



HAL
open science

INTEGRATION OF LIFE CYCLE ASSESSMENT METHODOLOGY AS AN ENVIRONMENT DISCIPLINE MODULE IN MULTIDISCIPLINARY ANALYSIS AND OPTIMIZATION FRAMEWORK

Thomas Bellier, Joseph Morlier, Cees Bil, Annafederica Urbano, Adrian
Pudsey

► To cite this version:

Thomas Bellier, Joseph Morlier, Cees Bil, Annafederica Urbano, Adrian Pudsey. INTEGRATION OF LIFE CYCLE ASSESSMENT METHODOLOGY AS AN ENVIRONMENT DISCIPLINE MODULE IN MULTIDISCIPLINARY ANALYSIS AND OPTIMIZATION FRAMEWORK. II ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems (Aerobest 2023), ECCOMAS Portugal, Jul 2023, Lisboa, Portugal. pp.102-119. hal-04188708

HAL Id: hal-04188708

<https://hal.science/hal-04188708v1>

Submitted on 26 Aug 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



INTEGRATION OF LIFE CYCLE ASSESSMENT METHODOLOGY AS AN ENVIRONMENT DISCIPLINE MODULE IN MULTIDISCIPLINARY ANALYSIS AND OPTIMIZATION FRAMEWORK

Thomas Bellier^{12*}, Joseph Morlier¹, Cees Bil², Annafederica Urbano¹ and
Adrian Pudsey²

1: Institut Clément Ader
ISAE-SUPAERO, Mines Albi, UPS, INSA, CNRS
Université de Toulouse
Toulouse, France
thomas.bellier@isae-supero.fr, <https://ica.cnrs.fr/home/>

2: School of Engineering
Royal Melbourne Institute of Technology
Melbourne, Victoria, Australia
<https://www.rmit.edu.au/>

Abstract. *As sustainability becomes one of the main challenges of the aerospace industry, we need to find new ways to integrate it into the design phase of aerospace systems. The Multidisciplinary Analysis and Optimization (MDAO) framework is a great host for an environmental discipline thanks to its modularity. However current Life Cycle Assessment (LCA) software do not integrate well with other computation tools, and are designed for low amounts of simulations on massive databases, while MDAO requires often many iterations with only slight variations. This work presents newly developed tools aiming at bridging those two valuable methods to enable better use of LCA within MDAO. Symbolic links between classic design variables and associated LCA parameter, python-based tools compatible with **OpenMDAO**, and optimization of the LCA algorithms to allow for multiple runs on variations of the same overall system makes it possible to integrate LCA considerations inside an MDAO model at reduced performance cost. The resulting framework makes ecodesign more accessible as environmental impacts can be used inside the design process, possibly as main objectives or constraints.*

Keywords: environment, life cycle, sustainability, multidisciplinary, ecodesign

1 INTRODUCTION

Integrating environmental concerns in a Multidisciplinary Analysis and Optimisation (MDAO) framework is challenging, for multiple reasons. The software, the language, and the people are different between the technical design and Life Cycle Assessment (LCA) of a project, which means that both tasks are performed at best with slow communication, at worst completely independently and the environmental analysis is carried out only on the already finished design. In that context, reducing environmental impact can be done during an MDAO, but that requires identifying beforehand which variables will impact the most relevant impacts, and the lack of integrated LCA can lead to important bias with many variables impacting the environmental aspect of a design being ignored.

Integrating LCA as an environmental discipline inside an MDAO would solve those problems, as it would give access to all relevant variables to the LCA module avoiding biases and errors, and also give access to all relevant environmental impact to the rest of the MDAO model, including as main constraint or objective, to directly optimise using them and not just analyse the result. This however presents multiple challenges: an LCA requires access to a lot of data and variables, which increases the links between the disciplines in the model. Also, as mentioned previously, those two processes are usually carried out by different departments, and there is an extremely limited choice of tools that uses the same programming language to be used together. This work presents the specificity of LCA in an MDAO context, the developed structure to integrate into python, and two simple examples to illustrate some of the potential benefits of this integration.

2 LIFE CYCLE ASSESSMENT

2.1 Principles

Life Cycle Assessment (LCA, also called Life Cycle Analysis) is a standardized method to evaluate the environmental consequences of a product or activity across its entire life. It's defined by a family of ISO norms [1], from ISO 14040 to ISO 14044, that can be extended by different standard guidelines, such as the European ILCD [2]. It's a very powerful tool to establish impact assessment, compare different products, and create environmental certifications as the defined methodology ensures the results are as complete as possible, and that every product tested for comparison or certification will go through the same fare analysis. LCA methodology is split into four main parts, as described in Figure 1. All of those need to be carried out properly. [3, 4]

2.1.1 Goal and Scope Definition

The first thing when conducting an LCA is to define correctly the problem. [5] Why is the study performed? What is the product studied and its purpose? Which impact are studied? Will it be compared to something else? Answering those questions requires looking at:

- Choosing a functional unit: the functional unit is a quantitative description of the service or utility for which the LCA is performed, and will be used as the reference to scale the output of the impacts and inventory analysis. It will be also the scaling definition for comparison. For example, when studying a wind turbine or any other

environmental standards defined by an external entity, those can require additional steps or requirements. If the LCA is intended to be publicly disclosed, the results need to be reviewed externally.

