Life Cycle Inventories for Engine Blisk LCA

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Abstract. The aviation industry has been growing continuously over the past decades. To ensure
sustainability and competitiveness for the aviation industry sector, a full understanding of the
environmental impacts is required, not only during use phase but along the entire life cycle,
including “Materials”, “Processes and Resources”, “Manufacturing and Production”, “Lifetime
Services” as well as “Reuse, End-of-Life and Recycling”. Core engine components, such as in-
tegral rotors (Blisks), are comprised of high value metallic alloys that require complex and re-
source consuming manufacturing processes. This paper will introduce an approach for Life-Cy-
cle-Inventory data acquisition during Blisk manufacturing as basis for a Life-Cycle-Assessment
(LCA) according to ISO 14040. A particular focus will be set on the data quality and confidence
level regarding measuring, acquisition, and analysis of in- and output flows within the Blisk
manufacturing process chain in scope. This includes the stages of material generation, forming
processes, heat treatments, machining, surface treatments and quality assurance. A greater em-
phasis is drawn to selected variations on mechanical machining processes. On this basis, first
results of an LCA for Blisk-manufacturing will be presented.

NOMENCLATURE

COM  Completeness
CMM  Coordinate Measuring Machine
EBC  Environmental Barrier Coatings
ECM  Electro-Chemical Machining
FPI  Fluorescent Penetrant Inspection
GEO  Geographical Correlation
LCA  Life-Cycle-Assessment
LCI  Life-Cycle-Inventory
LCIA Life-Cycle-Impact Assessment
Ni   Nickel
REL  Reliability
TEM  Temporal Correlation
TEC  Technological correlation
Ti   Titanium

1. Introduction
Global air traffic has roughly doubled every fifteen to twenty years and it is estimated that this trend
will continue in the near future, albeit with some limitations due to the Covid-19 impact [1]. The EU
roadmap Flightpath 2050 and the Clean Sky program [2] are currently the central drivers of the technol-
ygy development in the aviation sector. Besides the operation phase, resource efficient manufacturing
is relevant for the overall ecological assessment and the construction of aero engine components is of
great interest as the engine design has a large influence along the entire lifecycle. Integrally manufac-
tured compressor rotors known as Blisks (blade integrated disks) represent one of the most challenging
components within aero engines from a manufacturing point of view. Complex geometries, small toler-
ances, and highly resistant materials such as Titanium- and Nickel-based alloys require complex manu-
facturing process chains. The environmental impact of such process chains can be analyzed through the
Life Cycle Assessment (LCA), defined by ISO 14040/14044 as the scientific standard for assessing the
environmental impact of product systems. It describes a procedure for “compiling and assessing the
input and output flows and the potential environmental impacts of a product system during its life cycle" [3]. The procedure comprises the phases (Figure 1):

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.

2. **Life-Cycle-Inventory:** (focus of this paper)
   The second step includes the acquisition of life-cycle-inventory data. These resemble the in- and output flows of each individual process step including mass and energy flows (electrical energy, tools used etc.).

3. **Life-Cycle-Impact-Assessment:**
   In the third step the actual environmental impact of each process is calculated based on specific indicators, such as Global-Warming-Potential, water pollution etc. This step is conducted within software environments such as OpenLCA or GaBi (Ganzheitliche Bilanzierung, engl.: holistic balancing). [4]

4. **Interpretation:**
   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.

![Figure 1. The 4 stages of an LCA study: Goal & Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. [5]](source: Hermle AG)

An investigation framework and a concrete target must be defined in a first step regarding the product to be investigated as a functional unit or the processes to be analyzed. The Goal & Scope have been defined in the previous paper titled “Geometry Model for Future Blisk LCA” [6]. In this example, the functional unit is a Titanium blisk with a diameter of 440 mm and a total number of 30 compressor blades. Blisk manufacturing is characterized by a complex process chain, which is generically divided into four steps: raw material and workpiece generation, machining, surface treatment and quality assurance [7]. The present case study focuses specifically on 5-axis milling of the blisk as the primary step of shaping the compressor blading within the manufacturing chain. However, reference is also made to the other process steps as part of the life cycle stage "production" to explain the principal methodology for data acquisition for the entire process chain and the corresponding quality of the data base. This paper describes on the Life-Cycle-Inventory data collection, as well as first results from the Life-Cycle-Impact-Assessment.

