

A Modular Life Cycle Assessment Framework for Novel Aircraft Configurations and Sustainable Aviation Fuels

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Abstract. This work presents a modular framework for environmental impact assessment in conceptual aircraft design, developed within the UNICADO environment. The new architecture decouples individual life cycle phases and has been extended to various Sustainable Aviation Fuel (SAF) pathways. This enhanced flexibility enables a more robust and holistic trade-off analysis of an aircraft's environmental footprint early in the design process. The case study of UNICADO-LR-01 presents results on cumulative energy demand shares for each life cycle activity. Additional results reveal that the life cycle phases operations (62.0, 78.4, 84.6%) and energy carrier production (29.6, 14.3, 9.9%) are most dominant in terms of energy, CO₂, and NO_x, respectively. Results from SAF pathways suggest a shift towards the energy carrier production phase.

Introduction

The aviation industry is focusing increasingly on mitigating its environmental impact. Initiatives such as "Fly the Green Deal" [1] are being developed to promote sustainable aviation. The measures considered include novel aircraft configurations and sustainable aviation fuels, which could reduce climate impact compared to traditional fossil fuels. To appropriately assess these measures, a holistic approach in terms of a life cycle assessment (LCA) within the earliest stage of conceptual aircraft design has to be considered.

Most existing aircraft design and assessment tools are either not open code, lack flexibility for quick studies, or do not consider life cycle assessment evaluations at all. FAST (Future Aircraft Sizing Tool) [2] focuses on sizing and performance analysis for conventional and electrified aircraft without LCA evaluation. *AeroMAPS* [3] and *CASCADE* [4] serve as scenario-exploration frameworks for air transport decarbonization strategies, but provide little detail on aircraft life cycle phases. Tools such as *AD-LCA* Excel/Matlab methodology [5] and ecological assessment [6, 10] suffer from monolithic architectures that lack the flexibility required for advanced aircraft concepts and emerging technologies. And while offering LCA frameworks such as *qUWick* [7], *ecoLYFE* [8], or *AEco* [9], the implementations are not openly accessible to the broader research community.

To address this, an extensible *assessment framework* is being developed within the open-source conceptual aircraft design environment UNICADO [10]. As a use case, a long-range aircraft is assessed with multiple sustainable aviation fuel (SAF) pathways.

Methodology

Assessment Framework. The foundation for this work is the *ecological assessment* tool based on [6] (detailed documentation see [10]). While providing a solid basis for life cycle emissions and



impact assessment, the original tool was built with a monolithic architecture. This posed challenges within the UniSELECT project [11], as its goal is a climate-efficient long-range aircraft considering disruptive technologies (e.g., open rotor), configurations (e.g., blended-wing body), or operations (e.g., stopover flights). The former logic is shown in Fig. 1 (left). The tool provides a single interface for inputs and focuses on internal calculations. It includes a database of materials, fuels, and primary energy factors, as well as methods for the cradle-to-grave (from development to end-of-life) inventory and impact assessment (air quality index calculation and application of an altitude-dependent climate model to evaluate average temperature response).

