Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 116 (2023) 149–154

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference

A Comparison of Temporally Dynamic Life Cycle Assessment Methods for Ecological Evaluation in Aviation

Antonia Rahn[a,*], Kai Wicke[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 2489641-150. *E-mail address:* antonia.rahn@dlr.de

---

Abstract

Most Life Cycle Assessments (LCAs) in aviation are static and do not adequately reflect the long life cycles of aircraft and associated temporal impacts of emissions. However, these temporal aspects will become more important in the future, as the concept of freedom in the climate crisis is now joined by a revolutionary factor, which states that the timing of certain emissions and their consequences will play an increasingly important role in the assessment of aircraft. There are various dynamisation methods that can extend classical LCAs. A literature review including a list of benefits and limitations should provide information on which dynamic methods are particularly suitable for aviation. Especially in the aviation sector, the dynamic life cycle inventory offers great potential for mapping and evaluating the operational life of an aircraft in more detail. A thorough examination, for example with the help of a discrete-event simulation, can therefore offer the possibility of significantly improving the accuracy and quality of the LCA results and thus generate more extensive insights into the ecological impact of aircraft.

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

---

1. Introduction

In the context of the current climate debate, the risk of resource and water scarcity, increasing amounts of waste, air pollution, and global warming are frequently mentioned. A growing environmental awareness both in politics and in society is thus indispensable for implementing innovative solutions and is an essential criterion in the development, approval, and acceptance of new technologies. Air transportation in particular has become the focus of attention, as it is an important part of our globalised and modern world, but also contributes a relatively large share to the anthropogenic greenhouse effect. Despite the technological developments in improving efficiency, which will continuously reduce the average fuel consumption per flown passenger kilometre, aircraft emissions (in particular carbon dioxide (CO_2), nitrogen oxides (NO_X), and water vapour) are a major contributor to climate change. They are emitted into sensitive areas of the atmosphere during flight [1] and in some cases have very long residence times in the atmosphere, which can have major influences on decadal time scales [2]. Furthermore, there are several ground activities, such as regular maintenance and overhaul of aircraft, which cause high energy consumption on the ground. In the future, it will thus become increasingly important to design and evaluate aircraft not only in terms of their direct operating costs but also based on their environmental impact and its consequences.

A so-called Life Cycle Assessment (LCA) can be applied to assess the environmental impact throughout the aircraft life cycle and to identify key ecological drivers. LCA is described in ISO 14040 [3] and 14044 [4] and provides information on the environmental performance of a product taking into account its entire life cycle - from manufacturing to the end-of-life. The operational phase of aircraft is of particular interest, as aircraft have very long service lives of around 20 to 30 years and at the same time a high utilisation rate of up to ten flight hours per day [5]. These and the associated complex interactions between flight and maintenance events could make an additional extension of conventional LCA with temporally dynamic aspects reasonable to include long-term effects alongside the static results.

In the existing literature, no such temporal dynamics could be found in the field of aviation. However, there are numerous different approaches to implementing and executing time-dependent aspects in conventional LCA from other technology areas. Most studies that address that issue deal with application examples in the building [6–8] and energy sector [9–11]. Build-

10.1016/j.procir.2023.02.026

ings are particularly interesting for temporal aspects, as they have very long lifetimes and thus introduce time-dependent effects, such as technological processes or delayed emissions, which can be well covered within a time-induced LCA [12]. In the energy sector, the advantage is that a lot of data is already available on conventional energy networks, which can often change in the course of a single day (e.g., intermittent renewable energy sources or varying energy consumption in industry and private households). This allows temporal changes down to an hourly time resolution to be assessed and analysed. Furthermore, a large amount of historical energy data can be adapted to future scenarios, thus enabling prospective LCA. In addition, use cases that consider different end-of-life scenarios provide good requirements for the inclusion of temporal aspects, as these can often be assessed for centuries after the considered product system has reached the end of its life [13, 14].

