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Procedia CIRP 140 (2026) 461–466

www.elsevier.com/locate/procedia

33rd CIRP Conference on Life Cycle Engineering (LCE 2026)

Applying Discrete-Event Modelling to Enable Spatio-Temporal Life Cycle Assessment in the Aviation Sector

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Abstract

Aviation presents unique challenges for conventional Life Cycle Assessments (LCAs) due to its system complexity, long service lifetimes of aircraft, and highly globalised operations. While methodological approaches exist to account for temporal and spatial variations in Life Cycle Inventories (LCIs), they have been applied to limited extent or low spatio-temporal resolution. In this study, we demonstrate how spatio-temporally resolved datasets and life cycle simulation can be systematically integrated into LCAs for aircraft. For this purpose, we combine discrete-event modelling with the LCA framework, dividing the complex aircraft life cycle into individual events, such as single flights or maintenance activities. Each event is characterised by time and location attributes. In this study, maintenance activities are used as a representative use case to demonstrate the approach by allowing dynamic adaptation based on temporal and spatial factors. Our results show, that the implementation of dynamic LCIs in a discrete-event life cycle simulation framework has the potential to increase the accuracy of environmental assessments of aircraft and other complex technical systems. Such dynamic modelling could be particularly relevant for the application of novel technologies, as their benefits may vary substantially over time and space.

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

1. Introduction

Life Cycle Assessments (LCAs) provide crucial support for decision-makers in complex technical systems [1]. Beyond covering the entire product life cycle, environmental LCA prevent burden-shifting by enabling a complete assessment of environmental impacts across system boundaries and different impact categories. Aviation's complex global operations and long lifetimes cause environmental impacts to vary widely over time and space, which additionally complicates the LCA. As of August 2025, a total of 725 airlines were operating worldwide, serving 3,939 airports [2]. Moreover, deployed aircraft operate in complex patterns including seasonal route adjustments [3], fleet rotations [4], and strict maintenance schedules and regulations [5], which further complicate the accurate assessment of environmental impacts. Regional differences in regulations, energy infrastructures, and operational practices can amplify these variations. These characteristics make aviation an ideal case for exploring the benefits of spatially and temporally accurate LCA, as environmental impacts are highly context-dependent [6].

While dynamic LCAs have already been applied in aviation (addressing temporal aspects such as fleet turnover, technological improvements, or seasonal usage patterns [7–9]), little attention has so far been paid to variations across geographic locations [10,11]. Capturing such dynamics requires methods that explicitly link inventories to both time and place, for example, by incorporating distinct electricity mixes across regions. In this study, we present an approach for the application of spatio-temporal LCA, focusing on aircraft maintenance as a representative use case. Maintenance activities are particularly suitable as they are following a strict

10.1016/j.procir.2026.05.078

schedule across various times and locations and their environmental impacts are strongly influenced by local energy mixes. The method captures not only temporal changes during an aircraft's lifetime, but also variations in Life Cycle Inventories (LCIs) depending on the geographic location of activities. To approximate the impacts of these dynamics more realistically, the life cycle is modelled using a discrete-event life cycle simulation framework.

1.1. Spatio-Temporal Life Cycle Assessment

Although static LCA is still the most commonly used form of environmental analyses, recent methodological developments are focusing increasingly on integrating spatial and temporal aspects. Static approaches are based on long-term temporal and regional averages. This means that dynamic developments, such as changes in the electricity mix, seasonal fluctuations in utilisation, or regional differences in emissions, cannot be adequately mapped. To overcome these limitations, spatio-temporal extensions are being proposed that explicitly link inventory data to location and time [12,13]. The accuracy of environmental assessments can be significantly improved by employing these methods [14]. Next to more accurate overall impacts, regional hotspots and time-dependent processes can be visualised and taken into account for decision-makers. This is important for sectors such as energy supply or aviation, in which both the geographical location and the timing of an activity can have a significant impact on the environment.