2. **LCI data collection and quality**
   LCI data (life cycle inventory) forms the second pillar of a Life-Cycle-Assessment. Life-Cycle-Inventory-Data includes the input and output flows along the life-cycle phases. To achieve best possible
results, it is essential to have verified and validated Life-Cycle-Inventory-Data along the process chain. A large amount of general data is available in the form of databases such as Ecoinvent or GaBi [4]. However, for several high-end processes as employed in aviation verified and validated data does not yet exist on an acceptable quality level and thus must be acquired on the base of technical case-studies. An overview on the LCI-quality level for the process chain of Blisk-manufacturing, which has been subject of this work, is presented in Table 1.

In order to characterize different data quality levels the definition through a “pedigree matrix” [8] by WEIDEMA was chosen for this investigation. This also takes into account uncertainties, e.g. through measurements, calculations, estimations, or literature.

Depending on the data quality, WEIDEMA et al distinguish between five quality categories:

- **Reliability (REL):**
  Defines the data in terms of the approach for data acquisition (estimation vs. measurement)

- **Completeness (COM):**
  Characterizes the completeness of the data set in terms of flow in- and output coverage

- **Temporal Correlation (TEM):**
  Provides information about the comparability of the data over time

- **Geographical Correlation (GEO):**
  Qualitative statement about the geographical characterization of the data

- **Technological Correlation (TEC):**
  States the technological validity of the data

These five different indicators characterize the data quality in a score from 1 to 5, with 1 being the highest and 5 being the lowest score respectively (see appendix). Underlying algorithms allow the LCA-analyst to calculate a resulting standard deviation which sets the basis for a Monte Carlo simulation.

**Table 1:** overview on the average data quality characterization achieved for the LCI-data along the Blisk-manufacturing process chain [7] according to the Pedigree-Matrix.

| Cluster                                  | Process Step               | Reliability | Completeness | Temporal Correlation | Geographical Correlation | Technological Correlation |
|------------------------------------------|----------------------------|-------------|--------------|-----------------------|--------------------------|--------------------------|
| Raw Material & Workpiece Generation 2.2  | Casting                    | 2.6         | 2.3          | 1.7                   | 2.0                      | 3.0                      |
|                                          | Heat Treatment 1           | 2.5         | 2.0          | 1.0                   | 2.0                      | 3.0                      |
|                                          | Forging                    | 2.6         | 2.3          | 1.7                   | 2.0                      | 3.0                      |
|                                          | Heat treatment 2           | 2.7         | 2.0          | 1.0                   | 2.0                      | 3.0                      |
|                                          | Peeling                    | 2.8         | 2.0          | 1.0                   | 2.0                      | 3.0                      |
|                                          | Pre-Turning                | 2.1         | 2.3          | 1.8                   | 2.0                      | 3.0                      |
|                                          | Ultrasonic-Testing         | 2.7         | 2.0          | 1.0                   | 2.0                      | 3.0                      |
| Machining 2.1                           | Turning Roughing           | 1.6         | 1.1          | 1.1                   | 1.0                      | 1.4                      |
|                                          | Turning Finishing          | 1.6         | 1.1          | 1.1                   | 1.0                      | 1.4                      |
|                                          | Blue Etch                  | 2.1         | 1.9          | 1.1                   | 1.0                      | 2.8                      |
|                                          | Milling (Roughing)         | 1.6         | 1.1          | 1.1                   | 1.0                      | 1.4                      |
|                                          | Milling (Finish)           | 1.6         | 1.1          | 1.1                   | 1.0                      | 1.4                      |
|                                          | Milling/Drilling           | 1.7         | 1.1          | 1.3                   | 1.0                      | 1.1                      |
| Surface Treatment 2.3                    | 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                      |
| Quality Assurance 2.4                    | Cleaning                   | 2.3         | 2.1          | 1.0                   | 1.0                      | 2.6                      |
|                                          | 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                      |
In the following section 2.1, an in-depth example of LCI-data and its acquisition is given on the Machining processes (turning, milling). This is followed by individual sections for the processes of Raw Material Generation (2.2), Surface Treatment (2.3) and Quality Assurance (2.4).

2.1. Machining

The main elements of the Blisk-machining are the contour turning process and the blade shaping processes. The contour production is realized using turning processes and blade production using 5-axis milling processes. In blade production, milling is used to rough, semi-finish and finally finish the compressor blades. The primary energy and material flows in milling operations include electric power consumption, cooling fluid consumption, pressurized air consumption and tools used.