Despite the lack of publications in the field of aviation, there are some parallels that can be transferred from the existing literature. On top of the long life cycles of aircraft, the impact of different end-of-life scenarios is becoming increasingly important due to the growing number of ageing aircraft [15]. The high residence time of emissions in the atmosphere, especially CO_2 emissions, causes additional impacts that may last for decades or even centuries to come. In addition, flight and maintenance schedules already provide a useful benchmark for temporal analysis with high resolution, existing timestamps, and data availability, similar to that of energy systems. For these reasons, applying temporal aspects to the environmental assessment of aircraft can be a good way to introduce additional complexity and increase the understanding of dynamic interconnections.

This paper therefore addresses the extension of conventional LCA methods to allow a detailed consideration of the aircraft operational phase, especially over such long lifetimes. In particular, existing temporal dynamic approaches are to be evaluated and compared for the application in aviation. The remainder of this paper is divided into four sections. First, a general overview of existing time-dynamic LCA methods is given in Section 2. A comparison of the respective advantages and disadvantages will show which are particularly suitable for the application to aircraft. Subsequently, a case study from aviation will be used in Section 3 to show how and whether these dynamic methods can be adapted to aircraft, using the wash of a jet engine as an example. In Section 4, a possible approach for implementing the findings in a real simulation framework is briefly described and finally, the results of this work are summarised and conclusions are drawn.

2. Dynamic Life Cycle Assessment

This section will first show which temporal aspects exist in the field of LCA and how they can be implemented. A common keyword when researching temporal aspects in LCA is the term Dynamic Life Cycle Assessment (DLCA). Collinge et al. [16] describe a DLCA as an approach that takes into account temporal and spatial variations in industrial and environmental systems. DLCA is thus a suitable method for the dynamic implementation of environmental impact assessments, although no unified definition exists to date.

Within a review by Lueddeckens et al. [17], six dynamic approaches that could introduce a temporal component into the traditional LCA were identified, namely time horizon, discounting, temporal resolution of the inventory, time-dependent characterisation, dynamic weighting, and time-dependent normalisation. These six approaches each act in one of the four steps of a classic LCA (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation) and can be assigned accordingly. The authors conclude with a consensus that temporal aspects in LCA, especially temporally differentiated inventories and time-dependent characterisation, can significantly increase the accuracy of the assessment. However, a better understanding as well as the inclusion of sensitivity analyses are crucial for a further improvement in dynamic aspects.

Figure 1 illustrates the set-up of a classical LCA. The temporal methods summarised by Lueddeckens et al. are attached to the corresponding steps. For instance, the time horizon is defined in the goal and scope definition before the actual assessment, whereas the dynamisation of the inventory accordingly occurs during the compilation of the life cycle inventory. The dynamic characterisation takes place during the calculations in the life cycle impact assessment and the interpretation, which is performed after the assessment, allows for additional dynamisation in the form of dynamic weighting or interpretation.

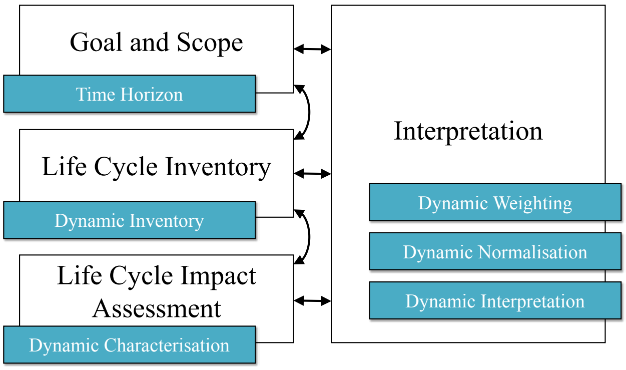

Fig. 1. The four steps of an LCA with possible temporal dynamisation aspects.

In the following, the temporally dynamic approaches are described as part of their corresponding LCA phase. A short literature review will describe the application as well as the advantages and disadvantages.

