Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 135 (2025) 837–842

www.elsevier.com/locate/procedia

32th CIRP Life Cycle Engineering Conference

Life Cycle Assessment of Turbofan Engines: A Reverse Engineering Approach

Anne Oestreicher*[a], Nils Kaup[a], Antonia Rahn[a], Joséphine Koffler[a], Gerko Wende[a]

[a] *DLR - German Aerospace Center, Institute of Maintenance, Repair and Overhaul, Hein-Saß-Weg 22, 21129 Hamburg, Germany*

* Corresponding author. *Tel.:* +49 40 2489641-155. *E-mail address:* anne.oestreicher@dlr.de

Abstract

As the environmental impact of the aviation industry becomes increasingly significant, there is a growing demand for detailed Life Cycle Assessments (LCAs) of aircraft components. Despite the evident necessity, comprehensive LCAs for turbofan engines remain relatively scarce. This is primarily due to the technical complexity of such engines and the lack of publicly available information on their detailed composition. The objective of this research paper is to present an LCA of an IAE V2500 engine, addressing its environmental footprint of its production. In order to determine the material composition and weight distribution for the LCA, a reverse engineering approach was employed. The resulting values were then employed in an LCA study. This included the extraction of raw materials and the manufacturing of the engine's components. The findings of this study indicate that the production of a turbofan engine has a considerable environmental impact, emitting over 65,000 kg CO_2 equivalents, with more than 61,000 kg CO_2 equivalents attributed to the materials used. Furthermore, we propose a model-agnostic methodology that can be applied to other engine models, thereby ensuring adaptability and scalability.

Keywords: life cycle assessment; aircraft engines; weight estimation; alloy melting energy

1. Introduction

In the context of the growing relevance of the environmental impact of aviation, it is increasingly important to perform comprehensive Life Cycle Assessments (LCAs) of individual aircraft components [1, 2]. Although such analyses are essential, detailed life cycle assessments of turbofan engines are rarely found in the academic literature [3]. This gap can be attributed to the technical complexity of these engines and the lack of detailed, publicly available information on their design and manufacturing processes [3].

The majority of existing studies concentrate on individual engine components (e.g., [4–6]), such as the High Pressure Turbine (HPT) blisks analyzed by Bergs et al. [5] and Fricke et al. [6], who considered aspects like raw material extraction and machining parameters. The study by Bergs et al. [5] concluded that in addition to the operational phase of an aircraft component, the manufacturing phase also has a significant environmental impact. Other studies offer only general, approximate evaluations of the entire engine as part of an aircraft, which rely on cost estimates [7, 8] or rough mass approximations [9–11], and typically neglecting to consider the specifics of alloy compositions and the energy required for component manufacturing. These studies compared different aircraft or flight scenarios, focusing less on engine details to maintain a broader scope.

The current study builds on previous assessments of the environmental impact of turbofan engines, addressing limitations in areas, such as material usage, alloying and manufacturing energy, and offers a more nuanced approach to these challenges. Therefore, the objective is to provide a more detailed evaluation of the environmental footprint of turbofan engines, contributing to a broader understanding of their true environmental impact and providing a model-independent methodology for future assessments of turbofan engines as for instance needed in the simulation of the environmental impact of aircraft fleets.

The IAE V2500 engine is used as a case study to demonstrate an LCA methodology for aircraft engines. The methodology starts with a comprehensive data collection, including mass estimation for each component of the engine (Chapter 3.1), followed by an analysis of the materials and resources

10.1016/j.procir.2024.12.091

involved (Chapter 3.2). The subsequent phase examines manufacturing processes, whereby the specific production techniques and their associated energy requirements are evaluated (Chapter 3.3). These processes are then correlated with component specification to finally conduct an LCA for quantifying the environmental impact of each component. While the current study specifically evaluates the climate change impact, all other environmental data are provided in the supplementary material. This study follows the established LCA method of DIN EN ISO 14040 [12] and DIN EN ISO 14044 [13], consisting of four steps: goal and scope definition (Chapter 2), data collection (Life Cycle Inventory (LCI), Chapter 3), impact evaluation (Life Cycle Impact Assessment (LCIA), Chapter 4) and result interpretation (Chapter 5).

