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Integrating Time-Dependent Electricity Datasets into Discrete-Event Life Cycle Assessment for Aircraft

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Abstract

Life Cycle Assessments (LCAs) are widely used to evaluate the environmental impact of aircraft throughout their entire life cycle. Ground-based processes, particularly during maintenance activities and the manufacturing of components or spare parts, are significantly influenced by energy use. However, the environmental assessment is highly sensitive to variations in the energy mix, which evolves over time due to the increasing adoption of renewable energy sources. In this study, we demonstrate that the time-dependent energy consumption of long-living products such as aircraft can significantly affect the LCA results. To address this, we use a combined discrete-event LCA framework, which disaggregates complex systems into individual units for detailed analysis. By incorporating time-varying electricity datasets, we demonstrate the feasibility of integrating temporal dynamics into LCA and highlight the potential impact of such dynamic factors on the environmental assessment. This consideration can be particularly important for emerging aircraft designs such as all-electric concepts, where electricity plays an important role during flight operations.

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Keywords: life cycle assessment; dynamic life cycle inventory; discrete-event simulation; aviation; maintenance

1. Introduction

Life Cycle Assessments (LCAs) have been demonstrated to be an appropriate methodology for a comprehensive evaluation of aircraft. In addition to flight operations, which is typically the most impactful phase, ground-based activities are receiving increasing attention due to their environmental impact [1]. Maintenance activities play a pivotal role in ensuring the continued airworthiness of aircraft. These activities are essential to extend the service life of aircraft, which can range up to 40 years. Aircraft undergo various maintenance activities during its operational life, ranging from routine checks to extensive overhauls.

A main contributor to the environmental impact is electricity required during maintenance activities. About 65 % of the Global Warming Potential (GWP) of all maintenance activities is required for lighting or heating the hangar and for operating specialised equipment [2]. A further 20 % is associated with the replacement and production of spare parts. However, as highlighted by Meissner et al. [3], the ecological footprint of individual maintenance activities could be reduced by up to 70 % through the use of fully renewable energy sources.

The energy mix, comprising sources such as fossil fuels as well as renewables and nuclear power, is subject to significant changes over time [4]. Different countries are pursuing individual energy transition plans to meet the challenges of climate change. However, each form of energy production has different constraints or consequences that can only be understood by a holistic environmental approach across different impact categories. Moreover, the transition from one energy mix to another is not rapid but rather linear [5]. Changes in the energy mix and their environmental consequences can therefore only be analysed over longer periods of time. Hence, the dynamisation of Life Cycle Inventorys (LCIs) is a promising approach, especially for products such as aircraft, which have relatively long life cycles and operational phases [6].

The objective of this study is to demonstrate the feasibility of incorporating a gradual transition in energy sources over time into LCA studies. This is demonstrated through aircraft maintenance activities, which occur continuously throughout its life cycle and are marked by substantial energy consumption. Our discrete-event LCA, which provides a detailed representation of the aircraft's life, has been enhanced with a dynamic LCI that updates the energy mix on an annual basis. The effects of this

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dynamic LCI are then compared with those of static inventories to determine whether the environmental outcomes are over- or underestimated. As a proof of concept, our analysis is applied to four European countries with diverse energy strategies.

2. Method

2.1. Goal and Scope

The aim of this study is to investigate the effects of time-dependent LCIs on the environmental impact of an Airbus A321 commercial aircraft with a service life of 25 years. To enable a direct comparison between the static and the dynamic inventory, the study considers the time-dependencies of the electricity mix during the aircraft's life cycle. The total environmental impact is provided in the functional unit over the entire life cycle of the aircraft. The primary focus of this analysis is on aircraft maintenance, as individual maintenance activities occur regularly throughout the lifespan of the aircraft and are highly dependent on energy consumption [2, 3]. This encompasses all maintenance operations which necessitate energy for the maintenance facilities and equipment as well as for the manufacturing of individual spare parts when components need to be replaced. The energy that is required for producing the fuel or for operating the airport is not included in the analysis. The aircraft is scheduled to enter service in 2025 and to be retired at the beginning of 2050.

The analysis is applied to four European countries, each with a distinct energy policy strategy. For each country, a reference scenario, where the energy dataset remains constant throughout the aircraft's lifetime, and a dynamic scenario with annual adjustments are included. The LCA is carried out with the open-source Python package Brightway2 [7] applying the Life Cycle Impact Assessment (LCIA) method EF 3.1 [8]. The life cycle simulation and the automated updating of the dynamic LCIs are carried out with DLR's in-house discrete-event simulation tool Life Cycle Cash Flow Environment (LYFE) as described in Section 2.3.