Dynamic Goal and Scope

The goal and scope phase of an LCA serves to determine an appropriate time horizon for the assessment, alongside the system boundaries, the functional unit, and limitations as well as assumptions. According to Dyckhoff and Kasah [18], choosing a suitable and sophisticated time horizon is a challenge. A distinction must be made between whether the time horizon should cover the duration of the product life cycle, the duration of the inventory modelling, or the duration of the impact assessment. Typical time horizons are identified by the Intergovernmental Panel on Climate Change (IPCC) as 20, 100, and 500 years [19]. Short time horizons emphasise the short-term processes of climate change with the risk that the ecological impacts are overestimated, while long time horizons tend to focus on the long-term processes and can lead to an underestimation [17]. The selection of an appropriate time horizon influences the calculation and interpretation of the results, but not the assessment process itself. For this reason, the choice of a time horizon is mainly dependent on the LCA practitioners and their application case, which is why it already takes part in the beginning of the assessment. In most studies, a time horizon of 100 years is chosen based on an informal 100-year standard, as defined in ISO standard 14067 on carbon footprinting and the Kyoto Protocol [20].

Dynamic Life Cycle Inventory

The subsequent inventory analysis is the most time-consuming part of an LCA, in which all processes that belong to the product system and information on resource inputs and emissions is collected. The result of the inventory analysis is called the Life Cycle Inventory (LCI). A very frequently used dynamisation option is the introduction of Dynamic Life Cycle Inventory (DLCI). A DLCI is performed by collecting temporally differentiated data at each point in time. Therefore, the life cycle of a product is divided into small time steps or segments and simulated based on, e.g., historical data or prospective simulations of future developments and scenarios [7]. However, creating such a dynamic inventory can be very time-consuming for the practitioner. Not only is it necessary to collect a lot of information (on background and foreground processes), but also to consider certain temporal aspects in order to place them in the timeline of a product's life cycle. For this reason, Collinge et al. [16] claim, that there is a method deficiency because the duration and timing of the process units are not always known.

One time-distributed LCI is mentioned by Collet et al. [21], who divided the impact categories of an LCA study into different time scales and only considered the most relevant and contributing processes in terms of time. Other studies use special dynamic tools, such as the temporalis tool [22], which is implemented as part of the open-source framework Brightway2, or the web-based tool DyPLCA developed by Pigné et al. [23], which takes a first step towards the temporal distribution of LCIs, but only for certain processes or life cycle phases. Filleti et al. [24], for instance, used the DyPLCA tool to conduct an LCA for the case study of a grinding machine and were able to see large differences in electricity and water consumption as well as in environmental impacts when compared to static approaches. Beloin-Saint-Pierre et al. [25] proposed an Enhanced Structural Path Analysis (ESPA) method that is able to assign time stamps to the respective entries of the inventory. An additional temporal information of the unit processes in the LCI database allows a very accurate ecological assessment, even if the large additional effort of collecting temporal LCI is not justified for every type of LCA study and must be decided on an individual basis [26].

Dynamic Life Cycle Impact Assessment

Another dynamic possibility is to apply dynamic characterisation factors within the Life Cycle Impact Assessment (LCIA). During the LCIA, the environmental impacts are assessed based on the collected LCI data. In this process, the inputs and outputs of the inventory are assigned to different impact categories. The dynamic characterisation factors are strongly dependent on the time horizon and change the sensitivity of the ecosystem over time. This means that emissions early in the life cycle are given higher weighting due to their decay characteristic than emissions near the end of the considered time horizon [17].

Levasseur et al. [27] have developed a dynamic carbon footprint calculator named dynCO2, which allows the calculation of greenhouse gas emissions for specific time periods in terms of radiative forcing. The radiative forcing determines the change in the Earth's atmospheric energy budget due to the changing effect of radiation from space [28]. This change is caused, for example, by emissions of CO_2, NO_X, or water vapour (H_2O), whose temporal profiles can be considered using the aforementioned approach, so that the result of LCA for each emission is a function of time rather than a single value. However, the use of dynamic characterisation is very time-dependent and requires the application of multiple temporal horizons for a holistic assessment. Despite the emergence of new perspectives that can be given by the dynamic characterisation factor, especially for long life cycles, it is important that this dynamic method transparently maps the sensitivities of different temporal assumptions. Furthermore, time-dependent characterisation is primarily limited to Global Warming Potential (GWP) and toxicity [7] and entails a lot of uncertainties which makes a comparison with static results very difficult [29].