2. Goal and Scope Definition

The goal of this study is to provide a detailed methodology for conducting an LCA of common turbofan engines, focusing on the production phase from cradle-to-gate. To achieve this, an extensive and openly available dataset was compiled, enabling a more accurate LCA than those currently available. The IAE V2500 engine, widely used in A320 aircraft, was selected due to its relevance in the aviation industry and its use in related research. The analysis includes all metallic components, covering both raw material extraction and manufacturing processes. Coating processes were excluded and it was assumed that all manufacturing, apart from raw material extraction, occurs in Germany. Furthermore, certain accessories and systems of the engine were not included in the analysis, as well as the gearbox, due to the difficulty in formulating assumptions or calculations regarding these components.

The total environmental impact is assessed based on the functional unit of 'one IAE V2500 engine produced' using a hotspot analysis to identify the most impactful stages of the production process. For the LCA calculation, the open-source, python-based brightway2 framework [14] and the ecoinvent 3.9.1. database [15] are used. Furthermore, the Environmental Footprint (EF) 3.1 method [16] is employed for the LCIA.

3. Inventory Generation

The data collection and analysis for this reverse engineering approach is based on the process flow illustrated in Figure 1. The reverse engineering process begins with defining the engine and breaking it down into modules and components. Subsequently, the weight and dimensions of these components are estimated to determine the material quantities and component sizes. This is followed by analyzing the material generation, which encompasses the extraction of raw materials and the evaluation of alloying processes. The manufacturing phase consists of two distinct stages: rough manufacturing, which encompasses techniques such as forging and casting, as well as fine manufacturing, which includes machining. Finally, an assessment of the environmental impact is employed to evaluate the environmental consequences of the manufacturing process.

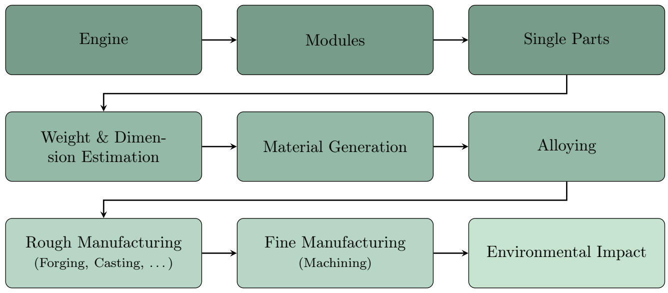


Fig. 1. Process flow of the reverse engineering approach.

The following subsections detail each step of the inventory generation process, highlighting the methodologies and techniques used. A total of 85 components across six modules were identified for the IAE V2500 engine assessment. Critical engine parts and their quantities, listed in Table 1, were compiled from technical documents, training manuals [17], construction guides [18] and lecture materials [19].

3.1. Engine Weight and Dimension Estimation

A comprehensive mass estimation was conducted for all components within the engine, with alloy identifications and dimensional estimates to serve as a foundation for the manufacturing process. For the mass estimation, the following methods were employed and the resulting data are presented in Table 1:

- Modeling axially symmetrical parts in CAD
- GasTurb Blade Calculator [20]
- NASA's WATE method for frames and housings [21]

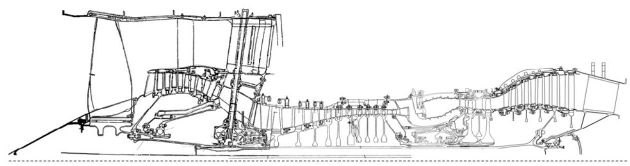


Fig. 2. Combined cross-section of the IEA V2500 engine, which was used to model the axially symmetrical parts, obtained from various sources [17, 18].