The goal and scope definition is very important and will influence every other step that comes after. It will determine the validity of the conclusions based on the LCA results.

2.1.2 Inventory Analysis

After the definition of goals and scope, every flow of any resource within the scope needs to be collected in an inventory analysis and scaled based on their contribution to the final functional unit. The analysis often relies on external databases of either generic flow and products, like Ecoinvent [8], or more specialized ones like the SSSD [9] for the space sector. The inventory analysis outputs a life cycle inventory, which contains a list of physical flows for the product or service described by the functional unit.

2.1.3 Impact Assessment

The impact assessment is the translation of the elementary flows of the inventory analysis into relevant environmental quantities or impacts. The three main steps described in the ISO 14040 norm are:

- Selection of the impact categories relevant to the choices made during the goal definition. Those impact categories need to have an environmental model and an associated indicator that can be quantified from the elementary flows of the inventory analysis.
- Classification of the elementary flows, by selecting the relevant flows for the selected impact categories and assigning them to the relevant impact.
- Characterisation of the impacts, by converting the classified elementary flows into values used in the impact categories indicators and environmental models, and then measuring the value of those impact indicators.

2.1.4 Interpretation

The results of the LCA and the values of the impact indicators are used as described after the goal definition. In most cases, the previous steps and especially impact assessment will add uncertainties due to the lack of information about an activity or the difficult correlation between raw outputs and environmental models. [10] Those uncertainties will also be interpreted. [11]

2.2 Challenges for aerospace

LCA is a generic technique and can be used for any project or object, including aerospace systems. However, it is mostly used for systems whose environmental impact is important for the general public. This includes the past years of civilian aviation, especially commercial aviation, as it has a significant contribution to climate change. [12, 13] Various LCA had been made for different aspects of civilian aviation. [14, 15] LCA on a

commercial aircraft reveals that most of the impact, especially on climate change, is due to the usage of kerosene during flight. [16] For that reason, further studies focus on the LCA of the fuel itself [17] or the usage of completely different technologies like hydrogen [18] or electric [19] plane engines.

There is far less available data for space and military projects. Military activities are too secret to share enough data for an LCA study, and space activities used to be considered too niche to have a significant impact, thus explaining the lack of extensive LCA. While an aircraft is not a launcher, the technologies used in aviation are often related to the ones used in space and this extensive research is a useful starting point for the LCA of a launcher. A state of the art of LCA in the space sector [20] shows that LCA for launchers is recent but expanding rapidly. Some reports have been made in the United States [21] or Russia [22], but ESA [23] is the major agency with the most involvement in LCA.

Space is a growing sector, on its influence on the environment is not negligible anymore [24, 25], on different impacts like the GWP [26] or the ozone layer destruction [27, 28]. Knowing the impacts of launchers in the high atmosphere has a lot of uncertainties [20], due to the difficulty of simulating or measuring gas propagation there. [29] This makes it difficult to know the impact of high atmosphere burning of kerosene [30, 31], the influence of black carbon [32] or other chemical residues, and the impacts of solid boosters [33–35] with non-carbon-based fuels.

3 INTEGRATION

3.1 Environment as a discipline

In all previously mentioned studies, and in most LCA studies in general, the environmental assessment is carried out once, on a finished design. This makes it possible to compare existing products or check for example the compliance of a proposed design with environmental requirements. However, this means that the environmental parameters are not optimised directly, as objectives. If we consider an MDAO problem, this out-of-loop LCA would be modeled as shown in Fig.2. In this example, the LCA is only done after optimisation and its outputs are entirely decoupled from the design process.

This common approach is generally used because LCA software doesn't allow integration of a project in some external development or optimisation tool. This means that in order to optimise the environmental impact using this structure, one must either do a very slow iterative optimisation process or extract from the LCA process the main contributing factors and add them manually in the optimisation loop.

The goal of this work is to integrate directly the entire LCA model inside the optimisation loop, to allow for quick and easy access to all of the environmental output of the LCA and use them as objectives, constraints, or simply internal variables. In that scheme, an MDAO problem with coupled LCA would have the structure presented in Fig.3. There, the LCA is fully integrated into the MDAO framework and is usable as any normal discipline module, which means that its outputs can be used in the optimiser or another function.