Dynamic Interpretation

In the fourth and final step, all questions from the goal and scope are answered in order to formulate conclusions and recommendations. In addition, important questions from the other phases are identified and evaluated in terms of their influence on the overall result. Here, several dynamic approaches can be assigned. The dynamic interpretation depends solely on the users' perception and includes, for example, the choice and consideration of the time horizon as well as the considered lifetime.

According to Yuan and Dornfeld [30], the longer the life of a product, the higher the uncertainty on the time scale. This is mainly due to the unpredictability of technological advancements or to unforeseeable political measures that, for example, prescribe certain actions or restrict processes. In order to include this effect in the calculation, a so-called weighting or discounting can be introduced. With dynamic weighting (and very similar dynamic normalisation), the emissions are calculated on a time scale for each year. In contrast to the real emission trajectories, which are considered as a function over time in the case of dynamic characterisation, an absolute value of the emission is assumed and weighted using an annually defined discount rate. This is done according to the principle that the ecological impacts that occur earlier are "more important" than those that occur later [7]. The discount rate thus increasingly lowers the weighting factor for emissions further in the future and represents the probability of an emission reduction technology.

According to Lueddeckens et al. [31], the choice of an appropriate discount rate has a very high impact on the final result, as for instance a too high discount rate can lead to an underestimation of the environmental impact and further harm the environment [30]. Frequently used discounting rates in the literature are often between 1-10 % [30–32], however, the usefulness of a discount rate and whether this rate should be time-dependent must be discussed in detail depending on the specific use case [7]. Fearnside [33], for example, proposes an approach called generations weight index, which lowers the discount rate after each generation. It might also be useful to create a model that reflects the real behaviour of life cycle emissions in the environment, a so-called environmental degradation mechanism [34]. Due to the general lack of consensus on existing dynamic weighting and normalization factors, the introduction of, e.g., discount rates leads to a number of further uncertainties that, in the worst case, trivialise the actual environmental impacts. Therefore, the application of a dynamic weighting or discounting is still a controversial issue in the field of LCA [35].

These identified and described dynamic approaches represent a very first selection and can be integrated either individually or in combination within an LCA. In the literature review conducted by Sohn et al. [36], an additional distinction was therefore made between *full DLCA* and *partial DLCA*. In full DLCA, time-induced changes are incorporated throughout all four steps of the assessment. However, the majority of observed DLCA studies are limited to selected dynamisation aspects in usually only one phase of the LCA, which is why they are referred to as partial DLCA.

3. Applicability in Aviation

To evaluate the application of the dynamic approach in aviation and to see which methods are most appropriate, a theoretical use case of a jet engine wash is presented. The maintenance event of an engine wash is carried out by the operator at regularly scheduled intervals, and leads to an improved engine performance and thus to lower fuel consumption on subsequent flights. By regularly cleaning the engine, it is possible to eliminate engine wear and reduce fuel consumption by up to 1.2 %. A detailed description of the engine wash process, also with regard to the ecological impact and saved emissions, can be found in the publication by Rahn et al. [38].

To assess the environmental benefits of these engine wash processes, it makes sense to consider the entire life cycle of an aircraft. The choice of the appropriate time horizon of the study is made in the first phase of the LCA and can be determined by the practitioner. Since most studies dealing with LCA in aviation choose a time horizon of 100 years, e.g., in the form of the GWP 100, a comparison with other literature sources is therefore easiest and recommended.

The operating plan of an aircraft lists all performed and planned flights and maintenance events and thus indicates exactly at what time the aircraft was at which location. Based on these individual time stamps, it is thus possible to specifically track when, for example, an activity with negative ecological impacts took place or emissions were emitted. This already lays the foundation for the LCI's dynamisation of the study. The total environmental impact of an aircraft can thus be determined at any point in its life cycle by calculating the sum of all events that have occurred up to that point. In the case of the engine wash, it is thus possible to determine at which time the engine wash (and thus the resulting ecological impact, e.g., due to the equipment required or the contaminated water) is carried out and which flights are subsequently affected by improved fuel performance. Detailed evaluations and decision-making analyses, e.g., whether the engine wash is reasonable, can thus be carried out more easily and the effects can be mapped over time.