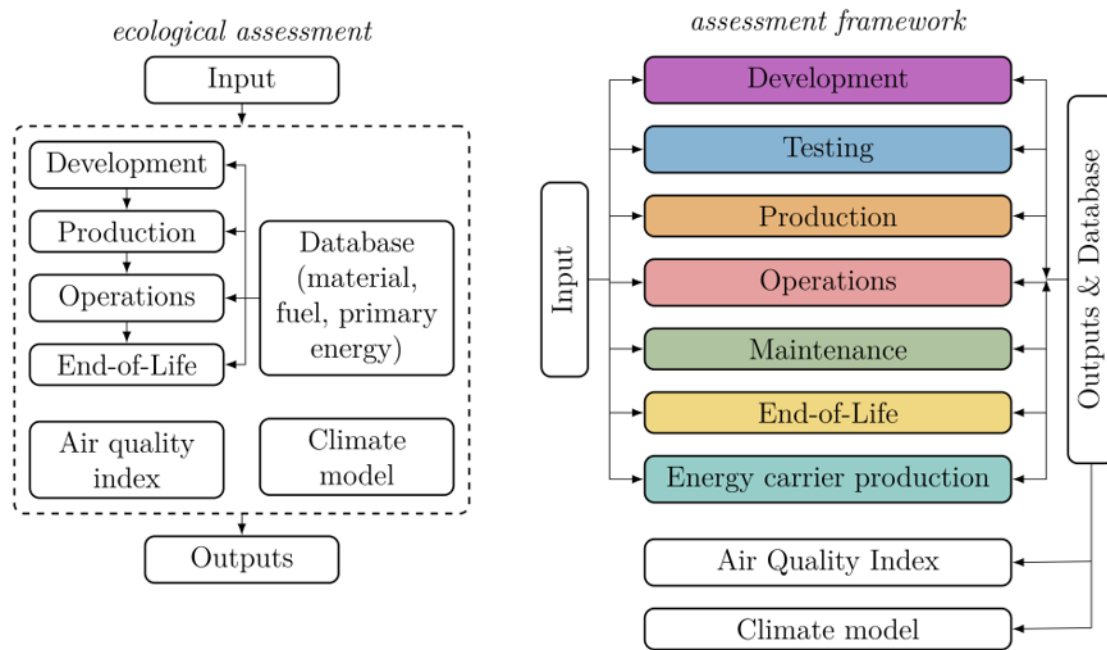


Fig. 1: Comparison of life cycle assessment tool by Schäfer (left, based on [6]) and assessment framework in UNICADO (right).

To address this issue, the tool was restructured into a modular *assessment framework* (right in Fig. 1). It treats each phase as individual stand-alone modules that have individual in- and output interfaces. This enables the exchange of phase-specific methods, e.g., by replacing the simplified electricity demand model in the development phase with more sophisticated data or higher fidelity methods. Additionally, several tools are split, e.g., the operations phase is divided into operations, maintenance procedures, and energy carrier production. The input settings are extended, e.g., Boeing Fuel Flow Method 2. For details, it refers to the open-source documentation [10].

Assessment Manager. To orchestrate the *assessment framework*, a manager tool was developed. This tool is integrated into the aircraft design platform (RCE) of UNICADO, enabling the connection of aircraft design results to the assessment. The data is exchanged with the common exchange file format (XML). Additionally, each tool has its own configuration file that varies depending on input settings (e.g., hours of system integration tests).

Sustainable Aviation Fuels. SAFs are one primary measure for decarbonization. Several production pathways are included in the *assessment framework*, such as Alcohol-to-Jet (AtJ), Hydroprocessed Esters and Fatty Acids (HEFA), Power-to-Liquid (PtL), and Biomass Gasification with Fischer-Tropsch (Gas+FT). For details, refer to [12].

Results and Discussion

A case study is presented of the long-range aircraft design UNICADO-LR-01 (Release 0.8.1). It is a kerosene-burning tube-and-wing turbofan configuration for 300 passengers and entry-into-

service 2020. The use case is the design mission with 6700 NM range with 77.8 t block fuel (details see aircraft references documentation [10]). Note that the results relate to the aircraft's lifetime with 369 flights/year for 30 years assuming:

- energy (heat, electricity) for personnel/offices developing the aircraft,
- energy (heat, electricity, fuel) for multiple tests & for additional test aircraft and engine (its production and end-of-life is allocated to testing),
- material and energy (heat, electricity, fuel) producing one aircraft (material production, component manufacturing, transport to assembly site, electric and heat energy needed for manufacturing & assembly personnel),
- fuel for operating an aircraft during its lifetime (total number of flights in its operating duration),
- material and energy (heat, electricity) maintaining an aircraft during its lifetime,
- energy for producing the required fuel (e.g., kerosene for flights, kerosene for transport during disposal, diesel during transportation to the final assembly site).

