope

An investigation framework and a target must be defined in a first step regarding the product to be investigated as a functional unit or the processes to be analysed. The goal and scope of this study have been defined in the first paper titled "Geometry Model for Future Blisk LCA" (Fricke *et al.*, 2021b), whereas the definition and acquisition of LCI data have been described in the second paper titled "Life Cycle Inventories for Engine Blisk LCA" (Fricke *et al.*, 2022). As continuation for the two previous papers, this paper describes the results of the life cycle impact assessment (LCIA) after the acquisition of LCI data of different Blisk manufacturing scenarios, which will be explained in the next sections.

2.1 Functional unit and process description

The present case study focuses on the LCA of two approaches for Blisk manufacturing with titanium and nickel alloys being used as the Blisk workpiece material. The following Blisk manufacturing scenarios are analysed for the LCA in this study:

- Scenario #1: Conventionally casted titanium Blisk with milled blades
- Scenario #2: Conventionally casted nickel (Inconel) Blisk with milled blades

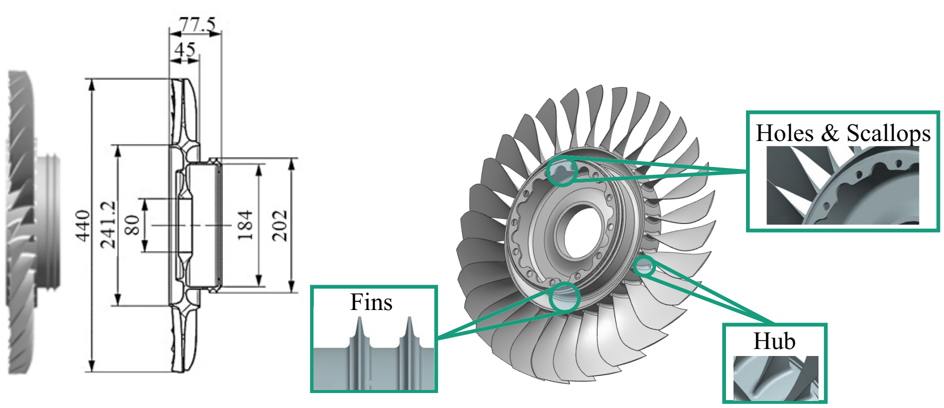
For Scenario #1, alloy Ti6Al4V is used as the raw material and carbide tools serve as milling tools for both roughing and finishing step. For Scenario #2, Inconel 718 alloy is used as the raw material with carbide tools used as milling tools for roughing and finishing steps. Cutting parameters for turning and milling are then selected to be suitable for each manufacturing scenario (Klocke, 2011).

In all scenarios, the functional unit is a Blisk demonstrator, which was designed based on analytical calculation methods (Hubig, 2012; Bräunling, 2015), with a diameter of 440 mm and a total number of 30 blades. Fins as well as several holes and scallops are also present in the Blisk. As already explained in the previous paper by Fricke *et al.* (2021b), the Blisk manufacturing can be described with a complex process chain that is generally divided into raw material and workpiece (part) generation, machining, surface treatment and quality assurance (Fricke *et al.*, 2021a). Figures 2 and 3 illustrate the reference Blisk demonstrator and the respective process chains in scope of this investigation. It is however important to note that because of the different alloy composition of the two scenarios in scope the performance of the titanium and the nickel Blisk can differ within the engine clearly with respect to temperature and mechanical load resistance. The two scenarios however perfectly represent the two basic rotor concepts for the low-pressure compressor and the high-pressure compressor. The idea is to assess these two basic approaches and in subsequent work dive into an ecological optimization of both components separately.

2.2 Life cycle inventory data for Scenario #1 and #2

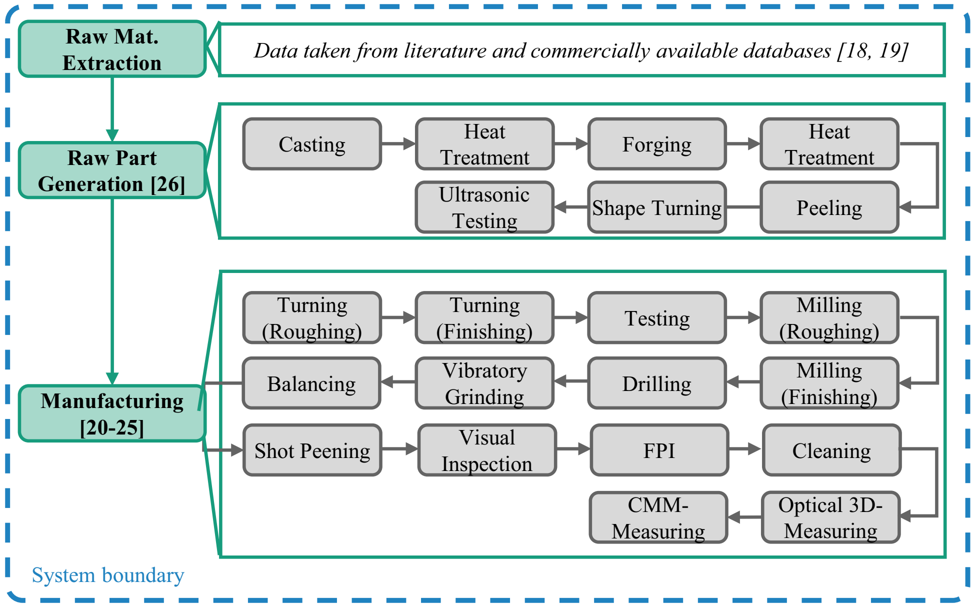
LCI data constitutes a critical component of LCA, serving as the second pillar. The LCI data are represented by the input and output flows of each process step in both manufacturing scenarios, which include mass and energy flows, e.g. electrical energy, coolant and compressed air. As described in the