The use of a DLCI has the additional advantage that dynamic characterisation or weighting can be applied more easily. Dynamic characterisation offers many advantages that might be of importance in the field of aviation. Numerous emissions are released during flight as well as on the ground, which have different effects on the environment. The assessment of the residence time of these emissions could provide useful insights for comparing, e.g., different fuel types with each other. For the implementation of dynamic characterisations, a large number of aspects is therefore important, which requires expert knowledge in the field of atmospheric physics. For each individual flight, the emissions can thus be viewed individually and over time. In the case of the engine wash, the relatively small changes in fuel consumption per flight can thus also be analysed over a longer period of time to observe long-term and secondary effects. Similarly, discounting functions are already used in economic calculations, e.g., in life cycle cost models in aviation that reflect annual changes in the value of cash flow [39]. The introduction of an annual discount rate in LCA can be easily implemented with the help of the aforementioned DLCI and would mitigate the ecological value in a similar way as in economic assessments. However, as mentioned above, there is no consensus among experts on whether environmental discounting is morally justifiable, as it tends to pursue policy targets and does not take into account the true environmental impact. For a successful and conscientious application, dynamic weighting functions need to be further investigated.

Using the example of engine wash, it could thus be shown that aviation is an excellent example for dynamic temporal extensions of classical LCA and that, under certain conditions, all of the identified dynamisation methods can be applied. Different effects can be observed at certain points in the lifetime, which has many advantages compared to existing LCA studies in the literature, that often only use static environmental assessments with average values per year or lifetime. In addition, the complex interaction of flights and maintenance events is particularly interesting, as they are not only highly interdependent in time, but can also influence each other, which is sometimes only measurable when looking at long-term impacts.

4. Future Work

An initial realisation of an DLCA has already been successfully implemented at the DLR Institute for Maintenance, Repair and Overhaul. We started with the dynamisation of the inventory, because, as mentioned above, flight and maintenance schedules already provide optimal dynamic framework conditions. Our DLCI is based on a discrete-event simulation which, with the help of the imported operating plans, generates a series of different events, each of which is assigned a discrete point in time during a simulation. In this way, the entire life cycle can be simulated and broken down into individual small intermediate steps, which can then be evaluated in detail. A production event at the beginning of the simulation and an end-of-life event at the end complete the aircraft life cycle simulation. The resulting event calendar contains (depending on the simulated lifetime) thousands of individual events, which can then be evaluated individually from an ecological point of view.

For a time-saving and efficient calculation, the LCA is calculated based on certain parameters that each individual event contains. The parameters for the flights are, for instance, the amount of consumed fuel with the associated emissions or the travelled distance. The individual environmental impacts for each of these events can thus be cumulated at the end of the lifetime to obtain the total impact of the aircraft. The presented approach for dynamising the inventory of a classical LCA thus provides a solid basis for detailed ecological analyses and further dynamisation. Figure 2 illustrates a segment of the simulation over the duration of one day. The flight events (blue) and maintenance events (red) are linked together to create the event calendar. Attached to the first flight event is an example of the parameters that can be used within the LCA calculation. In this case, these are, among other things, the distance and the consumed fuel.

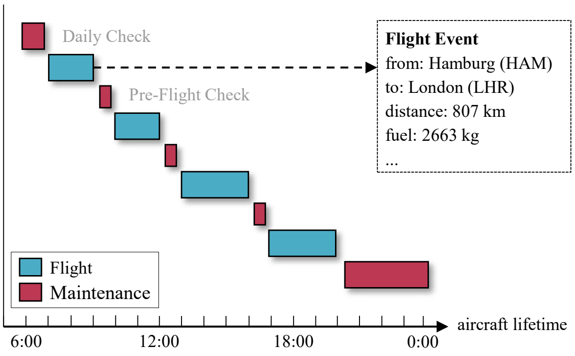

Fig. 2. Graphical visualisation of a discrete-event simulation based on a flight plan including flight and maintenance events for an aircraft over the course of one day. The attributes for a flight event are shown as an example.