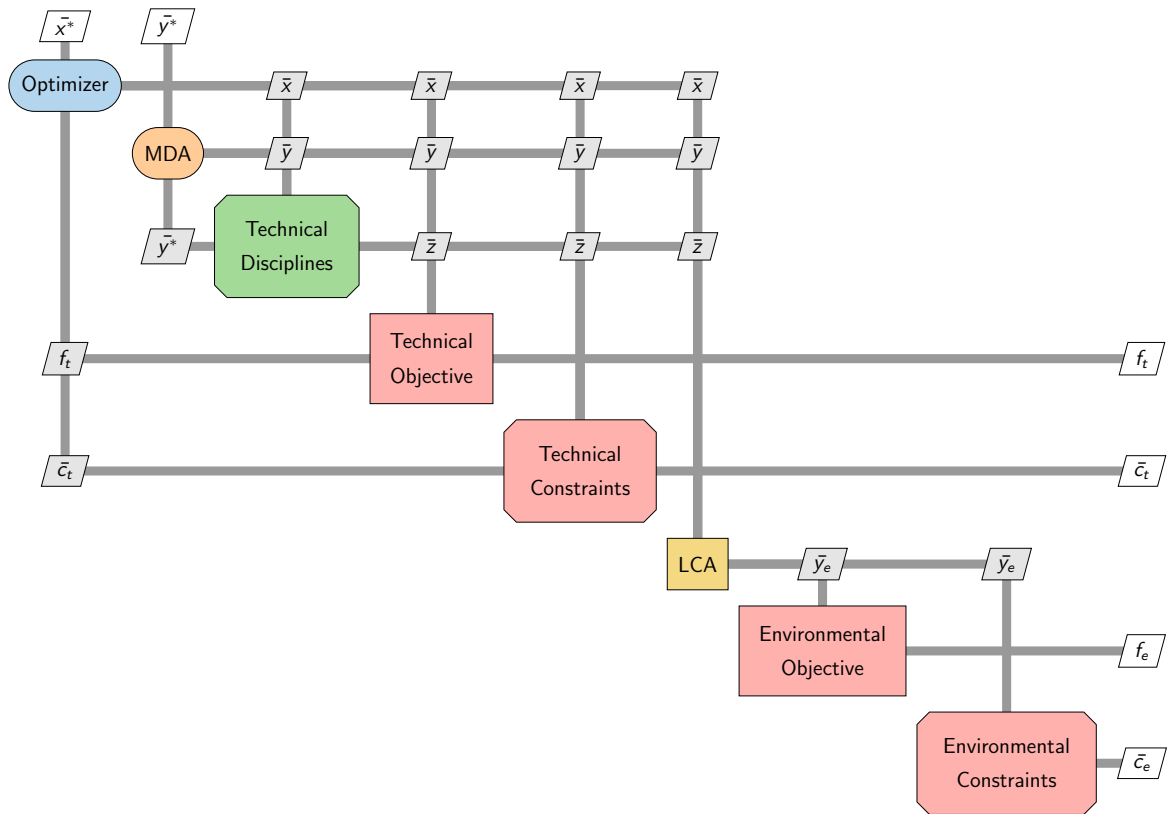


Figure 2: Generic XDSM diagram with decoupled LCA

To manage both aspects in one single environment, and stay compatible with a lot of existing projects, this development uses the *Brightway 2* [36] and *OpenMDAO* [37] python modules. Those are currently the only compatible tools for MDAO and LCA respectively.

3.2 Database linking

Linking LCA with a technical MDAO model still requires following the LCA principles described in Sec.2. Any database in *Brightway 2* [36] format would work.

3.2.1 Goal and Scope Definition

The Goal and Scope Definition has to be carried out like a normal LCA study. It's especially important to think of the intended coupling between the environment and other disciplines, and thus considering the following points:

- the functional unit should be directly related to the output of the overall MDAO model;
- the scope should integrate at least everything modeled in the MDAO;
- the studied impact may be used as constraints, objectives, or other variables within the MDAO framework.