Depending on the rotor design, disk elements such as the so-called "scallop" or bores are subsequently manufactured for machining the compressor blades. The resource consumption is qualitatively comparable with that of the milling process for blade production. In quantitative terms, however, this machining step is less prominent in a direct comparison as the machining time is significantly shorter. Figure 2 illustrates the specific in- and output flows for the machining processes including turning, milling and helical milling. As the data for the machining processes was mostly directly measured during the process, the overall quality of the data is considerably high (Figure 2, right). The raw material has lower level of reliability due to the uncertainty of upstream processes and possible deviations of alloy concentration depending on the material batch. The compressed air consumption was calculated based on generic data sheet information and therefore receives lower scores in terms of reliability and technical correlation. To improve the quality of the compressed air demand in the future an external sensor will be applied.

Figure 2. In- and Output flows of the Ti-Blisk machining process

| Flows                  | Value | Unit | Rel. | Com. | Tem. | Geo. | Tec. |
|------------------------|-------|------|------|------|------|------|------|
| Electricity            | 1400  | kWh  | 1    | 1    | 1    | 1    | 1    |
| Compressed Air         | 2000  | m³   | 2    | 2    | 1    | 1    | 1    |
| Raw Material           | 70    | kg   | 3    | 1    | 2    | 1    | 1    |
| Cutting Tools          | 16    | /    | 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    |

The LCI data for the turning and milling process is acquired both internally via the NC kernel of the milling machine and using external sensor technology. For the acquisition and processing of the LCI data a digital infrastructure is employed. This is organized according to a big data framework [9, 10]. The raw data is recorded at different frequencies via interfaces in the "data collection layer" and the processed to "user domain". Figure 3 shows an example of the LCI data chains for cooling lubricant consumption and power consumption within the introduced digital infrastructure. The water and coolant consumption is derived form the concentration of additives is measured over time by an automated Brix-sensor device. The data is transferred via OPC-UA communication to NI LabVIEW software. The coolant consumption has slightly lower scores as well, due to the low frequency of data acquisition. Electrical energy consumption (kWh) is also measured and transferred to LabVIEW acquisition by DeltaLogic AGLink interface. Compressed air consumption was calculated as well as chips values. Tools (mostly made of tungsten carbide) weight was measured.
2.2. Raw material and workpiece generation
The raw material generation data includes the processes involved in ore mining, transport, and preparation of the pure alloying elements. This data is derived from databases such as Ecoinvent. Workpiece production comprises sub-processes such as casting, heat treatment processes and forging of the raw part. The data on the resource consumption of these processes are mainly taken from the relevant literature or are based on expert knowledge. [11–14] (Figure 4a) The results show a considerably mixed level of data quality especially in the categories of reliability, completeness and technical correlation. This is due to the fact, that most data was collected based on the aforementioned literature which provided insight to comparable but not identical processes. The energy consumed is very generically described and not distinguished between electricity and gas. The temporal and geographical correlation however is considerably high due to the source of the data being from Europe and were published in the past few years.

2.3. Surface Treatments
After the “Machining” processes specific processes including coating, shot peening and vibratory grinding were performed and applied as part of the process chain. The data for these processes was collected and provided by industry partners and either directly measured or calculated. Based on the pedigree-matrix logic this results in considerably good data quality. However, the data was acquired from test samples rather than directly from the full size Blisk. This results in lower scores in terms of reliability and especially technical correlation. The composition of the grinding powder and compounds were not fully described resulting in lower scores in terms of completeness. Figure 4b illustrates the specific in- and output flows for the surface treatment processes. [15]
2.4. Quality Assurance
The final step within the Blisk process chain deals with the quality assurance. This includes Fluorescent Penetrant Inspection (FPI), visual inspection, 3D optical measurement and CMM-measurement. Apart from the FPI process the other processes were performed at Fraunhofer IPT and electrical data was directly measured. Therefore, the geographical and temporal correlation received highest scores. The "Reliability" and "Technical Representativeness" were slightly lower due to a not fully industrialized process. FPI received lowest scores, as neither the full composition of the dye, nor a fully comparable process could be performed and the data is based on literature and estimates. (Figure 4c)

3. LCA-modelling & LCIA results
The life cycle inventory (LCI) is followed by the impact assessment and interpretation of the LCA. The data on energy and material flows are converted into impact factors either manually or using appropriate software. At the current state of the work, two indicators are presented as an example. One well known and common category in this context is the Global-Warming-Potential (GWP). This factor here was modeled and calculated in the present case study using the CML method in the OpenLCA software environment [16]. In addition to the GWP, the "Aquatic Ecotoxicity" is presented here as a second exemplary factor. A full set of results according to the ecoDESIGN Transversal-Activity will be presented in the future.