CAD Modeling. Axially symmetrical parts were modeled using a CAD program with a scaled cross-section of the IAE V2500 engine. The cross-section, shown in Figure 2, was derived from sub-cross-sections obtained from various sources, including training manuals [17] and technical documents [18]. The scaling of the cross-section was achieved by using the known height of the Low Pressure Turbine (LPT) blades as a reference point. The volume was calculated by obtaining the radius, length and width from the cross-section.

GasTurb Blade Calculator. Simplified calculations were performed according to the GasTurb Manual [20]. The mass of a single airfoil m_{af}, composed of a material with density ρ_b, is calculated as follows:

Table 1. Evaluated engine parts and materials with calculated weight and energy consumption during manufacturing.

Module	**Parts**	**Module Weight** [kg]	**Materials**	**Energy Manufacturing** [kWh]
Fan Module	Fan Blades, Fan Disc	165	Ti-6Al-4V (100%)	331
Low Pressure Compressor (LPC)	Fan Case, Inlet Guide Vanes, Fan Frame, Disc Stg. 1.5 to 2.5, Blades Stg. 1.5 to 2.5, Vanes Stg. 1.5 to 2.5, LP Stub Shaft	674	Ti-6Al-4V (97%) CrMoV Steel (3%)	3,688
High Pressure Compressor (HPC)	Disc Stg. 3 to 8, Disc Stg. 9 to 12, Rear Rotating Seal, HPC Blades Stg. 3 to 12, Variable Inlet Guide Vanes, HPC Vanes Stg. 3 to 11, Front Compressor Case, Rear Inner & Outer Case, Rear Shaft	284	Ti-6Al-4V (58%) Inconel 718 (30%) Hastelloy X (12%)	975
Diffuser & Combustor	Diffuser Case, No. 4 Bearing Compartment, Inner & Outer Combustion Liner, HPC Diffusor	151	Hastelloy X (61%) Inconel 718 (32%) Haynes 188 (6%)	639
HPT	HPT Case, Duct Segment Stg. 1 & 2, HPT Blades Stg 1 & 2, HPT Vanes Stg. 1 & 2, Discs Stg. 1 & 2, Stg. 1 Inner & Outer Seal, Stg. 2 Seal & Plate	191	Inconel 718 (78%) Haynes 188 (9%) PW 1480 (8%) Inconel 713 (4%)	648
Low Pressure Turbine (LPT)	Disc Stg. 3 to 7, Seal Stg. 3 to 7, Stg. 6 Inner Seal, LPT Shaft, LPT Inner & Outer Duct, LPT Case, Turbine Exhaust Case (TEC) with No. 5 Bearing, TEC Struts, LPT Blades Stg. 3 to 7, LPT Vanes Stg. 3 to 7	492	Inconel 718 (60%) Inconel 713 (23%) CrMoV Steel (9%) MAR 247 (6%) Inconel 100 (2%)	1,610

$$m_{af} = \rho_b * (r_{tip} - r_{root}) * (\frac{t}{c})_{b,mean} * c^2_{b,mean} \quad (1)$$

with

$c_{b,mean}$ mean blade chord
$r_{tip} - r_{root}$ height of blade
$(\frac{t}{c})_{b,mean}$ mean blade material thickness ratio
ρ_b density of material

The values for $c_{b,mean}$ and $r_{tip} - r_{root}$ for all compressor blades were taken from technical documents [17]. For turbine blades, these dimensions were estimated based on scaled cross-section measurements, incorporating a typical stagger angle to account for the blade's orientation. The thickness ratio t_b was estimated using standard assumptions from the GasTurb Manual [20], with slight adjustments made for certain components like the HPT blades. The vanes were calculated similarly, considering both the compressor and turbine stages. The overall volume was then determined by geometric parameters such as radius, length and width, from the cross-sections.