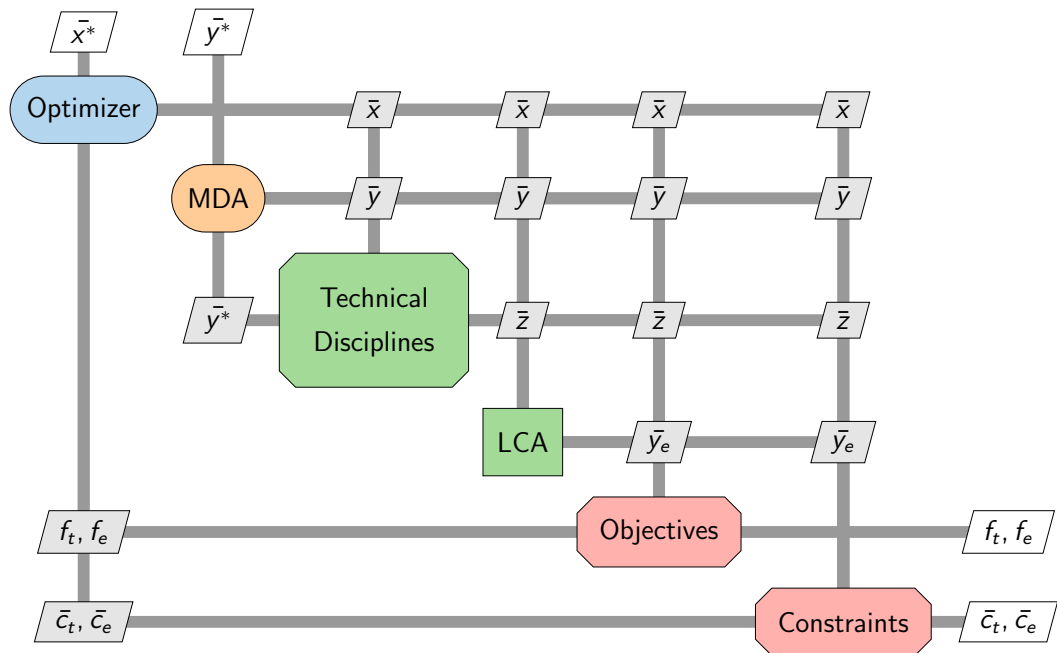


Figure 3: Generic XDSM diagram with integrated LCA

3.2.2 Inventory Analysis

The Inventory Analysis is the most important part of the coupling between MDAO and LCA. After completing the inventory analysis like a normal LCA, all of the inventory values that link with a MDAO variable need to be identified. In their declaration inside the MDAO framework, they need to be associated with the corresponding environmental database entry from *Brightway 2*. [36] That way, every time the LCA computation is done, those values are updated with their current value in the other MDAO discipline, hence creating the link between the environmental discipline and the others.

3.2.3 Impact Assessment

The impact categories are selected based on the goal definition and should be fixed throughout the optimisation process. The classification and characterisation is done using *Brightway 2*. [36]

3.2.4 Interpretation

The results of the LCA and the values of the impact indicators are used as planned in the scope definition, which means in most case converted into variables usable in and MDAO framework.

4 EXAMPLES

4.1 Sellar problem

4.1.1 Definition of the normal problem

The Sellar problem is a common example used to demonstrate and test the *OpenMDAO* library [37]. It can be mathematically described as the following optimisation problem:

$$\min : \quad x_1^2 + z_2 + y_1 + e^{-y_2} \quad (1)$$

$$\text{w.r.t. :} \quad x_1, z_1, z_2 \quad (2)$$

$$\text{subject to :} \quad (3)$$

$$3.16 - y_1 \leq 0 \quad (4)$$

$$y_2 - 24.0 \leq 0 \quad (5)$$

4.1.2 Multi-objective environmental variant

We assume arbitrarily that the Sellar problem describes an actual physical product, where y_1 would describe a quantity of steel and y_2 a quantity of wood. These two variables will now be linked to their respective entries in the environmental database, here *ecoinvent v3.8* [8]. The new environment module is configured to output the GWP impact of that system, only made of these masses of wood and steel, using the *ReCiPe* midpoint GWP100 method [38]. This integration gives us the new MDAO model highlighted on Fig. 4.

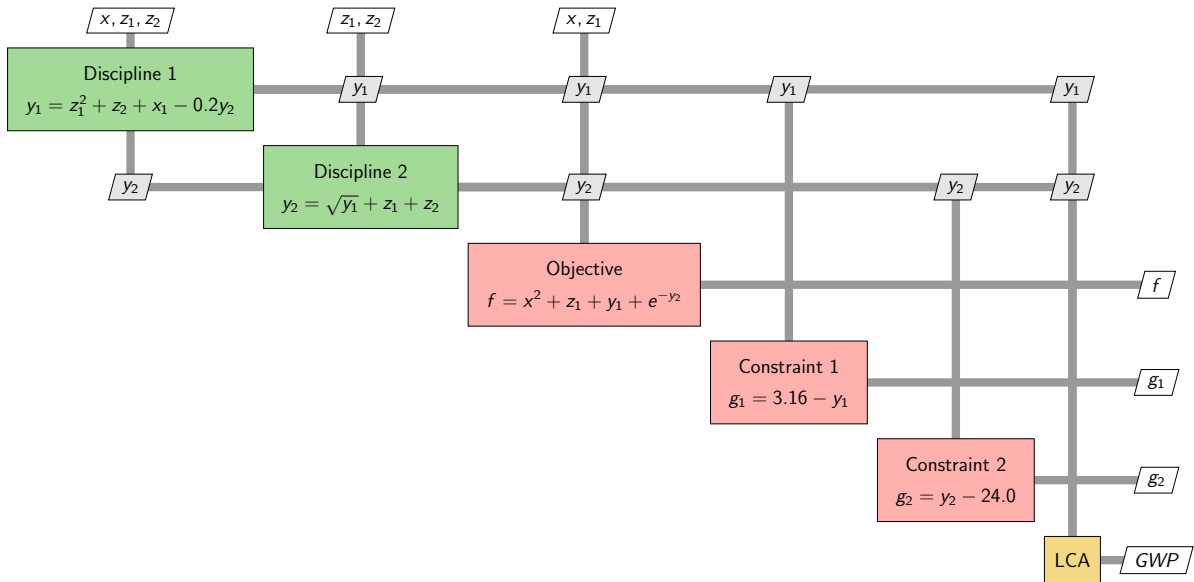


Figure 4: XDSM diagram of the Sellar problem augmented with an environment module

A multi-objective optimisation adding the newly computed GWP as the second objective is carried out. Using the NSGA-2 [39] algorithm implementation from the library *Pymoo* [40], with 50 individuals in the population and using a tolerance of 10^{-2} on the objectives as a termination criterion, it gives the Pareto front on Fig.5. The 2 extreme

points of the front are the result of a single objective optimisation using COBYLA [41] and are obtained with the values in Table 1.