2.2. Generation of the Life Cycle Inventory

An energy mix database is created as the basis for implementing the time-dependent energy datasets. These datasets contain the distribution of different types of energy production for four European countries, each with different energy profiles and policies:

- **Germany:** Germany is currently undergoing a significant transformation of its energy system, with the goal of achieving a substantial increase in the share of renewable energies over coming decades (also known as "Energiewende" [9]). The country plays a prominent role in shaping the European energy landscape due to its robust political framework that supports the transition towards a more sustainable energy future [10]. This includes, for example, the scheduled nuclear phase-out by 2024 and the politically-driven expansion of renewable energies.
- **France:** The French electricity supply is heavily reliant on nuclear energy, which, from an environmental perspective, already results in comparatively low CO_2 emissions from energy production. However, the French "Loi Énergie-Climat" [11] aims to reduce nuclear energy's share from 70 to 50 % by 2030, addressing concerns over nuclear waste and safety risks while promoting a more diverse energy mix through increased use of wind, solar, and geothermal energy.
- **Norway:** Norway plays a leading role in the expansion and utilisation of renewable energies, particularly hydropower, which covers almost all of the country's electricity needs. Due to its geographical location and strategic policy initiatives, the country has established a stable and enduring long-term energy strategy [12].
- **Poland:** Poland has one of the highest share of coal-fired power generation, which leads to relatively high environmental impacts, especially CO_2 emissions. The country is currently facing the challenge of transforming its traditional dependence on coal into a more sustainable energy mix by investing in renewable energies and nuclear power [13].

For each of these countries, an energy mix forecast was derived from the literature and an annual energy mix dataset was modelled within the LCI. As the energy forecasts are often only given in five- or ten-year increments, the remaining years were interpolated accordingly. Politically triggered decisions, such as the shutdown of German nuclear power plants in 2024 [14], were taken into account and incorporated. Figure 1 provides an overview of the renewable energy mix scenarios for Germany, France, Norway, and Poland. The LCI was modelled from the existing literature and using the background ecoinvent database version 3.9.1 with the cut-off by classification system model. For some scenarios, the ecoinvent database did not yet contain a corresponding energy production dataset for a specific location (e.g., nuclear power in Poland). In these cases, datasets from other locations were approximated. The respective reference scenarios consist of the energy mix from the year 2025, which remains constant throughout the aircraft's lifetime.

The LCIs for the other life cycle phases are derived from previous publications. The LCI for the aircraft production was adapted from Rahn et al. [17] with material datasets from Kaup [18]. The inventory of the maintenance activities is based on Rahn et al. [2]. The ecoinvent datasets *market for transportation, passenger aircraft* for very short- to medium-haul flights are used for flight operations. The aircraft's end-of-life is modelled using the *credit for avoided burden* method.

2.3. Discrete-Event Life Cycle Assessment

The 25-year life cycle of the aircraft is simulated using a discrete-event LCA. The discrete-event simulation is based on Pohya et al. [19] and Rahn et al. [17] and subdivides the aircraft's life cycle into individual segments. These segments are,