The data quality as described in previous Chapter 2 is also included in the first analysis through a Monte Carlo simulation. Based on the results of each flow within the individual pedigree-matrix (Figures 2,4) specific standard deviations were calculated for each material and energy flow. This calculation of standard deviation was performed within the OpenLCA software which based its algorithms on aforementioned approach by WEIDEMA et al. for Ecoinvent LCA-flows. [8] The Monte Carlo Simulation was conducted based on these individually determined standard deviations and 100 replications to create a first basic overview of the result’s distribution. This results in a normalized distribution as seen in Figure 5, left. The distribution shows a significant distribution from the mean values of both the GWP as well as the Aquatic Ecotoxicity Level due to high uncertainty factors in the raw material production. The results show that GWP and Aquatic Ecotoxicity have different relative contributions which indicates a differentiated distribution of influence factors depending on the ecological impact category that is being analyzed. Further results show that the energy requirements to produce the raw material and the resulting CO2-footprint tend to be high compared to other contributors (Figure 5, right).

Figure 5. Relative shares of primary energy consumption of the individual manufacturing processes (left); CO2 footprint of relevant alloying elements (right).

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 recycling rates, which play
a decisive role in the overall Life-Cycle-Assessment. Besides the raw material the second highest influence can be traced to electricity, for which the CO2 footprint is dependent on the region in which the process was performed. In this case the EU energy grid mix was considered. A more detailed definition of upstream flow influences like tools, raw material production and recycling will be the focus in future investigations. The influence of tool usage could not be fully modelled due to limitations within the accessible data bases. The influence of Tungsten and Cobalt could however be significant.

In order to investigate the influence of tool selection and milling strategy several process variations are proposed to gain an even more in-depth assessment of technical alternatives. Table 2 illustrates planned variations for the milling process of the Titanium and Nickel Blisk. The roughing and finishing processes will be alternated based on tool and strategy selection.

| Process   | Titanium-Blisk | Nickel-Blisk |
|-----------|----------------|--------------|
|           | # Tools | Strategy  | Cooling | # Tools | Strategy  | Cooling |
| Rough     | 1       | TC*       | Circumferential | Flood  | 5       | Ceramic  | Circumferential | “Dry” |
|           | 2       | TC        | Plunge Milling* | Flood  | 6       | TC        | Circumferential | Flood |
| Finishing | 3       | TC (Co < 10 %) | Circumferential | Flood  | 7       | PCBN**    | Circumferential | MQL*** |
|           | 4       | TC (Co > 10 %) | Circumferential | Flood  | 8       | TC        | Circumferential | Flood |

* Tungsten-carbide ** Polycrystalline-cubic-boron-nitride *** Minimum-quantity-lubrication

4. Summary & Outlook

When investigating a complex process chain such as Blisk production on the level of an ecological Life-Cycle-Assessment, several factors need to be taken into consideration to assure a high quality and comprehensible analysis. After the definition of the Goal & Scope as presented in a previous work the aim of this publication lay on the quantification of energy and material in- and output flows (LCI) from each individual process step. The investigation reveals that depending on the approach of data collection the quality of the data differs. This discrepancy of quality was defined through a “Pedigree Matrix” [8]. Machining and quality assurance processes had highest quality scores, as these processes were directly performed and measured at Fraunhofer IPT, whereas the raw material production data is mainly based on literature and estimations resulting in lower scores. The first results show that the ecological impacts reveal a significant normal distribution after Monte Carlo simulation because of data uncertainty. A main contributor to GWP arises through the raw material production. However, no recycling scenarios were included in the analysis and the influence of milling tools could not fully be modelled and will be the topic of further investigations. These investigations will focus on an alteration of materials, tools, milling strategy and enable a diverse assessment of overall ecological impact for Blisk manufacturing.

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Appendix

Table 3. Concept of pedigree matrix based on different indicator scores [8]

| 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 normal 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 | Representative-ness unknown or data from a small number of sites AND from shorter periods |
| Temporal correlation | Less than 3 years of difference to our reference year | Less than 6 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 |

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