Fig. 2 shows the cumulative energy demand (CED) results for all phases. In the *development* phase, the impact is driven by electricity and heat demand for the offices with the primary energy demand for electricity being the highest share. In the *testing* phase, the energy for the test aircraft production (2 for fatigue, 6 for flight tests) requires 30% of the total testing CED. Both the material production (22%) and the component manufacturing (38%) dominate the *production* phase. To be noted is that the primary scrap is recycled (e.g., for aluminum, a scrap ratio of 0.85 and a recovery rate of 0.9 is assumed). In *operations*, the landing and take-off cycle is with 1% negligible in terms of energy. The dominant phase in maintenance is the spare part production (88%). The *end-of-life* phase includes both energy credit as well as demand. The credit due to material is five times higher than the energy required for recycling, incineration, and landfill. While the phases *testing*, *operations*, *production*, and *end-of-life* require energy carriers (kerosene, diesel), only the first two are relevant with 4% and 96%, respectively.

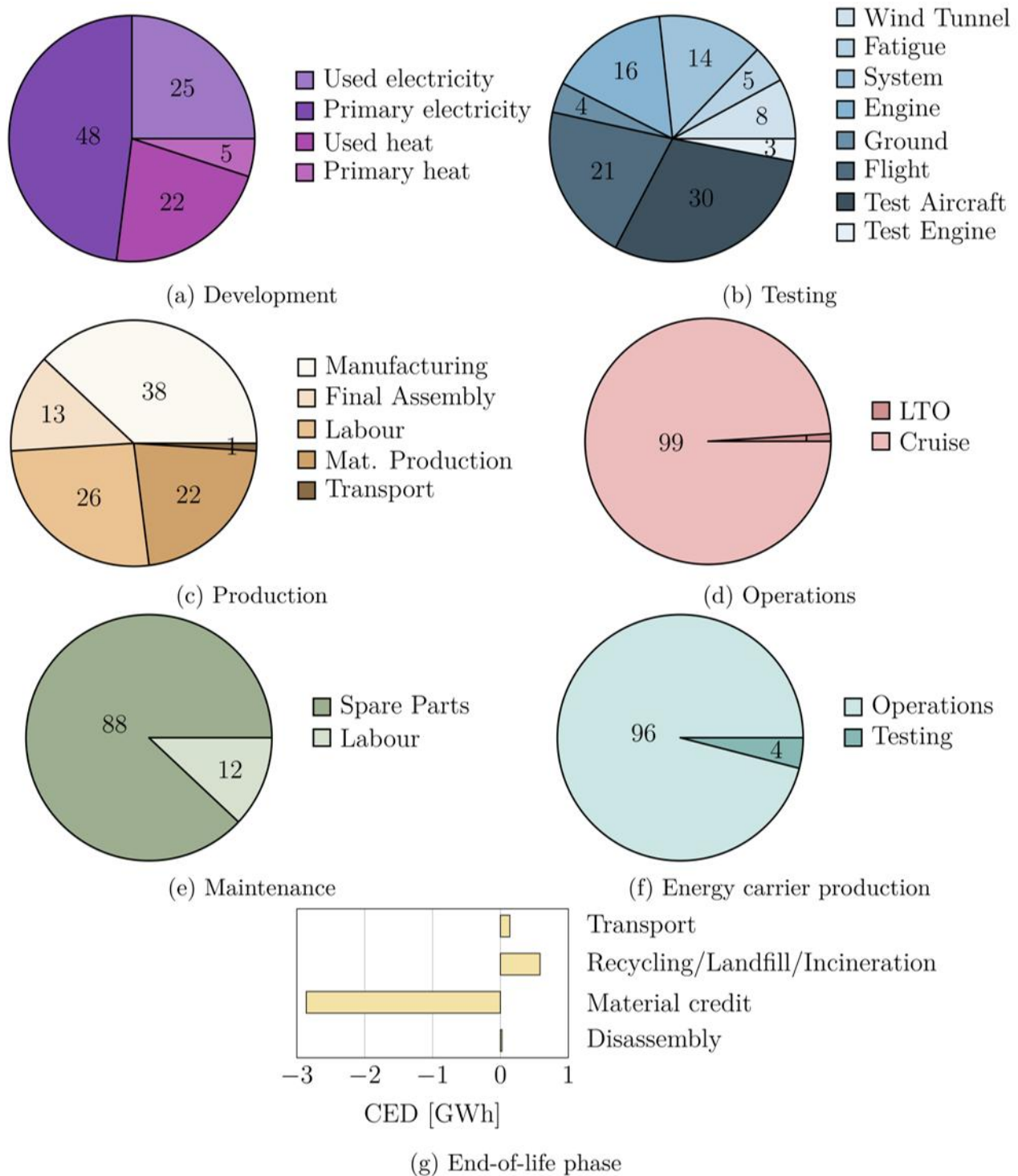


Fig. 2: Cumulative energy demand shares for life cycle phases of UNICADO-LR-01.

Table 1 shows how the individual phases contribute to the total impact with respect to CED, CO₂, and NO_x. The most influential phase is operations, followed by energy carrier production. This is due to the scaling to the entire service life (single mission operation requires 3.35 TJ which is < 1% of development CED). The total life cycle global warming potential (GWP) results in 93 gCO₂eq per MJ fuel burned during the operational flights (only CO₂ considered, cf. 89 gCO₂eq/MJ according to CORSIA [14]).

Table 1: Cumulative energy demand and emissions (CO₂, NO_x) inventory results for UNICADO-LR-01 lifetime.

	CED [%]	CO₂ [%]	NO_x [%]
Development	1.0	0.8	0.2