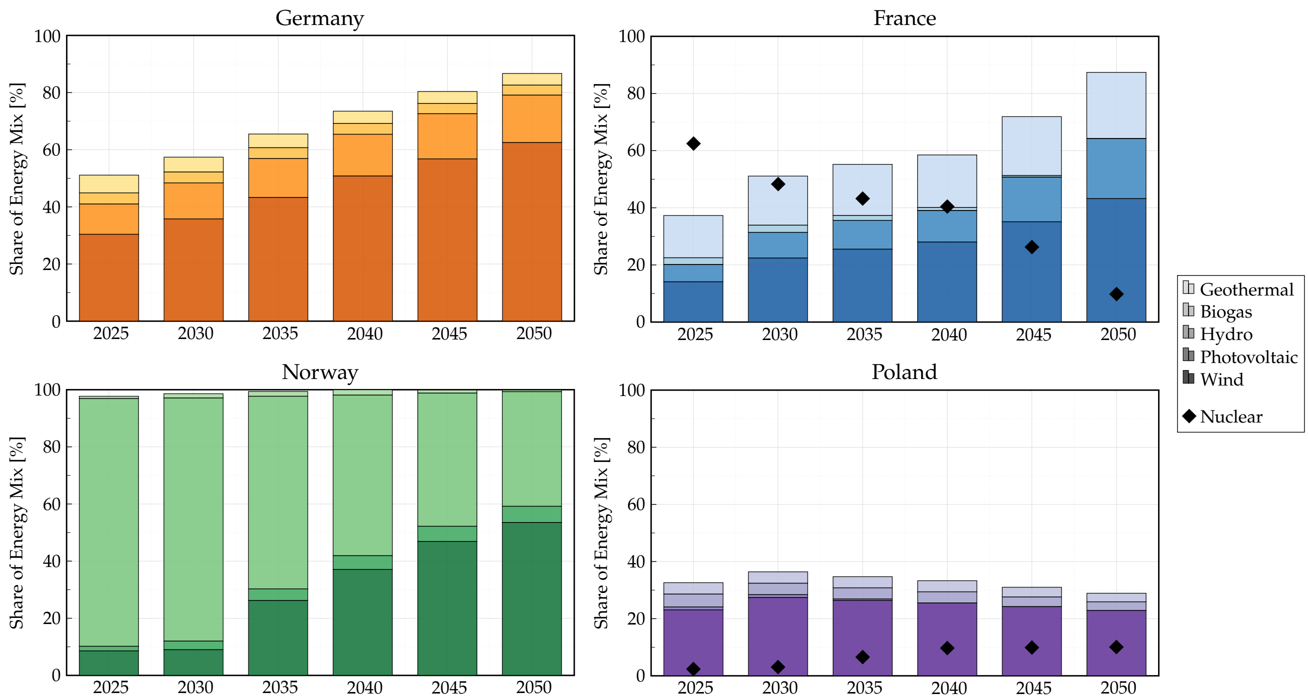

Fig. 1. Projected shares of renewable energy sources (wind, photovoltaic, hydro, biogas, and geothermal) and, where applicable, nuclear energy in the energy generation mix for Germany, France, Norway, and Poland from 2025 to 2050. Detailed data and country-specific considerations are provided in the supplementary material (adapted from [12–14, 10, 15, 16]).

for example, individual flights or maintenance events. In addition to a unique time stamp, the events also contain operational parameters and the environmental LCIs. During the simulation, each event is environmentally assessed, and the results are aggregated for the entire lifetime of the aircraft. This approach enables the analysis of temporal distribution and type of environmental results. Additionally, the simulated life cycle and the LCIs can be modified manually.

This simulation principle is used to integrate the annual energy datasets from the energy mix database. At the end of the year, all datasets that have electricity as an exchange are updated with the new energy mix dataset. From this point onwards, the LCAs of the individual events are calculated using the new energy mix leading to either higher or lower environmental impacts.

2.4. Maintenance Activities

Maintenance activities are carried out at regular intervals throughout the aircraft's operational lifespan. Approximately 65 % of the climate change impact of aircraft maintenance is currently related to energy that is needed for the operation of facilities or equipment and each individual maintenance event is dependent on electricity [2]. This includes, for instance, the energy needed for lighting and air conditioning the facilities as well as for operating specialised equipment. When components are replaced, the production of spare parts requires additional energy. In this analysis, it is assumed that the spare parts are newly manufactured prior to utilisation and are produced in the same country in which the maintenance is performed.

An overview of maintenance tasks that are based on electricity is listed in Table 1. For instance, during line maintenance, such as daily, weekly, or A-check, electricity is needed for the operation of the air conditioning unit, the towing of the aircraft with an electric towing unit, and the operation of the hangar and equipment. Shop maintenance involves a detailed inspection of critical aircraft components with high safety requirements, such as the engines or landing gears. This usually requires the production of spare parts if the existing components show signs of wear, degradation, or damage. The production of these parts requires the use of aircraft alloys, whose manufacturing processes also depend on a considerable amount of energy.

3. Results

The focus of the study results is twofold: to highlight the effects of employing time-dependent LCIs compared to static LCIs and to demonstrate the applicability and feasibility of this approach based on aircraft maintenance activities. To illustrate this, the environmental impacts of a single maintenance check are analysed over time and the results are interpreted in the context of the aircraft's overall lifespan. Finally, the overall maintenance-related deviations between the reference scenarios and the varying energy mixes for Germany, France, Norway, and Poland are compared across multiple impact categories.