WATE method. The frame and housing weight was estimated using NASA's WATE method [21], a tool designed to predict the weight and dimensions of aircraft gas turbine engines. The appropriate frame type was selected by evaluating various options to determine the best fit for the IAE V2500 engine design. The corresponding weight was then estimated using a reference chart that correlates the frame's diameter and type with its weight. The volume was calculated by reversing the process, using the assumed material density. Depending on the available data, the weight was either directly obtained from the WATE method or calculated by multiplying the estimated volume by the material density.

The calculated overall weight of an IAE V2500 engine type is 1,956 kg, including all aforementioned components detailed in Table 1. The discrepancy between the calculated overall weight and the original weight of 2,404 kg as per EASA Type Certificate [22] may be attributed to the exclusion of certain accessories and systems, as well as the non-inclusion of the gearbox in our calculations. These components are challenging to assume or calculate and thus were excluded from this study.

3.2. Material Generation and Alloying

This section addresses the energy consumption and environmental impact associated with the materials used in the IAE V2500 engine, covering the selection of suitable materials, the extraction and processing of raw materials and the energy required for alloy production. The following subsections will detail the methods and assumptions used in these calculations.

Material Selection. The material selection for the IAE V2500 engine components involved various sources. Some materials were clearly specified in IAE V2500 documentation, while others were identified through secondary sources. In certain cases, engineering estimates based on literature information were used to determine material choices. This method ensured that all materials were appropriately accounted for in the analysis.

Raw Material Extraction. The extraction and initial processing of raw materials, which form the basis of the materials used in the IAE V2500 engine, are critical stages that contribute to the overall environmental impact. These processes, included in existing LCA datasets like the ecoinvent 3.9.1. database [15], encompass the energy and resources required to extract raw materials from the earth and prepare them for further processing.

Alloy Melt Energy Calculator. Based on the theory of 'Theoretical Minimum Energies' [23], a calculator was developed to estimate the physical energy required to heat all elements of an alloy above their melting temperatures. This calculation reflects the energy necessary for the alloying process, where the constituent elements are melted together to form the final alloy. The furnace efficiency, assumed to be 29.5% [24], is also factored into the estimation. Although the results from this calculator are likely conservative, they align with literature indicating that the energy demands for melting various metals are generally within a similar range.

3.3. Part Manufacturing

The manufacturing process for each engine component comprises several key steps, each influenced by various process parameters. The primary objective of this study is to achieve the final macro geometry of the parts. For this assessment, three major manufacturing methods were analyzed: forging, casting and machining. It is assumed that each part undergoes either a forging or casting process prior to being machined to its final dimensions. The subsequent paragraphs will detail the process chain for each method, examine the impact of the Buy-to-Fly Ratio (BFR) on raw material consumption and explain how the energy consumption values were determined.

Buy-to-Fly Ratio. The BFR quantifies the ratio between the amount of material required at the start of the production process and the amount of material in the finished part. Literature indicates that BFR values can be substantial, with ratios reaching up to 10 or more, meaning that ten times the initial material is needed to produce certain components. These BFR values are used to estimate the raw material requirements for each manufacturing method and provide a basis for calculating the energy consumption associated with part manufacturing. For this assessment, three different BFR values are considered:

- BFR of 2.5 for casting [25];
- BFR of 2.4 for forging [26];
- BFR of 1.2 for forged blades and vanes.

Although no direct evidence could be found for the values of forged blades and vanes, observations from the research of Cheng et al. [27] indicate that the ratio is likely to be lower for gas turbine blades when compared to other BFRs.