Our next step is to adjust the discrete environmental impacts for each event using a suitable dynamic characterisation and, if appropriate, weighting method. A suitable tool for this could be the tool dynCO2 by Levasseur et al. [27], as it already enables the visualisation of emission profiles over time. However, this is so far limited to a time resolution of one year, which is why individual adaptations are necessary to apply it to the discrete-event simulation. Moreover, the dynamic characterisation can so far only be applied to the impact categories of GWP and toxicity, which is why the transfer to other categories still needs to be investigated.

The discrete-event simulation also allows the implementation of discounting functions, although we believe that for the time being only conservative discounting rates should be chosen in order not to underestimate the ecological impact.

5. Conclusion

The aim of this paper was to provide an overview of different temporal dynamic approaches for LCA. As a basis for this, an extensive literature research was carried out, with the help of which different dynamisation options, such as dynamic weighting or DLCI, could be clustered and evaluated. Based on the literature, the advantages and limitations could be listed and, by looking at a theoretical use case, the applicability for aviation could be evaluated. It could be shown that aviation provides an ideal example for the application of dynamic methods due to the aircraft's relatively long lifetimes and the long residence time of some emissions released during operation. In particular, the dynamisation of LCI is a promising approach in this context, as aircraft have a thoroughly scheduled operational phase with corresponding temporal information. This offers a variety of different analysis possibilities for both short- and long-term considerations. Furthermore, dependencies during the operation, for example, between flight and maintenance events, can be highlighted and mapped. A transfer to other long-life means of transport or technologies is likewise imaginable.

However, for the use of other dynamic methods, such as dynamic characterisation, there are still shortcomings and uncertainties, which is why, for the time being, they cannot be easily transferred to any air transport application. In some cases, such as dynamic discounting, their use can even artificially reduce the ecological impact, which can have far-reaching consequences. For future studies, it may be useful to look more closely at the aforementioned gaps to develop a much better understanding of these temporally dynamic methods.

References

[1] European Environment Agency, European Union Aviation Safety Agency, Eurocontrol, European aviation environmental report 2019, Luxembourg (2019). doi:10.2822/309946.

[2] E. Terrenoire, D. A. Hauglustaine, T. Gasser, O. Penanhoat, The Contribution of Carbon Dioxide Emissions from the Aviation Sector to Future Climate Change, Environmental Research Letters 14 (8) (2019) 084019. doi:10.1088/1748-9326/ab3086.

[3] International Organization for Standardization, Environmental Management – Life Cycle Assessment – Principles and Framework: ISO 14040:2006 (2006).

[4] International Organization for Standardization, Environmental Management – Life Cycle Assessment – Requirements and Guidelines: ISO 14044:2006 (2018).

[5] Aircraft Commerce, Aircraft Owner's & Operator's Guide: A320 Family Maintenance Analysis & Budget, Aircraft Commerce 44 (2006) 18–31.

[6] M. Hu, Dynamic Life Cycle Assessment Integrating Value Choice and Temporal Factors - A Case Study of an Elementary School, Energy and Buildings 158 (2018) 1087–1096. doi:10.1016/j.enbuild.2017.10.043.

[7] S. Su, X. Li, C. Zhu, Y. Lu, H. W. Lee, Dynamic Life Cycle Assessment: A Review of Research for Temporal Variations in Life Cycle Assessment Studies, Environmental Engineering Science 38 (11) (2021) 1013–1026. doi:10.1089/ees.2021.0052.

[8] Y. Zhang, Taking the Time Characteristic into Account of Life Cycle Assessment: Method and Application for Buildings, Sustainability 9 (6) (2017) 922. doi:10.3390/su9060922.

[9] C. Roux, P. Schalbart, B. Peuportier, Development of an Electricity System Model Allowing Dynamic and Marginal Approaches in LCA - Tested in the French Context of Space Heating in Buildings, The International Journal of Life Cycle Assessment 22 (8) (2017) 1177–1190. doi:10.1007/s11367-016-1229-z.