Figure 2 Blisk design and functional unit



Source: Figure by authors

Figure 3 Process chain scenario and data sources (Sphera Solutions, Inc, 2023; Ecoinvent, 2023; Shipway *et al.*, 2019; Qi *et al.*, 2009; Park *et al.*, 2001; Li *et al.*, 2021; Karpuschewski and Kalhöfer, 2011; Hernández *et al.*, 2017; Priarone and Ingarao, 2017)



Source: Figure by authors

previous paper by Fricke *et al.* (2022), the data acquisition is performed through direct measurement, estimation or assumption based on the literature. The main base of LCI data was presented in a previous collaborative paper publication with colleagues from DTU focusing on Ti-Blisk manufacturing (Rupcic *et al.*, 2022). This data has since been updated for the raw material and data on the Ni-Blisk was added (Figure 5). The quantified flows are then modelled in the software GaBi to calculate the environmental impact of the process based on specific indicators from the EF 3.0 indicator group, such as GWP.

The reliability and validity of LCI data are crucial for obtaining accurate results and while comprehensive databases like Ecoinvent and GaBi offer a basis of general data, certain specialized processes, such as those used in aviation, lack verified and validated data of acceptable quality. In such cases, data must be acquired through technical case studies.

To assess data quality, a "pedigree matrix" introduced by WEIDEMA is used, considering uncertainties arising from measurements, calculations, estimations and literature sources. WEIDEMA *et al.* classify data quality into five categories (see Table A1 in Appendix, table by Weidema *et al.*, 2013):

1. Reliability (REL): This category defines data based on the approach used for data acquisition, differentiating between estimation and measurement methods.
2. Completeness (COM): This category characterizes the extent to which data sets cover input and output flows comprehensively.
3. Temporal correlation (TEM): This category provides information on the comparability of data over time.
4. Geographical correlation (GEO): GEO offers a qualitative assessment of data's geographical relevance.
5. Technological correlation (TEC): TEC evaluates the technological validity of data.

These five indicators assign a score ranging from 1 (highest quality) to 5 (lowest quality), with algorithms allowing for the calculation of a resulting standard deviation. In the following sections, an in-depth example of LCI data and its acquisition is given on the Raw Material Generation (Section 2.1), Machining processes (turning and milling; Section 2.2), Surface Treatment (Section 2.3) and Quality Assurance (Section 2.4).

2.2.1 Raw material and workpiece generation

Raw material generation includes processes related to ore mining, transport and alloy preparation. Data comes from databases like Ecoinvent and expert knowledge. Data quality varies significantly, with mixed levels of reliability, completeness and technical correlation. Energy consumption data lacks specificity, making no distinction between electricity and gas. However, the data shows a high temporal and geographical correlation, originating from European sources published in recent years (Breuer, 2018). Figure 4 illustrates the data quality of the obtained LCI flows regarding raw part generation.

2.2.2 Machining

Blisk-machining primarily involves contour-turning and blade-shaping processes. The machining steps involve energy and material flows, including electric power consumption, cooling fluid consumption, pressurized air usage and tool utilization. While machining data quality is generally high due to direct measurements during the process, raw material data exhibits lower reliability because of upstream processes' uncertainties and potential alloy concentration variations. An in-depth overview of LCI data and its acquisition is presented for machining processes, encompassing turning and milling, in Figure 5.

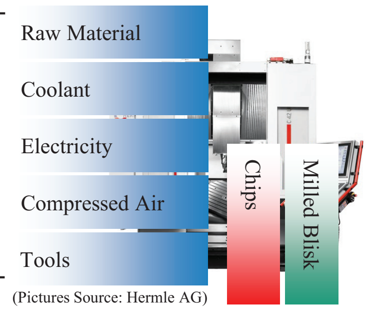
Figure 4 Relevant processes regarding raw material generation, the average pedigree matrix scoring and most important input and output flows (right)

Ti-Blisk

Flows	Value	Unit	Rel.	Com.	Tem.	Geo.	Tec.
Electricity	1400	kWh	1	1	1	1	1
Compressed Air	1200	m³	2	2	1	1	1
Raw Material	70	kg	2	1	2	1	1
Cutting Tools	5	/	1	1	1	1	1
Coolant	273	kg	1	1	1	1	1
Chips	66	kg	1	1	1	1	1
Milled Blisk	4	kg	1	1	1	1	1

Ni-Blisk

Flows	Value	Unit	Rel.	Com.	Tem.	Geo.	Tec.
Electricity	3200	kWh	1	1	1	1	1
Compressed Air	3400	m³	2	2	1	1	1
Raw Material	130	kg	3	2	2	2	2
Cutting Tools	16	/	1	1	1	1	1
Coolant	780	kg	2	1	1	1	1
Chips	123	kg	1	1	1	1	1
Milled Blisk	7	kg	1	1	1	1	1