Energy Consumption. The energy consumption for manufacturing each component was assessed based on different methods and sources. The total energy consumption $\sum E_{man}$ is the sum of the energy required for forging, casting and machining, as shown with Equation 2. The final results are shown in Table 1.

$$\sum E_{man} = \sum E_{forg} + \sum E_{cast} + \sum E_{machi} \quad (2)$$

- *Forging (E_{forg}):* The calculations for forged parts are based on unit process LCI models for hot forming [28]. For superalloys, material parameters were adjusted according to strain hardening exponents and strength coefficients [29].
- *Casting (E_{cast}):* The energy consumption for casting is derived from sustainable casting guidelines [30] and industry reports on turbine blade manufacturing [31]. The calculations for melting and injecting cobalt were extrapolated based on the density of Haynes 188, while dewaxing and firing energy were estimated using a constant factor. The melting energy was calculated using the specific heat capacity, melting temperature (T_{melt}) and an furnace efficiency of 29.5%.
- *Machining (E_{machi}):* The energy required for machining each part was calculated using data from Mouritz et al. [32]. Steel used in the engine was assumed to have the characteristics of stainless steel, while cobalt was assumed to have properties similar to nickel, based on literature suggesting comparable machining difficulties. The amount of material machined was determined from the BFR and the final volume of the component.

4. Life Cycle Impact Assessment

The LCIA results are derived by combining the environmental impacts associated with raw materials and the energy consumed during manufacturing. The overall LCIA value is calculated using Equation (3). Each part is analyzed for raw material usage and manufacturing energy, with the contributions aggregated to calculate the total LCIA result for the engine.

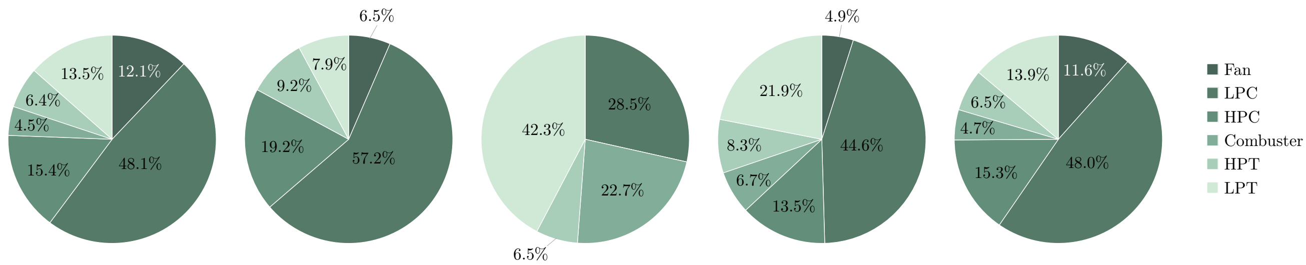
$$I_{LCIA,total} = \sum_i (m_{raw,i} * I_{material,i}) + \sum_i (E_{man,i} * I_{energy}) \quad (3)$$

with

I_{LCIA}	final LCIA result
$m_{raw,i}$	raw weight of part i
$I_{material,i}$	environmental impact of the material for part i
E_{man}	energy consumption for manufacturing of part i
I_{energy}	environmental impact of energy (per kWh)

The environmental impacts of the manufacturing processes in the category of Climate Change (CC) are summarized in Table 2. This table highlights the predominant influence of material-related impacts $I_{material}$, which contribute the largest portion of the total CC impact, accounting for 61,725 kg CO_2 eq. This is followed by the forging process I_{frog} with 2,270 kg CO_2 eq., the casting process I_{cast} with 1,280 kg CO_2 eq. and the machining process I_{machi}, which is responsible for 210 kg CO_2 eq. The total impact of the full manufacturing process is 65,485 kg CO_2 eq., which reflects the cumulative effect of all individual process steps. The LCA results of all impact categories are summarized in the supplementary material of this publication.

The pie charts in Figure 3 provide the overall results of the environmental impact distribution related to the materials and manufacturing processes used for all parts i of an IAE V2500



(a) Materials (b) Forging (c) Casting (d) Machining (e) Full Manufacturing

Fig. 3. Distribution of the environmental impact of engine manufacturing related to CC across engine modules (e). The breakdown includes impacts from different manufacturing steps: materials (a), forging (b), casting (c) and machining (d).