While temporal dynamics remain challenging to capture, a key step toward spatio-temporal LCA is the explicit consideration of geographical context, for instance, through computer-based tools such as Geographical Information System (GIS) [15–17]. The main application fields of spatio-temporal LCAs are the building industry, energy systems, and resource use, where the spatial dimension supports the analysis of material flows, electricity demand, and resource distribution. In the building sector, spatially explicit assessments are primarily applied to identify hotspots of Life Cycle Impact Assessment (LCIA) results within urban districts [18,19]. For energy systems, the integration of granular spatial and temporal information enhances the accuracy of electricity generation inventories [20]. Hauschild et al. (2018) [6] highlight how electricity mixes can differ significantly even between neighbouring countries. For instance, Denmark relies mainly on coal and wind power, whereas Sweden's mix is dominated by nuclear and hydropower. Building on this, Jordaan et al. [20] underline the importance of considering grid dynamics at higher temporal resolutions than annual averages (e.g., hourly) to ensure that the efficiency of energy systems is adequately captured.

Despite these advances, spatio-temporally explicit LCAs face several challenges. A major limitation is the availability and quality of spatially and temporally resolved data, which often restricts the scope of such analyses. In addition, the implementation of spatially differentiated characterisation factors remains resource-intensive and is not yet consistently applied across all impact categories [21–23]. Moreover, many studies still focus primarily on greenhouse gas emissions, even though research has shown that effects on other impact categories, such as acidification potential, ozone depletion potential, or photochemical oxidant formation potential are equally important to be considered [8].

1.2. Discrete-Event Life Cycle Simulation Framework

Life cycle simulation is a well-established and widely used approach for dynamically modelling the life cycle of products by tracking the flows of materials, energy, and information over time [24]. In this study, we employ a discrete-event simulation framework to capture spatial and temporal variations of aircraft maintenance. The spatio-temporal LCA is realised with DLR's in-house discrete-event simulation tool Life Cycle Cash Flow Environment (LYFE) [25]. LYFE is a Python-based life cycle simulation framework that models the aircraft lifetime based on dedicated flight plans as well as maintenance schedules. In LYFE, the life cycle of an aircraft is represented as a sequence of events. These events, such as flights, scheduled or unscheduled maintenance activities, or aircraft modifications, are processed chronologically in an event calendar that grows over the aircraft's lifetime. Each event is modelled as an object with specific attributes: all events have a timestamp, duration, and location, while event type-specific attributes capture further details. For flights these are, for example, route information, flight distance, fuel burn, passenger load, etc., and for maintenance they include maintenance type, downtimes, and performed tasks.

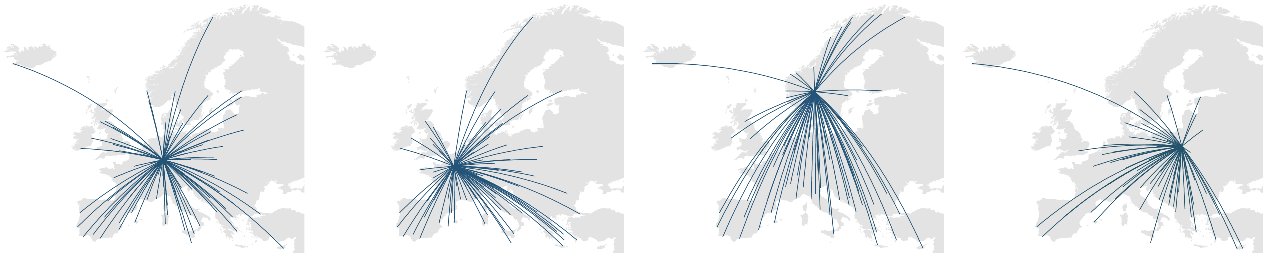
For the present study, this simulation model is further extended towards LCA by assigning environmental impacts to each event based on its parameters in time and space. Specifically, the corresponding national electricity mix of each country in which the event takes place is applied to all maintenance activities, and is updated dynamically for the respective year within the simulation horizon. This enables the integration of spatio-temporal variations into the LCIs while keeping the event-based modelling structure. A more detailed description of the environmental enhancement in LYFE was initially provided in Rahn et al. (2022) [25].

2. Method

Our earlier work addressed the relevant literature and theoretical background [26] and introduced a proof-of-concept integrating dynamic datasets to capture time-dependent effects on maintenance activities [7]. The present study extends this research by additionally incorporating spatial aspects.