[10] B. M. Zimmermann, H. Dura, M. Weil, Towards Time-Resolved LCA of Electric Vehicles in Germany, Metallurgical Research & Technology 111 (3) (2014) 169–178. doi:10.1051/metal/2014009.

[11] S. Cornago, Y. S. Tan, C. Brondi, S. Ramakrishna, J. S. C. Low, Systematic Literature Review on Dynamic Life Cycle Inventory: Towards Industry 4.0 Applications, Sustainability 14 (11) (2022) 6464. doi:10.3390/su14116464.

[12] E. Resch, I. Andresen, F. Cherubini, H. Brattebø, Estimating Dynamic Climate Change Effects of Material Use in Buildings - Timing, Uncertainty, and Emission Sources, Building and Environment 187 (2021) 107399. doi:10.1016/j.buildenv.2020.107399.

[13] S. J. Burnley, C. P. Boardman, The Use of Dynamic Life Cycle Assessment to Evaluate the Long Term Climate Change Impacts of Waste Management Processes, in: Proceedings of the 16th International Waste Management and Landfill Symposium, 2017.

[14] V. Göswein, F. Pittau, J. D. Silvestre, F. Freire, G. Habert, Dynamic Life Cycle Assessment of Straw-Based Renovation: A Case Study from a Portuguese Neighbourhood, Earth and Environmental Science 588 (2020) 042054. doi:10.1088/1755-1315/588/4/042054.

[15] T. Roetger, A. Elsayed, A. Bann, T. Cuddy, R. Thompson, 2019 Environmental Report: Aviation and Environment: Chapter 8: Towards Circular Economy.

[16] W. O. Collinge, A. E. Landis, A. K. Jones, L. A. Schaefer, M. M. Bilec, Dynamic Life Cycle Assessment: Framework and Application to an Institutional Building, The International Journal of Life Cycle Assessment 18 (3) (2013) 538–552. doi:10.1007/s11367-012-0528-2.

[17] S. Lueddeckens, P. Saling, E. Guenther, Temporal Issues in Life Cycle Assessment - A Systematic Review, The International Journal of Life Cycle Assessment 25 (8) (2020) 1385–1401. doi:10.1007/s11367-020-01757-1.

[18] H. Dyckhoff, T. Kasah, Time Horizon and Dominance in Dynamic Life Cycle Assessment, Journal of Industrial Ecology 18 (6) (2014) 799–808. doi:10.1111/jiec.12131.

[19] P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, Climate Change 2022: Mitigation of Climate Change: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022). doi:10.1017/9781009157926.

[20] P. M. Fearnside, Why a 100-Year Time Horizon Should be Used for Global Warming Mitigation Calculations, Mitigation and Adaptation Strategies for Global Change 7 (1) (2002) 19–30. doi:10.1023/a:1015885027530.

[21] P. Collet, L. Lardon, J.-P. Steyer, A. Hélias, How to Take Time into Account in the Inventory Step: A Selective Introduction Based on Sensitivity Analysis, The International Journal of Life Cycle Assessment 19 (2) (2014) 320–330. doi:10.1007/s11367-013-0636-7.

[22] G. Cardellini, C. Mutel, Temporalis: An Open Source Software for Dynamic LCA, Journal of Open Source Software 3 (24) (2018) 612. doi:10.21105/joss.00612.

[23] Y. Pigné, T. N. Gutiérrez, T. Gibon, T. Schaubroeck, E. Popovici, A. H. Shimako, E. Benetto, L. Tiruta-Barna, A Tool to Operationalize Dynamic LCA, Including Time Differentiation on the Complete Background Database, The International Journal of Life Cycle Assessment 25 (2) (2020) 267–279. doi:10.1007/s11367-019-01696-6.

[24] R. A. Filleti, D. A. Silva, E. J. Silva, A. R. Ometto, Dynamic System for Life Cycle Inventory and Impact Assessment of Manufacturing Processes, Procedia CIRP 15 (2014) 531–536. doi:10.1016/j.procir.2014.06.024.