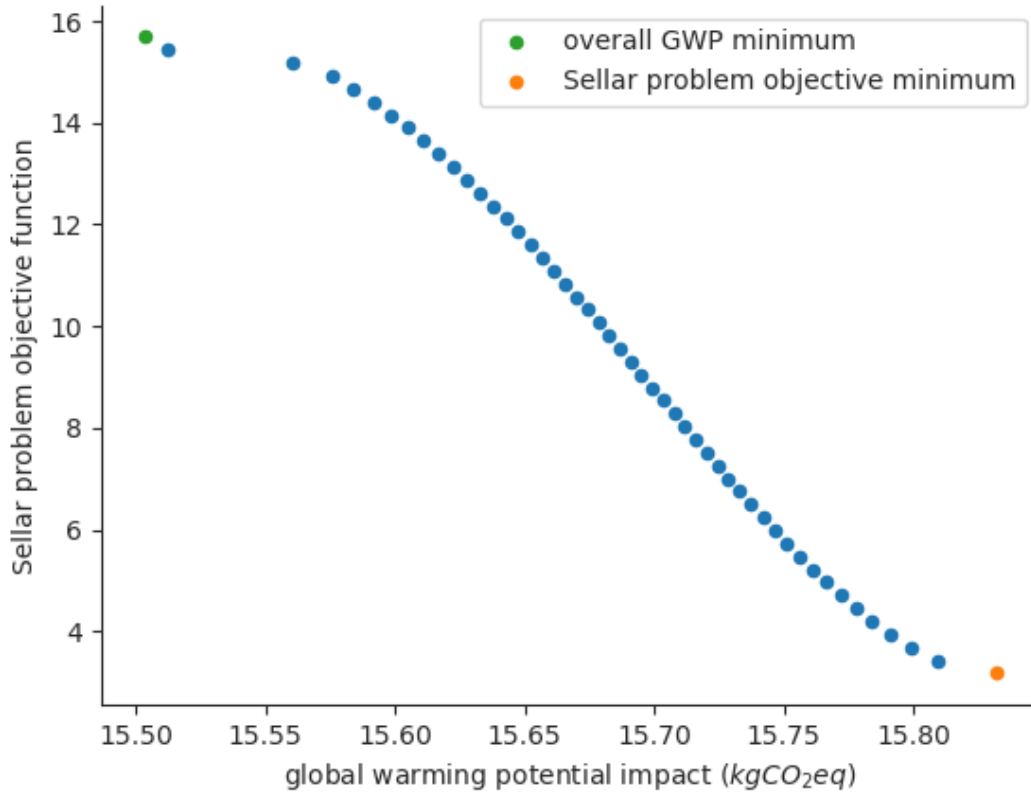


Figure 5: Pareto front of the Sellar optimisation problem augmented with an environment module

Table 1: Design variable and objective values for the extreme points of the Pareto front

x_1	z_1	z_2	GWP ($kgCO_2eq$)	Sellar objective
3.52	7.88×10^{-9} (≈ 0)	3.04×10^{-8} (≈ 0)	15.50	15.69
1.06×10^{-8} (≈ 0)	1.98	2.59×10^{-9} (≈ 0)	15.83	3.18

Using this technique, we can immediately assess the compromise on our original objective function if choosing a solution better for our chosen environmental parameter. It's important to note here that the Sellar problem doesn't represent any real problem and that any entry in any environmental database could have been assigned to any accessible variable from the *OpenMDAO* model. The next example presents an instance where the database and entries used actually match the technical problem.

4.2 Hybridised twin-turboprop aircraft

4.2.1 Hybrid Beechcraft King Air

The Beechcraft King Air is a line of twin-turboprop utility aircraft produced at more than 3000 units over 60 years and is therefore a good base for a hybrid aircraft. The library *Openconcept* [42, 43] proposes an architecture based on the King Air C90GT model, with a 3.75t MTOW and originally two 550shp turboprop engines. This aircraft is modified with the addition of an electric motor on each propeller, with a rating of at most 500hp and alimented with a battery of at most 2250kg and a specific energy of 450Wh/kg. The MTOW can be increased up to 5.70t.

4.2.2 Definition of the problem

The aircraft model of the King Air C90GT is modified with a hybrid system, which adds 7 design variables to the problem: engine power, motor power, battery weight, fuel capacity, cruise hybridisation, climb hybridisation, and descent hybridisation. To ensure the aircraft still flies, the model adapted in *Openconcept* [42, 43] adds 2 more design variables: MTOW and wing surface. The minimum and maximum values of these are presented in Table 3, with the initial value in the optimiser.

Our study focuses on two main objectives, the range and the global warming potential impact (GWP). The range is verified by simulating a trajectory. For the GWP, we use a simple LCA analysis using the *ecoinvent v3.8* [8] database. Like the previous example, the output used is the *ReCiPe* midpoint GWP100 method [38]. The database links are as shown in Table 2. When available, the location of the entry is set to Europe.

Table 2: Environmental coupling for the hybrid aircraft model

model parameter	Ecoinvent v3.8 entry
battery weight	'battery cell production, Li-ion'
motor weight	'electric motor production, vehicle'
engine weight	'internal combustion engine production, passenger car' ¹
empty weight ²	'aluminium production, primary, ingot'
fuel used	'market for kerosene'
electricity used	'market group for electricity, low voltage'

It is assumed that the aircraft will fly a thousand cycles at maximum range after being built. This model is obviously simplified here; but the idea of this example is that any design team with a more precise model and a better-suited database, or with access to a dedicated environmental study, can use those in a similar table to easily improve the environmental model being computed.