2.1. Goal and Scope

As a case study, we perform an environmental assessment of maintenance activities throughout the lifetime of a commercial aircraft in four different hub-and-spoke flight scenarios. Each scenario is based in a different European country and simulates a distinct airline profile. The primary spatio-temporal variation in our datasets is related to the electricity generation, as the energy mix differs substantially between countries. This variation influences maintenance activities, which are highly electricity-dependent and whose effects vary according to which impact category is under consideration [27]. To further illustrate the potentials of spatio-temporal LCA, we compare our outcome with a static and a temporal-dynamic LCA.



(a) Frankfurt Airport (b) Paris Charles de Gaulle Airport (c) Oslo Gardermoen Airport (b) Warsaw Chopin Airport

Fig. 1: Outgoing flight routes from four European airports under different scenarios. Each map shows all flights departing from the respective airport.

The study is exploratory in nature and intended to provide methodological insights for the LCA research community as well as for stakeholders from the aviation industry interested in advanced modelling approaches. The study covers the time horizon from 2025 to 2050. The functional unit is the complete set of Maintenance, Repair, and Overhaul (MRO) activities required to ensure the safe operation of one Airbus A321 aircraft in a hub-and-spoke network over a service lifetime of 25 years. The Environmental Footprint (EF) v3.1, described in Andreasi Bassi et al. (2023) [28], is chosen as LCIA method.

2.2. Maintenance Activities

Although maintenance contributes only a small share to the overall environmental impact of an aircraft, it is indispensable for maintaining the airworthiness and enabling the long-term performance and safety of the aircraft. In innovative aircraft concepts, that are increasingly fuelled by more renewable energy carriers, the shares of the impact might shift towards maintenance activities. MRO activities involve regular inspections ranging from minor daily checks to major overhauls. As these activities need to take place wherever the aircraft is located, they are particularly well-suited to spatio-temporal LCA approaches.

In general, an aircraft undergoes approximately more than 2,000 different maintenance events per year [29]. Routine tasks are performed frequently to address issues reported by flight crews and to keep the aircraft in optimal condition for upcoming flights. More comprehensive inspections and overhauls occur less frequently and often require the aircraft to be taken out of service, typically performed in controlled hangar environments with specialised equipment. In addition, safety-critical components with defined lifetimes, such as engines, are overhauled in workshop facilities, while the aircraft may receive replacement components to continue its service during this period.

Our earlier work indicated that electricity demand accounts for more than 65% of the Global Warming Potential (GWP) of all maintenance activities [29]. MRO processes rely not only on electricity to operate the hangar or maintenance equipment, but also on the exchange of spare parts, whose production lies outside the MRO process. The analysis considers the country-specific energy mix for all maintenance activities to reflect regional variations in electricity generation.

2.3. Scenario Description

In this study, four scenarios are defined, each representing one aircraft operating in a hub-and-spoke network with a dedicated home base. These home bases are:

- Frankfurt Airport (FRA), Germany
- Paris Charles de Gaulle Airport (CDG), France
- Oslo Gardermoen Airport (OSL), Norway
- Warsaw Chopin Airport (WAW), Poland

Figure 1 shows the four different operated flight networks for each scenario. The flight schedules are based on FlightRadar24 data of operators having their base at the respective airports. Maintenance activities are allocated either to the main base or, for minor tasks, to other airports within the network. In total, 38 countries are covered by more than 600 flight routes. It is assumed that each aircraft returns to its main base after every flight. Over the 25-year study horizon, we assume that all flight routes are distributed evenly.

Each scenario is examined through three separate simulations. Figure 2 presents a schematic of the simulation set-up, including the variations in temporal and geographical input data.