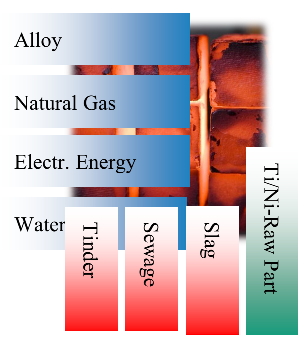


Notes: Rel.: Reliability; Com.: Completeness; Tem.: Temporal Correlation; Geo.: Geographical Correlation; Tec.: Technical Correlation
Source: Figure courtesy of Fraunhofer IPT 2015

Figure 5 Relevant processes regarding machining, the average pedigree matrix scoring and most important input and output flows (right)

Raw Material & Workpiece Generation

Process Step	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
Casting	2,6	2,3	1,7	2,0	2,0
Heat Treatment 1	2,7	2,0	1,0	2,0	3,0
Forging	2,6	2,3	1,7	2,0	2,0
Heat treatment 2	2,7	2,0	1,0	2,0	3,0
Peeling	2,8	2,0	1,0	2,0	1,0
Pre-Turning	2,1	2,3	1,8	2,0	1,0
Inspection	2,7	2,0	1,0	2,0	2,0



Source: Figure courtesy of Hermle AG 2018 and authors

2.2.3 Surface treatments

Surface treatments include processes like coating, shot peening and vibratory grinding. Industry partners provided the data, primarily through direct measurements or calculations. The data quality is generally good, but it is worth noting that the data was obtained from test samples rather than full-size Blisks, affecting reliability and technical correlation scores. In addition, incomplete descriptions of grinding powder and compounds impacted completeness scores (see Figure 6).

2.2.4 Quality assurance

Quality assurance is the final stage in the Blisk process chain, which includes various inspections and measurements. While most processes were conducted at Fraunhofer IPT and involved direct electrical data measurements, the quality assurance process called fluorescent penetrant inspection (FPI) received lower scores because of limited information on dye composition and the absence of fully comparable processes. Data for FPI was primarily based on literature and estimates (see Figure 7).

3. Results and analysis – life cycle impact assessment results and interpretation

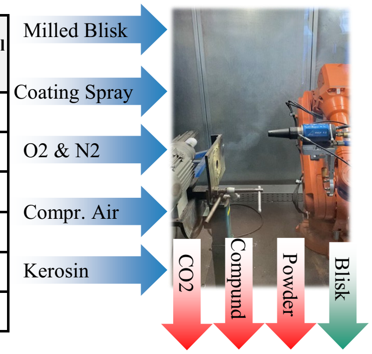
Based on the quantified LCI data, various indicators are calculated to compare the environmental impact of Blisk

Aircraft Engineering and Aerospace Technology
Volume 96 · Number 1 · 2024 · 2–13

Figure 6 Relevant processes regarding surface treatments, the average pedigree matrix scoring and relevant input and output flows (right)

Surface Treatments

Process Step	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
Coating	1,5	1,5	1	1	2
Vibr. Grinding	2,1	2,1	1,2	1,0	1,8
Manual Polishing	2,7	1,9	1,4	1,0	1,7
Peening	2,1	2,7	1,1	1,0	1,9
Balancing	3,0	1,3	1,5	1,0	2,0
Cleaning	2,3	2,1	1,0	1,0	2,6



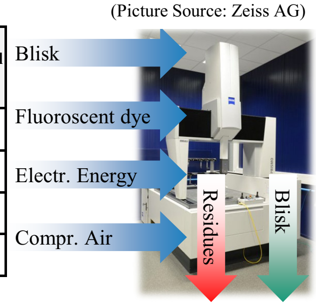
Source: Figure courtesy of authors and IOT – Surface Engineering Institute 2020

Figure 7 Relevant processes regarding surface treatments, the average pedigree matrix scoring and most important input and output flows (right)

Quality Assurance

(Picture Source: Zeiss AG)

Process Step	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
FPI	1,8	1,5	1,0	1,0	2,3
Visual Inspection	1,5	1,0	1,0	1,0	2,0
3D Inspection	1,6	1,0	1,0	1,0	2,0
CMM	1,7	1,0	1,0	1,0	2,0



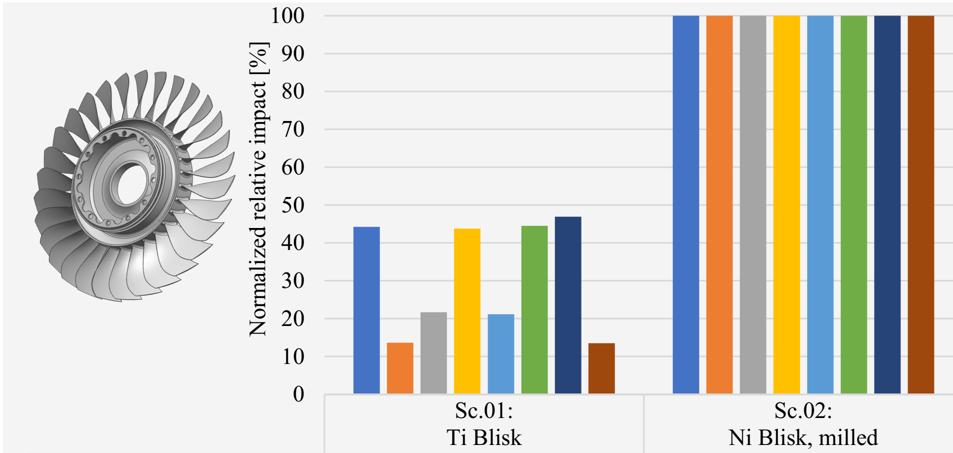
Source: Figure courtesy of Zeiss AG and Fraunhofer IPT 2017