Table 2. Results of LCIA in the impact category of Climate Change (CC).

Process Step	**CC** [kg CO_2 eq.]	**Distribution**
Material $I_{material}$	61,725	94.2 %
Forging I_{forg}	2,270	3.5 %
Casting I_{cast}	1,280	2.0 %
Machining I_{machi}	210	0.3 %
Full Manufacturing $I_{LCIA,total}$	65,485	100 %

engine. The analysis summarizes the individual parts in the generally known engine modules: Fan, LPC, HPC, Combustor, HPT and LPT. In terms of materials, the LPC accounts for the largest portion of the environmental impact, contributing 48.1%, followed by the HPC at 15.4% and the LPT at 13.5%. When examining the forging process, the LPC dominates with a significant impact of 57.2%, whereas the HPC adds 19.2% and the Combustor 9.2%. The process of casting shows a different distribution, with the LPT taking the main impact at 42.3%, while the Combustor contributes 28.5% and the LPC 22.7%. The machining process reflects a similar pattern to the previous forging processes, with the LPC contributing 44.6% of the environmental impact, the LPT 21.9% and the HPC 13.5%. Finally, considering the full manufacturing process, the LPC emerges as the largest contributor to the environmental impact at 48%, followed by the HPC at 15.3% and the LPC at 13.9%.

5. Interpretation of LCIA results

Having outlined the methodology and the results, we now discuss the detailed environmental implications of producing an IAE V2500 engine. The results show a significant concentration of the environmental impact on the LPC module. These components are not subjected to as extreme stresses and temperatures as compared to the HPC, Combustor and HPT modules. Therefore, not as highly-alloyed superalloys are needed. However, these components are larger and heavier, requiring significantly more material. Consequently, they also demand more manufacturing energy, which together increases the overall environmental impact. Similarly, the LPT module shows a high environmental load, particularly in materials, casting and machining, as here the component sizes are again increasing and more material and therefore manufacturing energy is needed. Additionally it must be mentioned, that the fan case and frame are included in the LPC module as well as the Turbine Exhaust Case (TEC) is part of the LPT module, which alone accounts for around 550 kg (LPC) and 130 kg (LPT) of the used material. The HPC, Combustor and HPT modules, which are exposed to extreme temperatures and pressures and therefore require more specific alloys, contribute together a moderate share of 26.3% to the environmental impact in the category of materials and 28.4% in forging as well as 28.5% in machining.

Overall, the concentration of the environmental impact on specific engine modules does not only highlight the critical areas for reducing the environmental footprint of engine manufacturing but also underscores the value of our detailed analysis. Unlike previous studies that often rely on indirect methods like cost-based estimations, our approach involved a thorough re-engineering of the engine. For instance, Chester [7] reports a value of 5.92×10^{11} kg CO_2 eq. for an aircraft engine, significantly higher than our result of 65,480 kg CO_2 eq. The large discrepancy likely stems from Chester's use of an Economic Input-Output LCA model, which converts economic costs to environmental impacts. While useful for broad approximations, this method can introduce substantial uncertainties, as it may oversimplify complex processes and material flows. Other studies by Lopes et al. [9], Lewis [11] and Rahn et al. [33], report values of 168,500 kg CO_2 eq., 62,514 kg CO_2 eq. and 202,108 kg CO_2 eq. per engine. These values are in a more suitable range for comparison with the current study. While Lopes and Rahn conducted LCAs on other engine types (Lopes focused on CF6-80 engines, Rahn analysed CFM65-5 engines) and especially Rahn included also the Nacelle of the engine, which could result in different results. Lewis conducted his study also on an IAE V2500 engine and gained similar results, even while not including manufacturing processes.