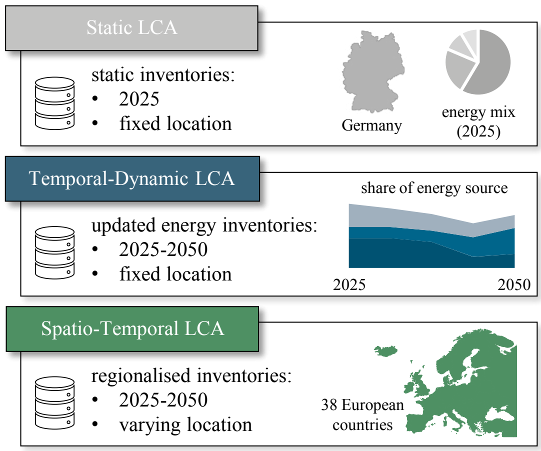


Fig. 2: Climate change impacts of a daily maintenance check at different European airports in the year 2025.

First, a *static LCA* is performed, in which no changes in the inventories occur over the aircraft's lifetime. In this case, all datasets are fixed to the reference year 2025, and maintenance is consistently assumed to take place in the same country, i.e., at the respective main base.

The second simulation is a *temporal-dynamic LCA* and is based on Rahn et al. (2025) [7]. The location remains the same for all maintenance activities, but the country's energy mix in the inventory is updated on a yearly basis. This yearly update directly influences the LCIA results of the MRO activities.

Finally, a location-dependency is further integrated within the *spatio-temporal LCA* set-up. Besides the changes of energy mix over time, it is additionally taken into account where the aircraft actually is. For instance, line maintenance tasks may occur at various airports along the aircraft's route (e.g., at Frankfurt Airport in 2025, which would be linked to the corresponding German energy mix of that year). If, subsequently, the aircraft flies to Paris Charles de Gaulle Airport and undergoes maintenance there, the inventory is instead based on the French energy mix. In contrast, larger scheduled checks, such as base maintenance, are typically concentrated at the airline's main base or designated maintenance facility, where the respective local energy mix is applied.

2.4. Generation of the LCI

The backbone of this study is the time- and location-dependent energy datasets. The share of different electricity sources ranges from renewables (wind, photovoltaic, or hydro) to fossil and nuclear energy. The energy mix data and forecasts for the next 25 years were obtained from the GENeSYS-MOD 2.9 database with the Directed Transition 1.0 scenario for 29 European countries [30]. Since the GENeSYS-MOD 2.9 database only provides projected energy mixes in 5-year increments, the intermediate years were extrapolated. For countries not covered by the GENeSYS-MOD 2.9 database, information from literature was used.

The foreground datasets were modelled using the ecoinvent database 3.11 with the cut-off by classification system model. In ecoinvent, all datasets are already allocated to specific locations. When a dataset for a given energy source in a particular location was not available, a proxy from a neighbouring country was applied. These energy datasets subsequently influence the inventories for maintenance activities. The maintenance inventory was taken from Rahn et al. (2024) [29]. All datasets contain electricity and were implemented in a modular structure, enabling direct replacement of the energy datasets during the life cycle simulation in LYFE.

3. Results

Due to differing national conditions and energy policies, energy mixes vary significantly across European countries, which in turn influence the resulting environmental impacts. Figure 3 presents a map of Europe showing all airports included in the applied flight networks. The colours indicate the environmental impact of performing a daily check in the year 2025 at each respective airport. Green shades represents a relatively low GWP per check (approximately 50 kgCO_2-eq.), whereas blue and purple shades indicate higher impacts resulting from more carbon-intensive energy mixes.

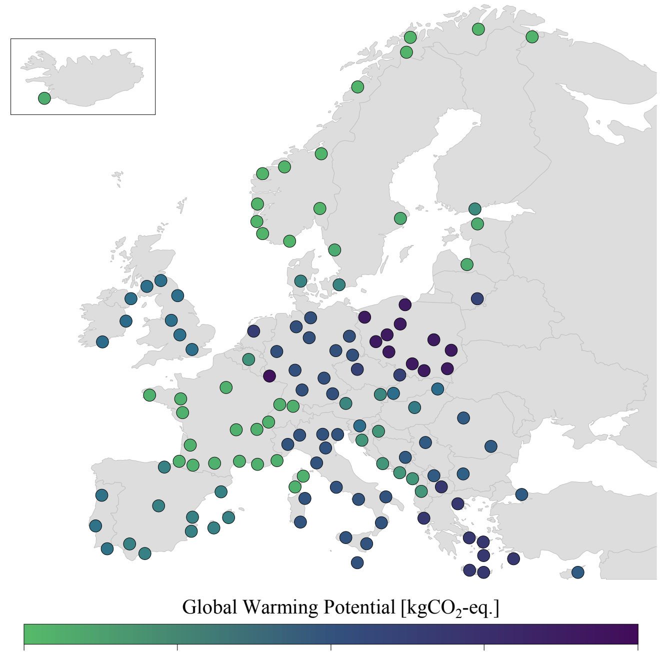


Fig. 3: Climate change impacts of a daily maintenance check at different European airports in the year 2025.