[25] D. Beloin-Saint-Pierre, R. Heijungs, I. Blanc, The ESPA (Enhanced Structural Path Analysis) Method: A Solution to an Implementation Challenge for Dynamic Life Cycle Assessment Studies, The International Journal of Life Cycle Assessment 19 (4) (2014) 861–871. doi:10.1007/s11367-014-0710-9.

[26] A. Pinsonnault, P. Lesage, A. Levasseur, R. Samson, Temporal Differentiation of Background Systems in LCA: Relevance of Adding Temporal Information in LCI Databases, The International Journal of Life Cycle Assessment 19 (11) (2014) 1843–1853. doi:10.1007/s11367-014-0783-5.

[27] A. Levasseur, P. Lesage, M. Margni, L. Deschênes, R. Samson, Considering Time in LCA: Dynamic LCA and its Application to Global Warming Impact Assessments, Environmental Science & Technology 44 (8) (2010) 3169–3174. doi:10.1021/es9030003.

[28] D. S. Lee, Aviation Greenhouse Gas Emissions, in: Environmental Report 2010, 2010, pp. 42 – 64.

[29] N. Ericsson, C. Porsö, S. Ahlgren, Å. Nordberg, C. Sundberg, P.-A. Hansson, Time-dependent Climate Impact of a Bioenergy System - Methodology Development and Application to Swedish Conditions, GCB Bioenergy 5 (5) (2013) 580–590. doi:10.1111/gcbb.12031.

[30] C. Yuan, D. A. Dornfeld, Embedded Temporal Difference in Life Cycle Assessment: Case Study on VW Golf A4 Car, in: Proceedings of IEEE International Symposium on Sustainable Systems and Technology, 2009.

[31] S. Lueddeckens, P. Saling, E. Guenther, Discounting and Life Cycle Assessment: A Distorting Measure in Assessments, a Reasonable Instrument for Decisions, International Journal of Environmental Science and Technology 19 (4) (2022) 2961–2972. doi:10.1007/s13762-021-03426-8.

[32] O. Boucher, Comparison of Physically- and Economically-based CO$_2$-Equivalences for Methane, Earth System Dynamics 3 (1) (2012) 49–61. doi:10.5194/esd-3-49-2012.

[33] P. M. Fearnside, Time Preference in Global Warming Calculations: A Proposal for a Unified Index, Ecological Economics 41 (1) (2002) 21–31. doi:10.1016/s0921-8009(02)00004-6.

[34] Q. Zhai, B. Crowley, C. Yuan, Temporal Discounting for Life Cycle Assessment: Differences Between Environmental Discounting and Economic Discounting, in: Proceedings of the IEEE International Symposium on Sustainable Systems and Technology, 2011. doi:10.1109/ISSST.2011.5936842.

[35] A. Levasseur, P. Lesage, M. Margni, R. Samson, Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment, Journal of Industrial Ecology 17 (1) (2013) 117–128. doi:10.1111/j.1530-9290.2012.00503.x.

[36] J. Sohn, P. Kalbar, B. Goldstein, M. Birkved, Defining Temporally Dynamic Life Cycle Assessment: A Review, Integrated Environmental Assessment and Management 16 (3) (2020) 314–323. doi:10.1002/ieam.4235.

[37] S. Ackert, Engine Maintenance Concepts for Financiers: Elements of Turbofan Shop Maintenance Costs.
URL http://www.aircraftmonitor.com/

[38] A. Rahn, A. A. Pohya, J. Wehrspohn, K. Wicke, A Modular Framework for Life Cycle Assessment of Aircraft Maintenance, AIAA AVIATION 2021 FORUM (2021). doi:10.2514/6.2021-2369.

[39] A. A. Pohya, J. Wehrspohn, R. Meissner, K. Wicke, A Modular and Lifecycle Based Discrete Event Simulation Framework for Quantifying the True Value of Aircraft Technologies, Maintenance Strategies, and Operational Procedures, Advances in Engineering Software (2021).

[40] B. K. Choi, D. Kang, Modeling and Simulation of Discrete-Event Systems, Wiley, Hoboken, NJ, USA, 2013. doi:10.1002/9781118732793.