manufacturing Scenarios #1 and #2. These indicators are taken from the EF3.0 impact category group. A representative set of these indicators – with significant results – is presented in this paper. In the following, the LCIA results are presented as depicted in Figure 8. While comparing both scenarios, the result is normalized to the higher value; therefore, the value of 100% means that the corresponding scenario has the higher value of the two in the respective indicator. It is noticed that Scenario #1 (titanium Blisk, milling) has lower values in all indicators than Scenario #2 (nickel Blisk, milling) to a considerable extent, because in almost all indicators the value of Scenario #1 is even less than half of Scenario #2. Firstly, this can be explained by the more complex and resource-consuming raw material generation process for Inconel 718, which contains more elements (around 15 individual metals, including chromium and molybdenum) compared with Ti6Al4V (three individual metals). Furthermore, the machining processes (turning and milling) of Inconel 718 are also more complex and resource-consuming than those of Ti6Al4V, as indicated by the LCI data (Figure 5), which ultimately leads to the higher CO2 footprint of nickel Blisk manufacturing compared to the titanium Blisk.

As a deep dive, the specific individual flows and their impact on GWP are analysed regarding Scenario #1 (the titanium Blisk) and Scenario #2 (the nickel Blisk), respectively. In Figures 9 and 10, the absolute (left) and relative (right) shares of elementary flows in the indicator GWP of both Scenarios #1 and #2 are presented. The results show that both scenarios have similar relative contributions in the impact category GWP, with raw material production being the highest contributors in the CO_2 footprint, constituting almost half (45%–49%) of the total calculated value. However, this analysis did not take recycling into consideration and depending on the alloy composition, the data situation is relatively untransparent and often heavily dependent on literature data. Electricity consumption is the second highest influence, comprising up to 40% of the total GWP. For the CO_2 footprint, the influence of tungsten carbide and cobalt through the tool usage is the third highest, which is up to 10%. Other minor influences are contributed through lubricants (around 2%).

Besides the "basic material and energy flows", the results according to process level are also investigated. Figure 11 shows the relative shares of main process flow in GWP of Scenario #1 (left) and Scenario #2 (right). Corresponding to the result of the basic material flows, the raw material generation has the highest influence on the CO_2 footprint. A higher recycling rate as well as the application of additive manufacturing processes for the raw part can also possibly address the significant impact of material generation on the ecological footprint. Furthermore, it is revealed that the central machining processes (milling and turning) also have a high impact on the ecological footprints in both scenarios, which form around 30%–36% of the total GWP. This significant influence of milling and turning processes can be addressed, for

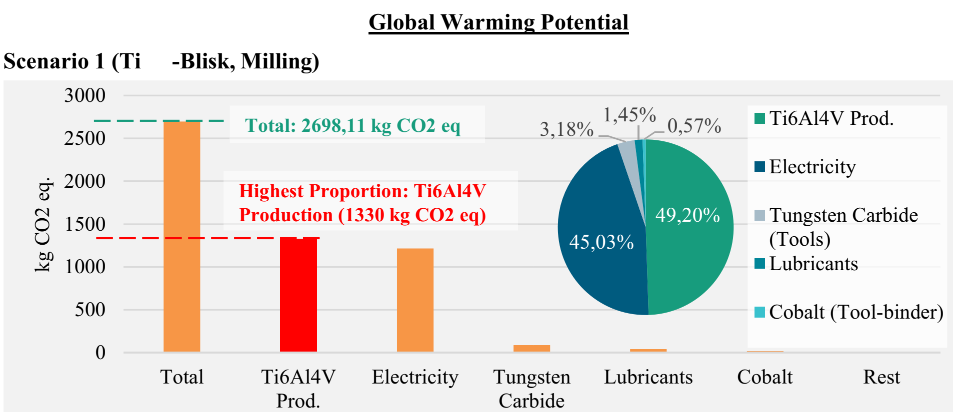
Figure 8 LCIA results for both Blisk scenarios



	Sc.01: Ti Blisk	Sc.02: Ni Blisk, milled
Climate Change	44	100
Ozone depletion	14	100
Human toxicity, cancer	22	100
Human toxicity, non-cancer	44	100
Particulate matter	21	100
Ionising radiation	45	100
Photoch. ozone formation	47	100
Acidification	14	100

Source: Figure by authors

Figure 9 Absolute and relative shares of elementary flows in the indicator global warming potential of Scenario #1 (titanium Blisk, milling)