Over the course of the simulation horizon, the share of renewable energy sources increases in each country. This development directly affects the environmental impact of maintenance activities. By 2050, the climate change impact of energy production is on average 34% lower compared to 2025.

The simulation results in terms of GWP for all maintenance activities with the three simulation set-ups are presented in Figure 4. For the four flight schedule scenarios, the results of the *static*, *temporal-dependent*, and *spatio-temporal LCAs* are shown. In the *static LCA*, the total climate change impacts differ considerably depending on the main hub location. The OSL and CDG scenarios show the lowest impacts, with around 1,250 tCO_2-eq. over the entire aircraft lifetime. This can be explained by the already low-carbon energy policies in Norway and France. Norway's electricity mix is largely based on hydropower, while the French mix contains a high share of nuclear energy (which is not defined as renewable, but still associated with very low carbon emissions). In contrast, the 2025 Polish energy mix (represented in the static WAW scenario) is highly dependent on fossil fuels, leading to climate change impacts that are, for instance, more than 70% higher than in France.

When *temporal* aspects are included (blue bar), major changes can be observed, especially for the WAW and FRA scenarios. Even though the location of every maintenance check remains the same, the evolving energy mix over time strongly affects the climate change results. In the WAW scenario, incorporating temporal dynamics leads to a 31.5% difference in outcome. For Germany (FRA), this corresponds to 23.2%. In France (CDG) and Norway (OSL), the effects are negligible, as the potential for further carbon reduction in their energy mixes is limited.

Incorporating additional geographical aspects (green bar) shows both under- and overestimations compared to the previous approaches. In countries with a comparatively climate-friendly energy mix, the assumption that maintenance takes place exclusively in one country leads to a slight underestimation of the overall climate change impacts, as in the cases of France and Norway. Although the majority of maintenance checks are carried out at the main hub, in reality some are also performed at airports in other countries, where more carbon-intensive energy mixes can lead to higher impacts. In the WAW scenario, on the other hand, the static approach tends to overestimate the impact, since the aircraft also flies to airports with lower energy impacts.

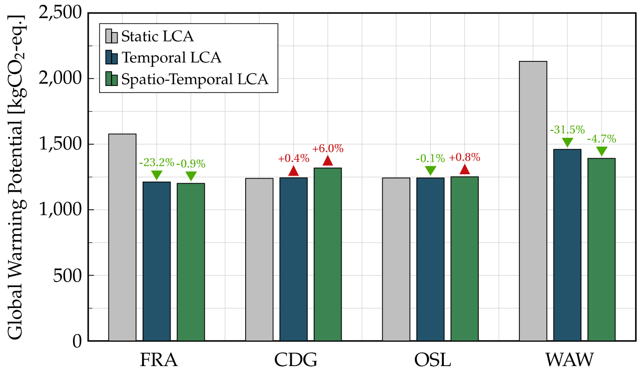


Fig. 4: Overview of the total GWP for all maintenance activities after 25 years. The numbers above each bar indicate the relative deviation compared to the preceding bar: negative values correspond to lower impacts, while positive values indicate higher impacts.

In addition to climate change impacts, ionising radiation and water use were assessed as relevant complementary impact categories. Both show strong dependencies on the underlying national energy mix and therefore provide important insights for the overall LCA results. Ionising radiation is primarily driven by nuclear energy, whereas water use is influenced by hydropower and thermal or nuclear plants. The supplementary material of this article contains the complete set of LCA results for all impact categories on an annual basis.

4. Discussion

The results of this study demonstrate that temporal and spatial aspects can substantially influence estimated environmental impacts, particularly when compared to commonly used static assessments. The following discussion explores these effects in detail and considers their implications for both methodology and practice.