3.1. Impact of Individual Maintenance Checks

The environmental impact of maintenance changes from year to year due to the use of the time-dependent energy mix.

Table 1. Overview of the electricity requirements for line, base, and shop maintenance (taken from [2]).

Maintenance Type	Electricity Required for
Line Maintenance	air conditioning unit, ground power unit, special equipment, electric towing, tyre production, heat exchanger during engine wash, ...
Base Maintenance	hangar operations, special equipment, electric towing, aircraft interior production, ...
Shop Maintenance	workshop operations, special equipment, electric towing, spare part production, ...

This change is illustrated by a single maintenance check. The A-check is a line maintenance check carried out approximately four to five times a year with a total duration of ten hours. In addition to visual checks, it includes a tyre pressure check with possible tyre replacement and an optional engine wash by the airline. During this A-check, energy is used to operate the hangar and equipment. Electricity is used for the tyre production or refurbishment, if needed. The water for the engine wash is heated by a heat exchanger.

Figure 2 illustrates the environmental impact of one single A-check at five-year intervals for the four locations. The GWP of the A-check is comparable across all four countries, with values approximating 10.5 tCO_2-eq. In the reference year 2025, the highest environmental impact is observed in Poland, with a value of 10.672 tCO_2-eq., and the lowest impact is in Norway, with an environmental impact of 10.397 tCO_2-eq. The climate change impact decreases over time in all four countries. In particular, in Germany and Poland, the impact declines by 2.7 % and 1.9 %, respectively. As France and Norway already benefit from more climate-friendly energy mixes, the environmental impact of the A-check indicates less significant changes in this impact category. The outcomes of other impact categories are provided in the supplementary material.

3.2. Life Cycle Assessment Results

An evaluation of the environmental impact across all life cycle phases reveals that maintenance plays a relatively minor role, with flight operations emerging as the most significant contributor to environmental burdens. In the majority of impact categories, the contribution of the maintenance phase is less than 1 %. This is consistent with existing literature that frequently considers maintenance to be a less impactful life cycle phase and often omits it from detailed analyses [20]. However, certain environmental impact categories demonstrate a higher contribution from the maintenance phase. Notable exceptions include water use (2.5 %), freshwater eutrophication (3.1 %), minerals and metals depletion (5.9 %), and carcinogenic effects

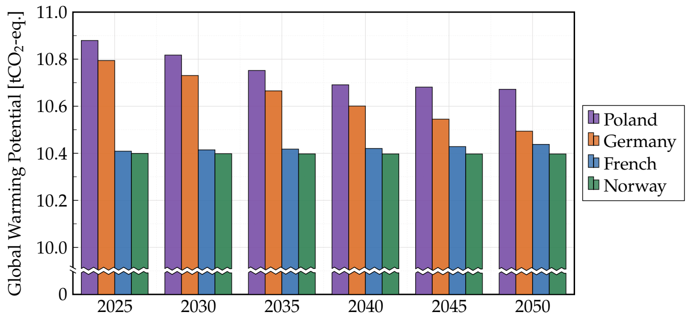

Fig. 2. Overview of the GWP for the A-check from 2025 to 2050 for the four countries Poland, Germany, France, and Norway. To clearly present the differences between the four countries, the vertical axis has been truncated for visualisation purposes.

(11.7 %). The LCA results of all life cycle phases and impact categories are summarised in the supplementary material of this publication.

3.3. Comparative Analysis of Overall Maintenance Impacts

Following the assessment of the overall life cycle, a comparative analysis of the static and dynamic maintenance inventory over a period of 25 years is conducted. The accumulated ecological impacts of all maintenance tasks for the impact categories with the greatest variability (climate change, freshwater eutrophication, ionising radiation, and land use) are illustrated in Figure 3. Additional results are included in the supplementary material. The percentage deviation is compared with a reference scenario that maintains the energy mix consistent with that of 2025 throughout the simulation time. Depending on the countries' energy policy approaches, the impact deviations are positive or negative in various impact categories. A negative deviation indicates that the environmental impact is lower than that of the reference scenario. Conversely, a positive deviation indicates an increase in impact compared to the reference.