¹Ecoinvent does not include an entry for aircraft engine.

²Excludes motors, engines, and batteries.

4.2.3 Single objective optimisation

Table 3 presents the design variables values and results after optimisation for this problem, with the range fixed at 400NM and using the GWP as the sole objective, using COBYLA [41]. Figure 6 presents the resulting trajectory and energy consumption for this 400 nautical miles range solution.

Table 3: Example of hybrid aircraft optimisation for a range of 400NM

variable	min	init	max	value	units
MTOW	4000	5000	5700	5700	<i>kg</i>
wing surface	15	25	40	34	<i>m²</i>
engine power	0	1000	3000	298	<i>kW</i>
motor power	450	1000	3000	652	<i>kW</i>
battery weight	20	1000	3000	1607	<i>kg</i>
fuel capacity	500	1000	3000	500	<i>kg</i>
cruise hybridisation	0	0.5	1	0.71	
climb hybridisation	0	1	1	0.785	
descent hybridisation	0	0.5	1	0.337	
GWP				0.712	<i>kgCO₂eq/km</i>

As expected, the electrification reduces both the fuel consumption and the range of the aircraft. In order to minimise the size of the engine and stay in the best efficiency window, the engine will run almost always at the same power setting while the differences in throttle setting will be absorbed by the electric system, which is always close to 100% efficiency.

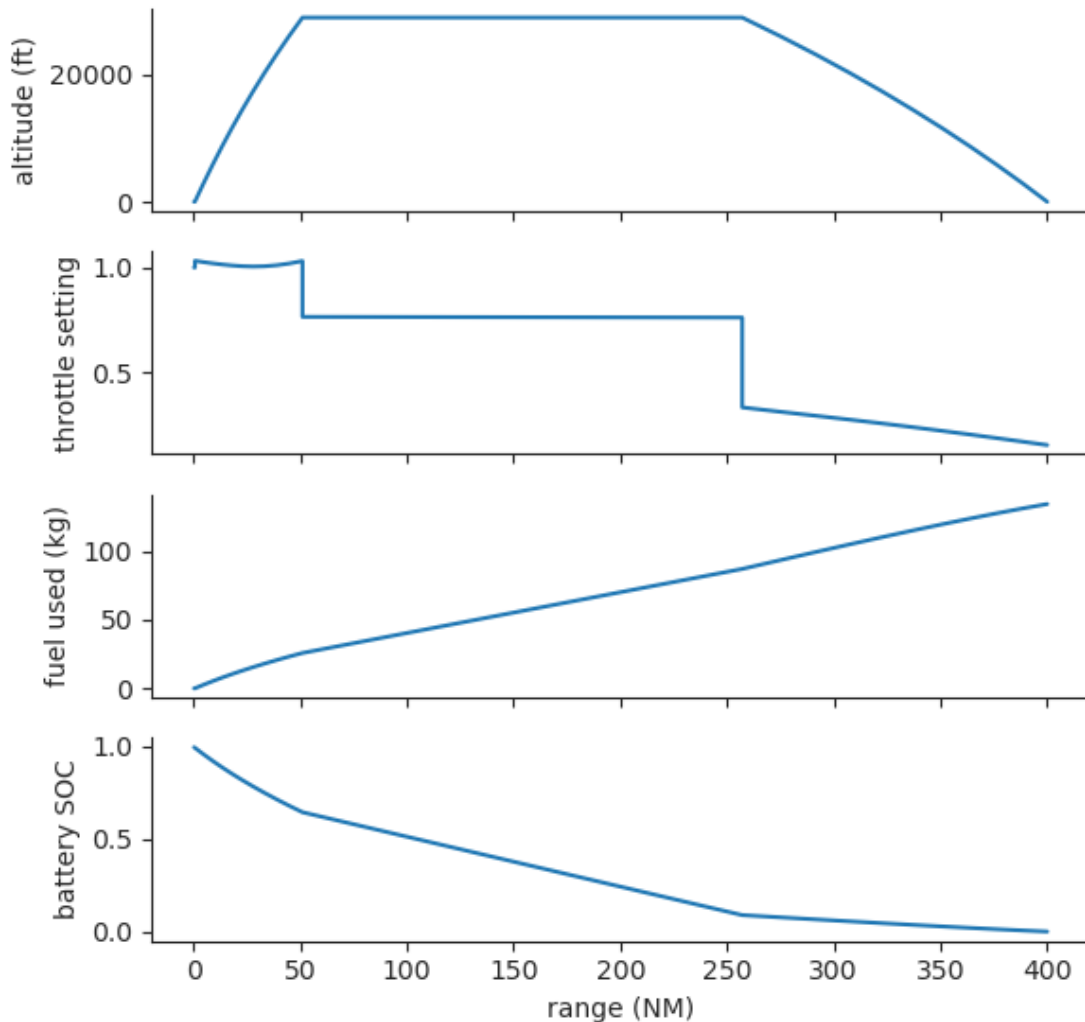


Figure 6: Optimal trajectory and energy utilisation for a hybrid aircraft with 400 nautical miles range

4.2.4 Multi-objective optimisation results

A multi-objective optimisation of the same aircraft design problem adding the range as the second objective instead of a fixed parameter is carried out. Using the NSGA-2 [39] algorithm implementation from the library *Pymoo* [40], with 12 individuals in the population and using a tolerance of 10^{-2} on the objectives as a termination criterion, it gives the Pareto front on Fig.7.