A central aspect of this study is the methodological approach used to incorporate temporal and spatial dimensions into the aviation LCA. The assessment was performed using the discrete-event simulation framework LYFE, with input data from FlightRadar24, the GENeSYS-MOD 2.9 database, and the ecoinvent database. While the simulation model provides a flexible framework for evaluating maintenance-related energy consumption across different countries over time, it is not without limitations. For several countries and years, energy mix data were missing in the GENeSYS-MOD 2.9 database. Consequently, approximations from neighbouring countries and for years with missing data were necessary. Moreover, energy forecasts are widely debated, and every scenario relies on a set of assumptions. These assumptions introduce uncertainty, particularly for countries with highly carbon-intensive or rapidly evolving energy systems. Prospective datasets introduce additional uncertainty, which can result in a reduction of reliability and accuracy in the LCA results. Nevertheless, they are imperative for the representation of dynamic future system changes, which static data is unable to represent.

The temporal and spatial granularity of the model influences the assessment results. In this study, energy mix changes are introduced on an annual basis and regional variations within countries are not captured. Increasing temporal or spatial resolution could reveal additional patterns but would require substantially more data and computational effort. The modular structure of LYFE allows energy datasets to be replaced at any point in the simulation. As each event stores its own attributes on time and location, LYFE enables the change of background energy data for individual analyses. This is especially relevant for energy sources like photovoltaics, for which differences between day and night could provide further insights. Beyond energy mix dynamics, future studies could also incorporate spatio-temporal variation in other datasets. One example is the location-dependent supply of critical raw materials, such as titanium, which may be influenced by geopolitical factors [31].

The new spatio-temporal assessment of this study further highlights the importance of considering all impact categories. Ionising radiation and water use are particularly sensitive to the energy mix, as nuclear and thermal power generation dominate these categories. This highlights that spatio-temporal effects can vary significantly across impact categories. Solely focusing on GWP may lead to misinterpretation of results and hidden burden-shifting effects. Finally, we find that the transferability of the model to other industrial sectors depends on the availability of high-quality data. For non-stationary use cases, such as other modes of transport, a spatio-temporal approach can reveal important insights.

5. Conclusion and Outlook

In this study, we analysed the effect of integrating spatial and temporal aspects into LCA in aviation. Especially in our chosen use case, which is characterised by long operational lifetimes of aircraft, high utilisation profiles, and global/intercontinental operations, the potential benefits of incorporating spatially-resolved inventories are very promising. Neglecting both temporal and geographical aspects can lead to significant under- or overestimations. Although maintenance activities contribute less to the overall environmental impact compared to flight operations, they remain relevant from a life cycle perspective.

Future aviation-related LCA studies should consider including these aspects, despite the considerable effort required to develop more spatially and temporally detailed LCIs. This becomes particularly important when other life cycle phases are modelled with spatio-temporal detail, as this can significantly impact the accuracy and validity of the results. The production of power-to-liquid fuels, for example, is highly dependent on the energy mix, therefore its impacts will significantly change over time. Similarly, novel aircraft concepts that are hydrogen-powered or fly with electric propulsion rely a lot more on the changing energy mix. Hence, decision-making that strives to achieve net-zero aviation needs the insights of a spatio-temporal approach that better reflects changing systems and complexity.

References

[1] M. Jegen, Life Cycle Assessment: From Industry to Policy to Politics, The International Journal of Life Cycle Assessment 29 (2024) 597–606. https://doi.org/10.1007/s11367-023-02273-8.

[2] OAG Aviation Worldwide Limited, Airline Frequency and Capacity Statistics, 2025.

[3] F. Dobruszkes, J.-M. Decroly, P. Suau-Sanchez, The Monthly Rhythms of Aviation: A Global Analysis of Passenger Air Service Seasonality, Transportation Research Interdisciplinary Perspectives 14 (2022) 100582. https://doi.org/10.1016/j.trip.2022.100582.

[4] L. Clarke, E. Johnson, G. Nemhauser, Z. Zhu, The Aircraft Rotation Problem, Annals of Operations Research 69 (1997) 33–46. https://doi.org/10.1023/A:1018945415148.