Testing	6.2	5.7	4.9
Production	0.3	0.2	0.1
Operations	62.0	78.4	84.6
Maintenance	0.9	0.6	0.2
End-of-Life	0.0	0.0	0.0
Energy carrier production	29.6	14.3	9.9
Total	56.8 PJ	3.24 Tg	13.7 Gg

Switching to SAF affects both dominant life cycle phases of aviation energy demand. Table 2 shows that the conversion efficiency of the different production pathways varies widely between 13.8% and 55.6%, reflecting substantial energy losses during synthesis and upgrading (note that a high efficiency does not automatically imply a low CED, since it depends on the primary energy factors; compared to fossil kerosene PEF = 1.24, efficiency = 80%). CORSIA eligibility (10% reduction to the fossil baseline) can thus only be achieved if biogenic CO₂ sources, renewable electricity, or carbon capture technologies (e.g., direct air capture) are applied to offset the combustion-related impact.

Table 2: Process energy efficiency and tank-to-wake global warming potential with and without offset.

	Energy efficiency [%]	GWP [g CO₂eq/MJ]	GWP (no offset)² [g CO₂eq/MJ]
AtJ (Alcohol-to-Jet)	35.5	45.7	153
HEFA	55.6	16.2	86.9
PtL¹(Power-to-Liquid)	13.8	22.6/513	91/522
Gasification +Fischer-Tropsch	27.2	4.52	266

¹ PtL electricity from wind or current German electricity mix.

² Biogenic offset for HEFA, AtJ, Gas+FT & DAC for PtL.

Conclusion and Future Work

This work has presented a fully modular and extensible Life Cycle Assessment framework in UNICADO. By decomposing the monolithic legacy tool into a suite of modules orchestrated by an assessment manager, the new architecture provides the flexibility required for holistic trade-off analyses of novel aircraft and fuel technologies such as SAF. Future work will focus on expanding the library of impact assessment methods like CED and ReCiPe midpoint categories to translate the calculated inventories into a broader range of environmental damage categories.

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