In contrast, our reverse engineering approach provides a more accurate reflection of the engine's environmental impact. The lower CO_2 eq. value aligns more closely with realistic expectations, highlighting the importance of detailed LCAs over generalized estimation methods. However, consumables like coolants and lubricants, engine accessories and other engine systems were not included in the current calculations. An inclusion of these components, as well as composite materials in the fan module and coatings, would result in a higher environmental impact.

6. Conclusion

This study analysed the environmental impact of the production of an IAE V2500 engine to be 65,480 kg CO_2 eq. using data gained from a re-engineering approach. It could be shown that the LPC and LPT modules are the primary contributors to the environmental impact due to the high amount of material used.

Our results highlight the critical need for precise, component-level LCAs, as evidenced by the significant discrepancies with studies that rely on broader, less detailed methods. In fact, a comparison with existing literature clearly shows that our LCA ranks among the most comprehensive assessments currently available. The need of precise LCA methodologies is given, especially for complex systems like aircraft engines and are crucial for reliable engineering decisions and effective environmental policy-making.

Furthermore, the methodology developed in this research provides a model-independent framework that can be applied to other engine types, thereby ensuring adaptability and scalability for future assessments. This methodology provides a detailed, component-specific analysis, enabling a more precise assessment of the overall environmental footprint of an aircraft. These insights are crucial for not only optimizing individual components and the aircraft design, but also for simulating entire aircraft fleets, which ultimately contributes to the reduction of the environmental impact of the aviation industry.