In the climate change category, the German scenario shows a 5.0 % reduction in comparison to the reference year, which is primarily attributable to the expansion of renewable energy sources. In Poland, the projected decrease in GWP is approximately 4.2 %, which is less pronounced than in Germany due to a slower renewable energy transition. Conversely, France experiences a slight increase in climate impact. This rise is linked to the slow and gradual reduction in nuclear energy production, which is considered a low-carbon energy source. This illustrates the potential climate implications of transitioning away from nuclear energy in favour of alternative sources. The climate change impact in the Norwegian scenario remains broadly consistent as the country's utilisation of hydroelectric energy has a relatively minimal effect on this category. A similar trend emerges in the impact category of freshwater eutrophication.

The impact category of ionising radiation encounters the potential damage caused by radioactive substances, primarily resulting from the radiation emitted during the generation of electricity in nuclear power plants and from the handling and long-term storage of radioactive waste. Due to the high proportion of nuclear power in the French energy mix, the results of the baseline scenario in France are more than twice as high compared to the other countries. The expansion of renewable energies leads to an impact reduction of almost 25 % compared to the French reference scenario. As Poland's energy strategy encourages the construction of nuclear power plants in the future, it's impact in the ionising radiation category may increase by up to 16 % after 25 years.

Contrary to that, the values in the land use impact category increases in almost all countries. The reason for this is the expansion of renewable energies, especially photovoltaic, which involves large areas of land use. Germany already has the greatest environmental impact in the land use category due to the currently high share of photovoltaic - leading to a slower increase in this impact category. In Poland, the gradual expansion of nuclear energy is the reason for the decreasing land use impact as nuclear power has a relatively low land use intensity.

4. Discussion

The results show that the inclusion of time-dependent datasets in the LCI leads to different overall environmental impacts compared to a static inventory. When accounting for time-dependency, the environmental impacts decrease over time in most impact categories. This reduction is primarily driven by the countries' efforts to transition towards more sustainable and lower-emission energy production. The approach to achieving this can vary drastically as demonstrated by a comparative analysis of the four European countries: Germany, France, Norway, and Poland.

Products with long life cycles are particularly suited to implementing time-dependent inventories. Due to their long lifetimes, the effects of changes in the LCI over time become most apparent, which increases the potential for over- or underestimating environmental impacts throughout the life cycle. The most pronounced example of an overestimation of the LCIA results (by more than 25 %) can be observed when utilising the French static LCI for the impact category of ionising radiation. Given the high share of nuclear power in the French energy mix, which already exhibits a high impact in ionising radiation, even a gradual reduction in nuclear power exerts a substantial influence. In contrast, in the impact category land use, the impact tends to be underestimated with static LCIs in most countries. In this case, the use of renewable energy sources leads to a higher demand for land, for instance, as a result of the expansion of ground-mounted photovoltaic systems.

The complex relationship between the energy mix and the impact categories considered in the LCIA can result in a rapid burden shifting from one category to another. The use of time-dependent LCIs makes this visible and highlights the significance of conducting a comprehensive and accurate interpretation at the end of the assessment. However, extending the temporal scope to 2050 introduces significant uncertainties in projections of energy generation mixes, particularly due to unforeseen changes in technology, policy, or market dynamics.