As expected, to increase the range of the aircraft the electric part of the hybrid system has to decrease, which leads to higher fuel consumption and in the end higher impact on the climate. With a range of 300NM or less, the cruise and descent are fully electric and the engine is only used for takeoff. For a range of more than 500NM, the engine produces more than half of the power during cruise.

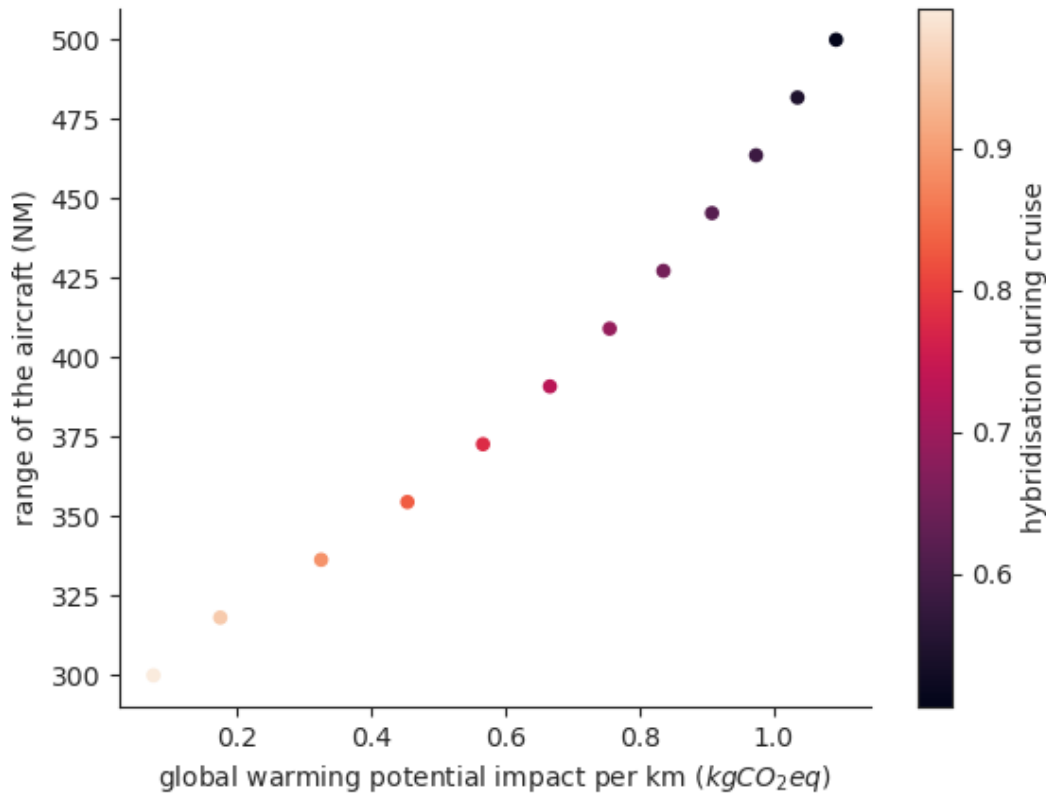


Figure 7: Pareto front for the multi-objective hybrid aircraft optimisation

A reduction of the range from 500NM ($1.1kgCO_2eq/km$, 50% hybridisation) to 370NM ($0.56kgCO_2eq/km$, 78% hybridisation) means a 26% reduction in range implies a 50% reduction in CO_2 emissions. And because our model uses life cycle assessment and not just fuel consumption, this includes other effects that penalise the hybrid aircraft, such as the production of the aircraft itself, with costly batteries and a shorter lifespan for the shorter range design.

5 CONCLUSION

The two simple examples presented highlight the potential of linking directly LCA to a MDAO model. By having access to the environmental impact in the main optimiser, we can use them as the main objective, like the GWP here, but given that they behave like other variables, they could have also been used as constraints or within another discipline and propagated further into the model. This approach also eliminates many biases in ecodesign, as the environment-related variables are computed using a proper methodology. In the aircraft example, that means including manufacturing, electricity, and other greenhouse gases instead of focusing on simply the carbon dioxide emitted by burning fuel in-flight.

Some limitations still appear: the added complexity may impair the computational performance of the MDAO model, and LCA result can be given with an associated un-

certainty, for which the amplitudes can vary enormously depending on the given problem; this uncertainty would be ignored when used as MDAO variables. Furthermore, the limited choice of common tools limits the application to only work with *OpenMDAO* and *Brightway 2*, which also limits the number of potential users. But the test results are promising, and further development may reduce uncertainties and performance penalties, and simplify the process to make it more accessible to inexperienced users. This idea will be applied in the future to complete aerospace models, especially realistic launchers, with extensive LCA to promote this ecodesign methodology for ambitious projects.