[5] R. Meissner, A.A. Pohya, O. Weiss, D. Piotrowski, G. Wende, Regulatory Pathways to Certifiable Condition Based Maintenance Solutions in Aviation: A Comprehensive Review, Progress in Aerospace Sciences 158 (2025) 101143. https://doi.org/10.1016/j.paerosci.2025.101143.

[6] M. Hauschild, R. Rosenbaum, S.I. Olsen, Life Cycle Assessment: Theory and Practice, Springer International Publishing, Cham, Switzerland, 2018.

[7] A. Rahn, J. Koffler, A. Oestreicher, G. Wende, Integrating Time-Dependent Electricity Datasets into Discrete-Event Life Cycle Assessment for Aircraft, Procedia CIRP 135 (2025) 966–971. https://doi.org/10.1016/j.procir.2024.12.135.

[8] R. Sacchi, V. Becattini, P. Gabrielli, B. Cox, A. Dirnaichner, C. Bauer, M. Mazzotti, How to Make Climate-Neutral Aviation Fly, Nat. Commun. 14 (2023) 3989. https://doi.org/10.1038/s41467-023-39749-y.

[9] F. Field, R. Kirchain, J. Clark, Life‐Cycle Assessment and Temporal Distributions of Emissions: Developing a Fleet‐Based Analysis, Journal of Industrial Ecology 4 (2000) 71–91. https://doi.org/10.1162/108819800569816.

[10] D. Keiser, L.H. Schnoor, B. Pupkes, M. Freitag, Life Cycle Assessment in Aviation: A Systematic Literature Review of Applications, Methodological Approaches and Challenges, Journal of Air Transport Management 110 (2023) 102418. https://doi.org/10.1016/j.jairtraman.2023.102418.

[11] L. Rupcic, E. Pierrat, K. Saavedra-Rubio, N. Thonemann, C. Ogugua, A. Laurent, Environmental Impacts in the Civil Aviation Sector: Current State and Guidance, Transportation Research Part D: Transport and Environment 119 (2023) 103717. https://doi.org/10.1016/j.trd.2023.103717.

[12] N. Rogy, A. Pastor, A. Sferratore, N. Géhéniau, A. Hélias, E. Loiseau, Taking the Spatio-Temporal Effects of Climate Change into Account for Life Cycle Assessment of Prospective Scenarios to Secure Water Supplies in Agricultural Areas, Sci. Total Environ. 915 (2024) 169345. https://doi.org/10.1016/j.scitotenv.2023.169345.

[13] X. Wang, B. Huang, X. Zhang, Q. Liu, Y. Wang, Y. Long, From Waste to Carbon Benefits - A Dynamic Spatiotemporal Model for Assessing Carbon Reduction Potential in Urban Concrete Recycling Systems, Resources, Conservation and Recycling 224 (2026) 108538. https://doi.org/10.1016/j.resconrec.2025.108538.

[14] Y. Yi, J. Wu, F. Zuliani, M.C. Lavagnolo, A. Manzardo, Integration of Life Cycle Assessment and System Dynamics Modeling for Environmental Scenario Analysis: A Systematic Review, Sci. Total Environ. 903 (2023) 166545. https://doi.org/10.1016/j.scitotenv.2023.166545.

[15] S. Shi, X. Yan, A Critical Review on Spatially Explicit Life Cycle Assessment Methodologies and Applications, Sustainable Production and Consumption 52 (2024) 566–579. https://doi.org/10.1016/j.spc.2024.11.015.

[16] M. Hiloidhari, D. Baruah, A. Singh, S. Kataki, K. Medhi, S. Kumari, T. Ramachandra, B. Jenkins, I.S. Thakur, Emerging Role of Geographical Information System (GIS), Life Cycle Assessment (LCA) and Spatial LCA (GIS-LCA) in Sustainable Bioenergy Planning, Bioresour. Technol. 242 (2017) 218–226. https://doi.org/10.1016/J.biortech.2017.03.079.