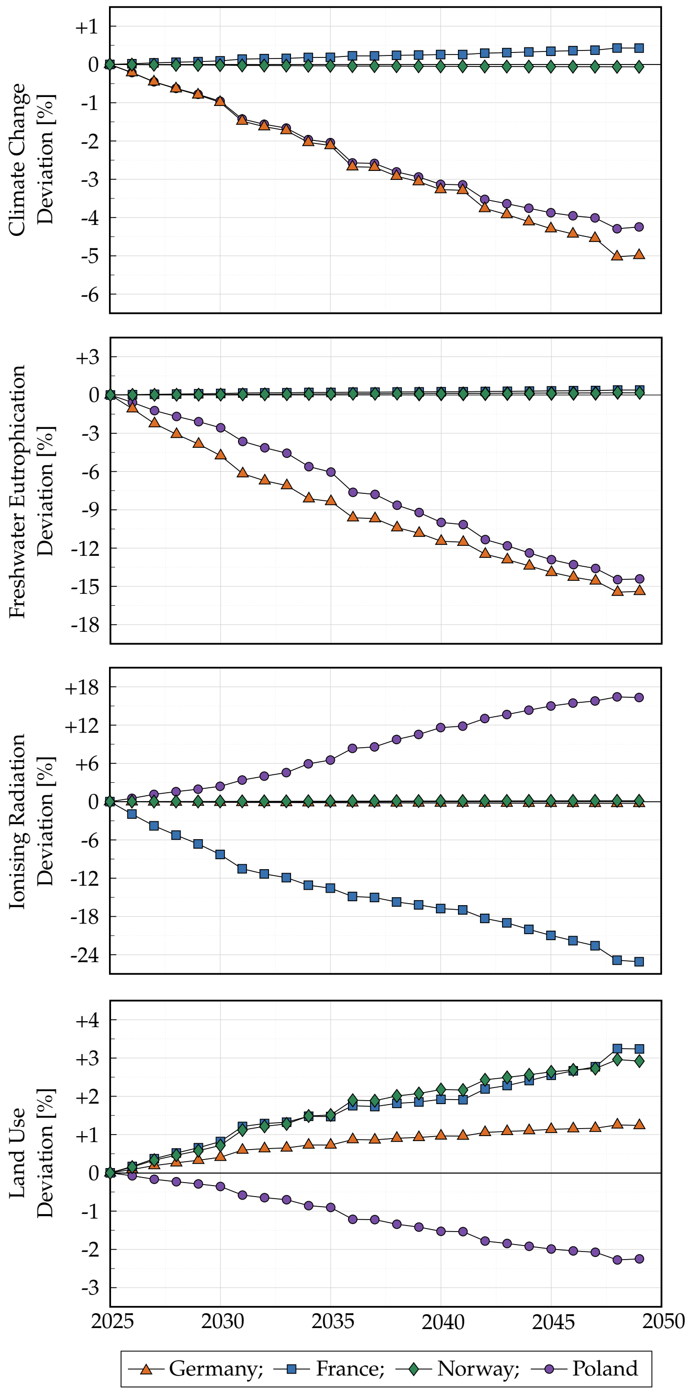

Fig. 3. Comparison of the aggregated dynamic impacts for aircraft maintenance across the four impact categories climate change, freshwater eutrophication, ionising radiation, and land use for scenarios representing Germany, France, Norway, and Poland. Each graph compares the dynamic results with the reference scenario.

5. Conclusion and Outlook

Our findings indicate that there is potential for an over- or underestimation of the ecological impact of up to 25 % when utilising static energy datasets in comparison to dynamic LCI. This has significant implications for the interpretation of LCA results and subsequent recommendations for action. The utilisation of dynamic datasets is therefore strongly encouraged, especially for products with long service times. However, due to the considerable additional effort involved in collecting dynamic LCIs, this is not feasible for every type of LCA. Pinsonnault et al. [21] therefore recommend making a decision on the use of a dynamic LCI on an individual basis.

The application of the time-dependent LCIs refers solely to electricity consumption during the maintenance process. As this study is intended as a proof of concept, technological advancements for other maintenance-related aspects have not been included. For a more realistic result, all inventories would have to be time-dependent. Additionally, it was assumed that an aircraft is always maintained in the same country. However, the integrated flight schedule in the discrete-event simulation makes it possible to track where the aircraft is at any given time. The inclusion of temporal effects can therefore be extended with geographical aspects.

The discrete-event LCA described here is suitable to simulate the aircraft's life cycle on an event-based manner and include temporal aspects of environmental impacts. In addition to the dynamisation of the underlying background inventory, the timing of the individual events can also be defined in the discrete-event LCA based on a wide variety of factors. In comparison to existing time-dynamic LCI approaches (e.g., the Python package for time-explicit LCA *bw_timex* [22] or the web-based tool DyPLCA [23]), specific flight or maintenance schedules as well as some condition-based events play a role in modelling. This makes it possible to simulate and change the environmental impact of single events over time. Changes in the overall system can be directly observed by comparison with the reference and thus support decision-making.

The discrete-event simulation does not accumulate emission profiles and their progression. An extension with existing tools, such as the Brightway package *bw_temporalis* [24], which is designed for dynamic LCA, could be a suitable approach for this purpose. In addition to that, prospective assessments for the consideration of new technologies need to be included in the analysis. This can be achieved by incorporating factors such as technological advancements and innovations, which necessitate more comprehensive and granular datasets. Temporal datasets come with inherent limitations and uncertainties, particularly when projecting into the future. However, the incorporation of dynamic inventories helps to address a significant source of uncertainty associated with static approaches, thereby emphasising the importance of temporal considerations in LCA studies.

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