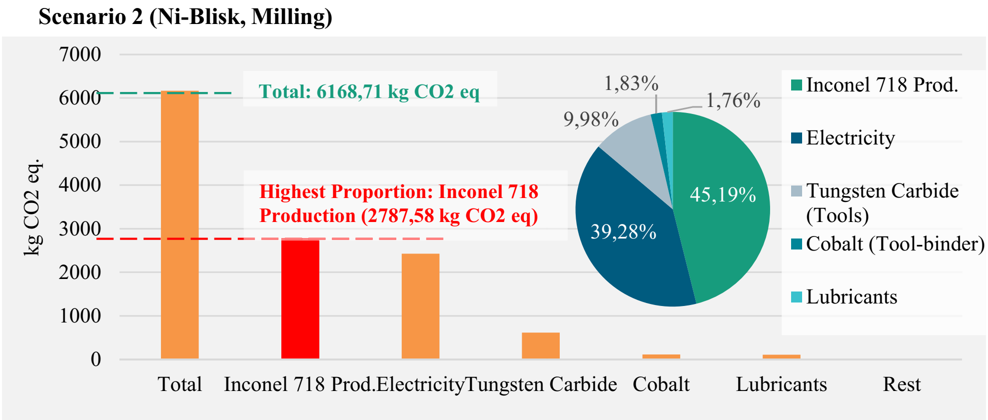
Source: Figure by authors

instance, by developing more efficient processes (improved machining strategies, e.g. tool selection) and adaptation of the process chain (substitution of processes, e.g. milling replaced with ECM), which will be addressed in future studies.

It is worth noting that while raw material generation has the highest influence in terms of GWP, this is not always the case in the other impact indicators. An example of this is presented in Figure 12, which shows the absolute and relative shares of basic flows for the indicator Freshwater Aquatic Ecotoxicity, respectively. Here, cobalt has the highest impact, at around 50% of the total value. Cobalt is solely used in the milling tools of the machine process. A substitution of the tools or the process in general could potentially improve the overall eco-footprint in these categories. The same reasoning is true for tungsten carbide (ca. 10%), which makes up 90% of the milling tool's weight composition.

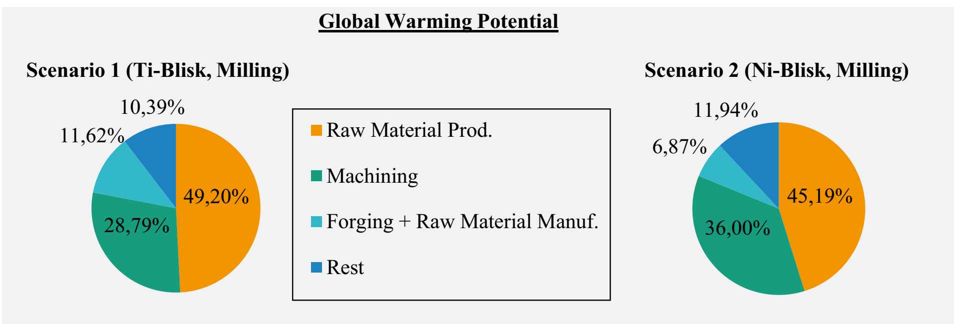
As an interim conclusion, it can be stated that a major contributor regarding the ecological footprint – specifically the CO2 footprint – during Blisk manufacturing can be associated with the raw material generation. A reduction of this impact can be addressed by introducing alternative raw material generation processes such as additive manufacturing and increasing

Figure 10 Absolute and relative shares of elementary flows in the indicator global warming potential of Scenario #2 (nickel Blisk, milling)



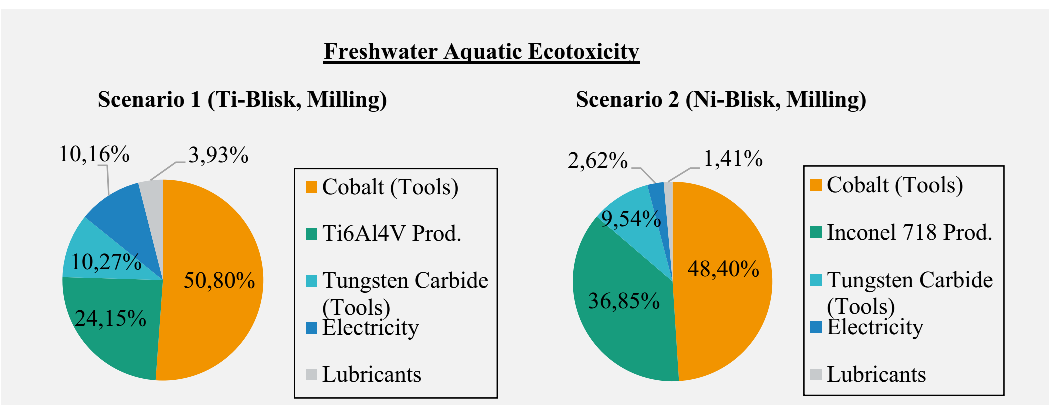
Source: Figure by authors

Figure 11 Relative shares of main process flow in the EF3.0 indicator global warming potential of Scenario #1 (titanium Blisk, milling) and Scenario #2 (nickel Blisk, milling)



Source: Figure by authors

Figure 12 Relative shares of basic flows for EF3.0-indicator "freshwater aquatic ecotoxicity"



Source: Figure by authors

recycling and repair rates. On the contrary, the ecological impact generated through the machining processes cannot be neglected. An optimization of machining strategies based on alternative tool and technology selections has the potential to reduce the overall environmental footprint.