[17] M. Kaita, S. Harun, Application of Integrated LCA-GIS Model in the Agricultural Sector: A Brief Overview, IOP Conf. Ser.: Earth Environ. Sci. 1167 (2023) 12015. https://doi.org/10.1088/1755-1315/1167/1/012015.

[18] S. Abu Dabous, A. Shanableh, R. Al-Ruzouq, F. Hosny, M.A. Khalil, A Spatio-Temporal Framework for Sustainable Planning of Buildings Based on Carbon Emissions at the City Scale, Sustainable Cities and Society 82 (2022) 103890. https://doi.org/10.1016/j.scs.2022.103890.

[19] T. Mao, Y. Liu, Y. Liu, M. Hao, W.-Q. Chen, Towards Sustainable Building Landscapes: A Spatially Explicit Life-Cycle Analysis of Carbon Emissions and Mitigation Strategies, Landscape Ecology 39 (2024). https://doi.org/10.1007/s10980-024-01953-6.

[20] S.M. Jordaan, C. Combs, E. Guenther, Life Cycle Assessment of Electricity Generation: A Systematic Review of Spatiotemporal Methods, Advances in Applied Energy 3 (2021) 100058. https://doi.org/10.1016/j.adapen.2021.100058.

[21] A. Koyamparambath, P. Loubet, S.B. Young, G. Sonnemann, Spatially and Temporally Differentiated Characterization Factors for Supply Risk of Abiotic Resources in Life Cycle Assessment, Resources, Conservation and Recycling 209 (2024) 107801. https://doi.org/10.1016/j.resconrec.2024.107801.

[22] K. Vasilakou, P. Nimmegeers, Y. Yao, P. Billen, S. van Passel, Global Spatiotemporal Characterization Factors for Freshwater Eutrophication under Climate Change Scenarios, Sci. Total Environ. 959 (2025) 178275. https://doi.org/10.1016/j.scitotenv.2024.178275.

[23] N. Engberg, C. Blanco, V. Barbarossa, C. Bakker, R. Balkenende, J. Lian, B. Sprecher, Forecasting Future States of the Environment with Machine Learning - A Case Study on Water Scarcity, Journal of Industrial Ecology (2025).

[24] Y. Matsuyama, S. Fukushige, Y. Umeda, Simulating Life Cycles of Individual Products for Life Cycle Design, Procedia CIRP 38 (2015) 159–164. https://doi.org/10.1016/j.procir.2015.08.025.

[25] A. Rahn, K. Wicke, G. Wende, Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment, Sustainability 14 (2022) 10598. https://doi.org/10.3390/su141710598.

[26] A. Rahn, K. Wicke, G. Wende, A Comparison of Temporally Dynamic Life Cycle Assessment Methods for Ecological Evaluation in Aviation, Procedia CIRP 116 (2023) 149–154. https://doi.org/10.1016/j.procir.2023.02.026.

[27] J. Albano, A. Rahn, J. Bachmann, G. Wende, Life Cycle Inventories for Aviation: Background Data, Shortcomings, and Improvements, Cleaner Engineering and Technology 22 (2024) 100813. https://doi.org/10.1016/j.clet.2024.100813.

[28] S. Andreasi Bassi, F. Biganzoli, N. Ferrara, A. Amadei, A. Valente, S. Sala, F. Ardente, Updated Characterisation and Normalisation Factors for the Environmental Footprint 3.1 Method, Luxembourg, Luxembourg.

[29] A. Rahn, M. Schuch, K. Wicke, B. Sprecher, C. Dransfeld, G. Wende, Beyond Flight Operations: Assessing the Environmental Impact of Aircraft Maintenance Through Life Cycle Assessment, Journal of Cleaner Production 453 (2024) 142195. https://doi.org/10.1016/j.jclepro.2024.142195.

[30] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, C. von Hirschhausen, Designing a Model for the Global Energy System - GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS), Energies 10 (2017) 1468. https://doi.org/10.3390/en10101468.

[31] T. Hoff, B. Sprecher, A.A. Pohya, G. Wende, D. Peck, The Impact of Circular Strategies on Titanium Supply and Demand in the Aviation Industry, Resources, Conservation and Recycling 222 (2025) 108476. https://doi.org/10.1016/j.resconrec.2025.108476.