References

[1] K. Dahlmann, S. Matthes, M. Plohr, M. Niklaß, J. D. Scheelhaase, F. Wozny, Klimawirkung des Luftverkehrs - Wissenschaftlicher Kenntnisstand, Entwicklungen und Maßnahmen.
[2] A. Bjørn, C. Chandrakumar, A.-M. Boulay, G. Doka, K. Fang, N. Gondran, M. Z. Hauschild, A. Kerkhof, H. King, M. Margni, S. McLaren, C. Mueller, M. Owsianiak, G. Peters, S. Roos, S. Sala, G. Sandin, S. Sim, M. Vargas-Gonzalez, M. Ryberg, Review of life-cycle based methods for absolute environmental sustainability assessment and their applications, Environmental Research Letters 15 (8) (2020). doi:10.1088/1748-9326/ab89d7.
[3] A. Oestreicher, A. Rahn, J. Ramm, J. Städing, C. Keller, K. Wicke, G. Wende, Sustainable Engine Maintenance: Evaluating the Ecological Impact of Life Limited Part Replacement, Proceedings of 34th Congress of the Internation Council of the Aeronautical Sciences ICAS 2024 (2024).
[4] S. Vinodh, G. Sivaraj, S. Nithish, R. Veeramanikandan, Life Cycle Assessment of an Aircraft Component: A Case Study, International Journal of Industrial and Systems Engineering 27 (4) (2017) 485. doi:10.1504/IJISE.2017.10008235.
[5] T. Bergs, T. Grünebaum, K. Fricke, S. Barth, P. Ganser, Life cycle assessment for milling of Ti- and Ni-based alloy aero engine components, Procedia CIRP 98 (2021) 625–630. doi:10.1016/j.procir.2021.01.165.
[6] K. Fricke, T. Bergs, P. Ganser, S. Gierlings, J. Albano, Life Cycle Inventories for Engine Blisk LCA, IOP Conference Series: Materials Science and Engineering 1226 (1) (2022) 012103. doi:10.1088/1757-899X/1226/1/012103.
[7] M. Chester, Environmental Life-cycle Assessment of Passenger Transportation, Dissertation, University of California, Berkeley (2008).
[8] J. Verstraete, Creating a Life-Cycle Assessment of an Aircraft.
[9] J. V. Lopes, Life Cycle Assessment of the Airbus A330-200 Aircraft, Master Thesis, Universidade Técnica de Lisboa, Lisbon, Portugal (2010).
[10] S. Howe, Environmental Impact Assessment and Optimisation of Commercial Aircraft, Master Thesis, Cranfield University, Cranfield, England, UK (2011).
[11] T. Lewis, A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios, Master Thesis, Norwegian University of Science and Technology, Trondheim, Norway (2013).
[12] European Committee for Standardization, ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework (2006).
[13] European Committee for Standardization, ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines (2018).
[14] C. Mutel, Brightway: An Open Source Framework for Life Cycle Assessment, Journal of Open Source Software 2 (12) (2017) 236. doi:10.21105/joss.00236.
[15] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, The International Journal of Life Cycle Assessment 21 (9) (2016) 1218–1230. doi:10.1007/s11367-016-1087-8.
[16] S. Andreasi Bassi, F. Biganzoli, N. Ferrara, A. Amadei, Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. doi:10.2760/798894.
[17] International Aero Engines, V2500 General Familiarization & Boroscope Training (2000).
[18] International Aero Engines, Pratt & Whitney, V2500 Line and Base Maintenance: Chapter 4 - ATA 72 - Engine Construction (2016).
[19] MTU Aero Engines, Design moderner Niederdruckturbinen (05.03.2024).
[20] J. Kurzke, GasTurb Details 6.
[21] R. J. Pera, E. Onat, G. W. Klees, E. Tjonneland, A Method to Estimate Weight and Dimensions of Aircraft Gas Turbine Engines.
[22] European Union Aviation Safety Agency, Type-Certificate Data Sheet for Engine V2500-A5, V2500-D5, V2500-E5 Series.
[23] R. J. Fruehan, O. Fortini, H. W. Paxton, R. Brindle, Theoretical Minimum Energies to Produce Steel for Selected Conditions.
[24] X. Chamorro, N. Herrero-Dorca, D. Bernal, I. Hurtado, Induction Skull Melting of Ti-6Al-4V: Process Control and Efficiency Optimization, Metals 9 (5) (2019). doi:10.3390/met9050539.
[25] K. Salonitis, M. R. Jolly, B. Zeng, H. Mehrabi, Improvements in energy consumption and environmental impact by novel single shot melting process for casting, Journal of Cleaner Production 137 (2016) 1532–1542. doi:10.1016/j.jclepro.2016.06.165.
[26] D.-J. Cha, D.-K. Kim, J.-R. Cho, W.-B. Bae, Hot shape forging of gas turbine disk using microstructure prediction and finite element analysis, International Journal of Precision Engineering and Manufacturing 12 (2) (2011) 331–336. doi:10.1007/s12541-011-0043-6.
[27] C. Lv, L. Zhang, Z. Mu, Q. Tai, Q. Zheng, 3D FEM simulation of the multi-stage forging process of a gas turbine compressor blade, Journal of Materials Processing Technology 198 (1-3) (2008) 463–470. doi:10.1016/j.jmatprotec.2007.07.032.
[28] J. J. Buis, J. W. Sutherland, F. Thai, Unit Process Life Cycle Enventory Models Of Hot Forming Processes, Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference 2013 (2013).
[29] R. Rajendran, M. Venkateshwarlu, V. Petley, S. Verma, Strain hardening exponents and strength coefficients for aeroengine isotropic metallic materials – a reverse engineering approach, Journal of the Mechanical Behavior of Materials 23 (3-4) (2014) 101–106. doi:10.1515/jmbm-2014-0012.
[30] H. Mehrabi, M. Jolly, K. Salonitis, Sustainable Investment Casting, 14th World Conference in Investment Casting (2016).
[31] Safran, The birth of a turbine blade: Accessed on: 16.09.2024 (07.07.2021). URL https://www.youtube.com/watch?v=1tM96B77n0U
[32] A. P. Mouritz, Introduction to aerospace materials, Woodhead Publishing in materials, Woodhead Publishing, Cambridge UK, 2012.
[33] A. Rahn, K. Wicke, G. Wende, Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment, Sustainability 14 (17) (2022) 10598. doi:10.3390/su141710598.