3.1 Life cycle costing

The life cycle costing (LCC) evaluation of both Blisk scenarios is done based on the manufacturing costs of one complete Blisk component with a total number of 30 blades. The manufacturing costs of both process sequences were calculated based on the approach of Klocke (2011), following the standard VDI 3321 (VDI, 1994). Therefore, the overall manufacturing costs KF were calculated based on the machine hour rate KMH, labour costs KLH and the tool costs KW; see following equations:

$$K_F = K_{MH} \cdot t_g + K_{LH} \cdot t_g + K_W \qquad (1)$$

Thereby, only the productive time in the process was considered the basic time t_g because all non-productive activities, such as workpiece changing time, idle time or setup time, apply for both manufacturing routes in the same way. For the same reason, costs for work-holding equipment, presenting costs and process development are neglected in the calculation, as are overhead costs.

The labour costs KLH are considered at €60/h including ancillary wage costs while one operator can manage two machines at a time.

For the calculation of the machine hour rate the imputed depreciation (KA = €80,000/a) and imputed interest per year (KZ = €20,000/a) as well as maintenance costs (KI = €20,000a), annual room costs (KR = €600/a; 20 m^2 for €30/m^2) and energy costs (KE = €3.75/h; 15 kW for €0.25/kWh) were considered. The machine in the underlying example is operated in a single shift (TN = 1,600 h/a). Under all mentioned assumptions and approximations, the costs of one machine hour sums up to

KMH = €79.13/h:

$$K_{MH} = \frac{K_A + K_Z + K_I + K_R + K_E}{T_N} \qquad (2)$$

This value, however, represents the actual costs of operating a machine tool and does not contain any margins. In addition, it must be considered that a number of underlying neglections (e.g. overhead costs and no setup time) and assumptions made may influence this number. The tool costs were evaluated based on average commercial list prices from different tool suppliers. The machining time of the titanium Blisk was measured to be approximately 70 h, whereas the machining time for the nickel Blisk 'was measured to be approximately 200 h.

Table 1 illustrates the Blisk scenario-specific costs regarding machine costs, labour costs and tool and raw material costs. It is visible that the manufacturing of the nickel Blisk is up to three times more expensive on an economic level compared to a titanium Blisk.

Figure 13 illustrates the distribution of costs regarding tools and materials. While the main driver is the raw material in both scenarios, the Inconel raw material is much more expensive than the titanium alloy. As overall more tools and electricity are used for the nickel process, the prizes in these categories are also higher. Regarding overall LCC, the impact category known as environmental costs is also depicted in Figure 14. In the case of the nickel Blisk, the internal raw material causes the highest environmental cost (50%), followed by electricity (30%). Regarding the titanium Blisk, the environmental costs caused by the titanium alloy and electricity are identical (47%).

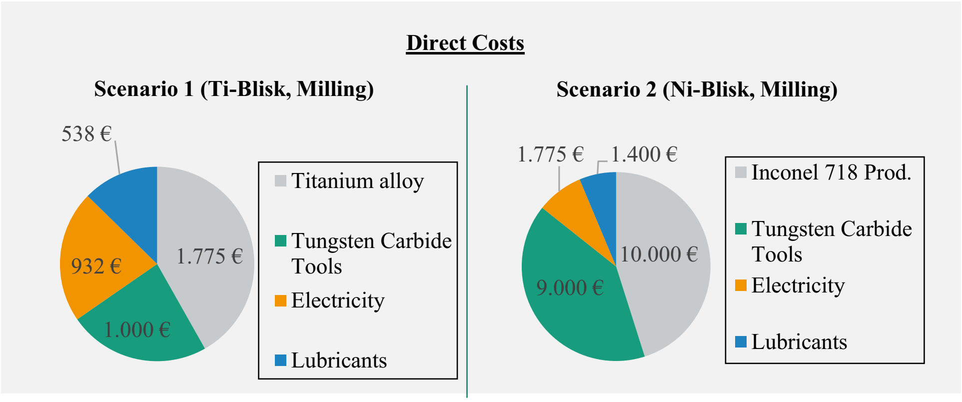
As an interim conclusion it can be summarized, that – because of the longer machining time and higher material and tool costs – a production of a nickel Blisk is three times more expensive than titanium Blisk. Because of lower tool wear during titanium Blisk manufacturing, the main economic impact originates in labour and machining costs. In the latter case, especially electricity costs and raw material costs are the main drivers. In the case of the nickel Blisk machining, the economic impact of tools is higher because of higher overall

Table 1 Overview of specific cost categories for Blisk machining

Blisk scenario	Machine costs K_M	Labour costs K_L	Tool and raw material costs K_W	Total manufacturing costs K_F
Titanium	€5,539.1	€4,200	€2,775	€12,514
Nickel	€15,826	€12,000	€19,000	€46,826

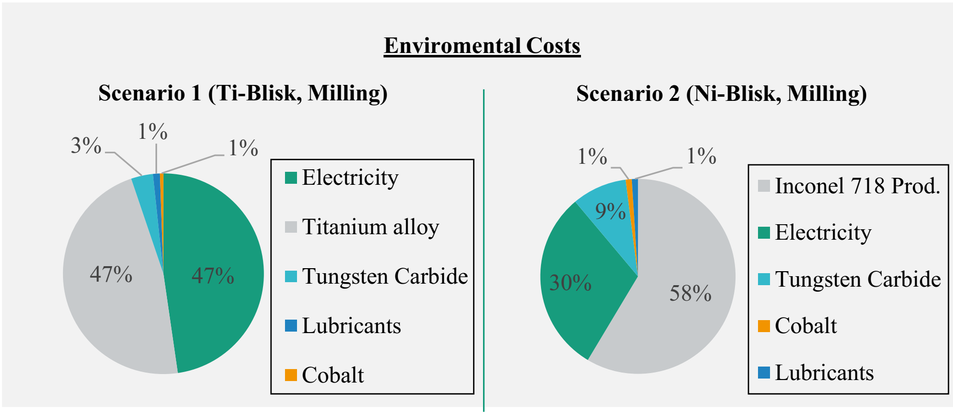
Source: Table by authors

Figure 13 Distribution of material and tool costs for both Blisk scenarios



Source: Figure by authors

Figure 14 Environmental costs caused by the manufacturing of both Blisk scenarios



Source: Figure by authors

tool wear. Nonetheless, the largest influences arise from electricity consumption and raw material costs.

4. Discussion & summary

In this paper, the results of LCIA for two Blisk manufacturing scenarios (milled titanium Blisk and milled nickel Blisk) are presented and discussed. Based on the standardised approach of ISO 14040/44, the first two steps of goal and scope definition and LCI data acquisition were presented based on the detailed description of previous papers (Fricke *et al.*, 2021b; Fricke *et al.*, 2022).

Based on these findings An LCIA was conducted and various EF3.0 impact indicators were calculated using the software GaBi, with primary focus in this investigation on the impact indicator GWP. The results show, that the titanium Blisk generates an overall lower ecological impact compared with the nickel Blisk in all EF3.0 impact categories. This is due to the fact that the raw material impact, machining time and tool wear are higher during the nickel Blisk manufacturing. An in-depth assessment of the particular impact of specific material and energy flows reveals that a main driver of specifically the CF of both components comes from the raw material (if recycling is not included).

The large Impact on the ecological footprint during material generation can be reduced by higher recycling rates of metal chips and other wastes, as well as alternative raw material generations such as additive manufacturing. On the main process level, the central machining processes (milling and turning) also have significant influences on the ecological footprints. This can be addressed by developing more efficient processes (improved machining strategies, e.g. tool selection), the use of "greener materials" (e.g. less cobalt and tungsten in milling tools) and adaptation of the process chain (substitution of processes, e.g. milling replaced with ECM). The LCC assessment comes to similar conclusions. The manufacturing of the nickel Blisk results in higher costs, which are mainly driven by raw material and milling tool purchases, as well as longer machining times that result in higher costs of electricity and labour. Future investigations will focus on the third manufacturing scenario (nickel Blisk with ECM) as well as variations of the milling processes to minimise the negative impacts during the machining processes.

References

Atılgan, R., Turan, Ö., Altuntaş, Ö., Aydın, H. and Synylo, K. (2013), "Environmental impact assessment of a turboprop engine with the aid of exergy", *Energy*, Vol. 58, p. 664.

Bergs, T., Grünebaum, T., Fricke, K., Barth, S. and Ganser, P. (2021), "Life cycle assessment for milling of Ti- and Ni-based alloy aero engine components", *Procedia CIRP*, Vol. 98, p. 625.

Bräunling, W.J.G. (2015), *Flugzeugtriebwerke: Grundlagen, Aero-Thermodynamik, Ideale Und Reale Kreisprozesse, Thermische Turbomaschinen, Komponenten, Emissionen Und Systeme*, 4th ed Springer Vieweg, Berlin.

Breuer, R. (2018), "NACHHALTIGKEITSBERICHT OTTO FUCHS 2016 | 2017".

Clean Sky 2 Joint Undertaking (2017), Development Plan.

Clean Sky 2 JU (2015), "CleanSky2–- Joint technical programme: the European aeronautical industry's proposal for the continuation and extension of the clean sky joint technology initiative with a new clean sky 2 programme under the european union's horizon 2020 framework programme for research and innovation. Brussels, 23", Brussels.

Ecoinvent (2023), "Ecoinvent database: the ecoinvent database is a life cycle inventory (LCI) database that supports various types of sustainability assessments", available at: https://ecoinvent.org/wp-content/uploads/2022/10/ecoinvent-sectorial-Brochure-2022_online_F.pdf

Fricke, K., Bergs, T., Ganser, P., Gierlings, S. and Albano, J. (2022), "Life cycle inventories for engine blisk LCA", *IOP Conference Series: Materials Science and Engineering*, Vol. 1226, p. 12103.

Fricke, K., Gierlings, S., Ganser, P., Seimann, M. and Bergs, T. (2021a), "A cradle to gate approach for life-cycle-assessment of blisk manufacturing", *Turbo Expo: Power for Land, Sea, and Air*.

Fricke, K., Gierlings, S., Ganser, P., Venek, T. and Bergs, T. (2021b), "Geometry model and approach for future blisk LCA", *IOP Conference Series: Materials Science and Engineering*, Vol. 1024, p. 12067.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds), (2018), *Life Cycle Assessment: Theory and Practice*, Springer International Publishing.

Hernández, A.B., Beno, T. and Fredriksson, C. (2017), "Energy and cost estimation of a feature-based machining operation on HRSA", *Procedia CIRP*, Vol. 61, p. 511.

Hubig, C. (2012), *Fertigungsgerechtes Konstruieren Von Hochdruckverdichterschaufeln in Blisk-Bauweise*, Shaker, Aachen.

International Organization for Standardization (ISO) (2020), "ISO 14040:2006/amd 1:2020(en) environmental management – Life cycle assessment – Principles and framework – AMENDMENT 1: ISO 14040:2006".

Karpuschewski, B. and Kalhöfer, E. (2011), "Energiebedarf für die hartmetallherstellung".

Klocke, F. (2011), *Manufacturing Processes 1 – Cutting*, Springer, Berlin.

Li, L., Cao, S., Li, J., Nie, R. and Hou, L. (2021), "Review of rotor balancing methods", *Machines*, Vol. 9 No. 5, p. 89.

Lüdemann, L. (2014), *Vergleich Von Softwarelösungen Für Die Ökobilanzierung – Eine Softwareergonomische Analyse*, Wissenschaftliche Gesellschaft für Technische Logistik.

Musacchio, A., Corona, A., Cencioni, L., Serra, A., Bartocci, P. and Fantozzi, F. (2020), "Defining key environmental performance factors (KEPF) for gas turbines eco-design and production through life cycle assessment", in *Proceedings of the ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition – 2020: Presented at ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition, September 21-25, 2020, online, the American Society of Mechanical Engineers; Curran Associates, Inc, New York, NY, Red Hook, New York, NY*.

Musacchio, A., Serra, A., Cencioni, L., Colantoni, S., Bartocci, P. and Fantozzi, F. (2021), "Decarbonizing materials and machining for the gas turbines sector through life cycle assessment", in *Volume 6: Ceramics and Ceramic Composites; Coal, Biomass, Hydrogen, and Alternative Fuels; Microturbines, Turbochargers, and Small Turbomachines*, *American Society of Mechanical Engineers*.

Park, N.K., Kim, I.S., Na, Y.S. and Yeom, J.T. (2001), "Hot forging of a nickel-base superalloy", *Journal of Materials Processing Technology*, Vol. 111 Nos 1/3, p. 98.

Pearce, B. (2020), "2020 COVID-19: Outlook for air travel in the next 5 years".

Priarone, P.C. and Ingarao, G. (2017), "Towards criteria for sustainable process selection: on the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches", *Journal of Cleaner Production*, Vol. 144, p. 57.

Qi, H., Azer, M. and Ritter, A. (2009), "Studies of standard heat treatment effects on microstructure and mechanical properties of laser net shape manufactured INCONEL 718", *Metallurgical and Materials Transactions A*, Vol. 40 No. 10, p. 2410.

Rupcic, L., Pierrat, E., Fricke, K., Moll, T., Hauschild, M.Z. and Laurent, A. (2022), "Improving environmental performances of integrated bladed rotors for aircraft", *CIRP Annals*, Vol. 71 No. 1, p. 13.

Shipway, N.J., Barden, T.J., Huthwaite, P. and Lowe, M. (2019), "Automated defect detection for fluorescent penetrant inspection using random forest", *NDT & E International*, Vol. 101, p. 113.

Sphera Solutions, Inc (2023), "Managed LCA content (GaBi databases)", available at: https://sphera.com/life-cycle-assessment-lca-database/

VDI (1994), *Schnittwertoptimierung: Grundlagen Und Anwendung*, Düsseldorf.

Vinodh, S., Sivaraj, G., Nithish, S. and Veeramanikandan, R. (2017), "Life cycle assessment of an aircraft component: a case study", *International Journal of Industrial and Systems Engineering*, Vol. 27 No. 4, p. 485.

Weidema, B., Bauer, C. and Hischier, R. (2013), "Data quality guideline for the ecoinvent database version 3: Overview and Methodology Ecoinvent. Report 1", St. Gallen.

Appendix

Table A1 Concept of pedigree matrix based on different indicator scores

Indicator	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partially based on assumptions	Non-verified data partly based on qualified estimates	Qualified estimates	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out fluctuations	Representative data from only some sites relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
Temporal correlation	Less than three years of difference to our reference year	Less than six years of difference to our reference year	Less than 10 years of difference to our reference year	Less than 15 years of difference to our reference year	Age of data unknown or more than 15 years
Geographical correlation	Data from area under study	Average data from larger area (area under study is included)	Data from smaller area than area under study, or from similar area	Data from slightly similar production conditions	Data from unknown or distinctly different area
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Related processes or materials but same technology or data from processes under study but from different technology	Related processes or materials but different technology, or data on laboratory scale processes and same technology	Related processes or materials but on laboratory scale of different technology

Source: Table by Weidema *et al.* (2013)

Corresponding author

Kilian Fricke can be contacted at: kilian.fricke@ipt.fraunhofer.de