ACKNOWLEDGEMENTS

This work was supported by the Royal Melbourne Institute of Technology (RMIT) and the Toulouse graduate School of Aerospace Engineering EUR TSAE grant, 17-EURE-0005.

REFERENCES

- [1] ISO. *Environmental management. Life cycle assessment. Principles and framework*. 2020. ISBN 978-0-539-01348-1. OCLC: 9521571302.
- [2] I. for Environment and Sustainability (Joint Research Centre). *International Reference Life Cycle Data System (ILCD) Handbook :general guide for life cycle assessment : detailed guidance*. Publications Office of the European Union, 2010. ISBN 978-92-79-19092-6. URL <https://data.europa.eu/doi/10.2788/38479>.
- [3] M. Z. Hauschild. Introduction to LCA Methodology. In M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, editors, *Life Cycle Assessment: Theory and Practice*, pages 59–66. Springer International Publishing, Cham, 2018. ISBN 978-3-319-56475-3. doi:10.1007/978-3-319-56475-3_6. URL https://doi.org/10.1007/978-3-319-56475-3_6.
- [4] O. Jolliet, M. Saade-Sbeih, S. Shaked, A. Jolliet, and P. Crettaz. *Environmental Life Cycle Assessment*. CRC Press, 2015. ISBN 978-1-4398-8770-7. URL <https://books.google.ae/books?id=LYvwCgAAQBAJ>.
- [5] M. A. Curran. Overview of Goal and Scope Definition in Life Cycle Assessment. In M. A. Curran, editor, *Goal and Scope Definition in Life Cycle Assessment*, LCA Compendium – The Complete World of Life Cycle Assessment, pages 1–62. Springer Netherlands, Dordrecht, 2017. ISBN 978-94-024-0855-3. doi:10.1007/978-94-024-0855-3_1. URL https://doi.org/10.1007/978-94-024-0855-3_1.
- [6] K. R. Haapala and P. Prempreeda. Comparative life cycle assessment of 2.0 MW wind turbines. *International Journal of Sustainable Manufacturing*, 3(2): 170, 2014. ISSN 1742-7223, 1742-7231. doi:10.1504/IJSM.2014.062496. URL <http://www.inderscience.com/link.php?id=62496>.
- [7] R. K. Rosenbaum. Selection of Impact Categories, Category Indicators and Characterization Models in Goal and Scope Definition. In M. A. Curran, editor, *Goal*

- and Scope Definition in Life Cycle Assessment*, LCA Compendium – The Complete World of Life Cycle Assessment, pages 63–122. Springer Netherlands, Dordrecht, 2017. ISBN 978-94-024-0855-3. doi:10.1007/978-94-024-0855-3_2. URL https://doi.org/10.1007/978-94-024-0855-3_2.
- [8]ecoinvent Association. ecoinvent Database, 2021. URL <https://ecoinvent.org/the-ecoinvent-database/>.
- [9] A. Wilson, M. Vasile, C. Maddock, and K. Baker. The Strathclyde Space Systems Database: A New Life Cycle Sustainability Assessment Tool for the Design of Next Generation Green Space Systems. Sept. 2018.
- [10] E. A. Groen, E. A. M. Bokkers, R. Heijungs, and I. J. M. de Boer. Methods for global sensitivity analysis in life cycle assessment. *The International Journal of Life Cycle Assessment*, 22(7):1125–1137, July 2017. ISSN 1614-7502. doi:10.1007/s11367-016-1217-3. URL <https://doi.org/10.1007/s11367-016-1217-3>.
- [11] E. A. Groen and R. Heijungs. Ignoring correlation in uncertainty and sensitivity analysis in life cycle assessment: what is the risk? *Environmental Impact Assessment Review*, 62:98–109, Jan. 2017. ISSN 0195-9255. doi:10.1016/j.eiar.2016.10.006. URL <https://www.sciencedirect.com/science/article/pii/S0195925516300907>.
- [12] R. K. Pachauri, L. Mayer, and I. P. on Climate Change, editors. *Climate change 2014: synthesis report*. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2015. ISBN 978-92-9169-143-2.
- [13] D. S. Lee, D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt, A. Gettelman, R. R. De León, L. L. Lim, M. T. Lund, R. J. Millar, B. Owen, J. E. Penner, G. Pitari, M. J. Prather, R. Sausen, and L. J. Wilcox. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244:117834, Jan. 2021. ISSN 1352-2310. doi:10.1016/j.atmosenv.2020.117834. URL <https://www.sciencedirect.com/science/article/pii/S1352231020305689>.
- [14] A. Johanning and D. Scholz. A First Step Towards the Integration of Life Cycle Assessment into Conceptual Aircraft Design. 2013. URL <https://reposit.haw-hamburg.de/handle/20.500.12738/1372>. Accepted: 2020-08-26T09:17:21Z.
- [15] A. Johanning and D. Scholz. Conceptual Aircraft Design based on Life Cycle Assessment. In *ICAS 2014 Proceedings-29th Congress of the International Council of the Aeronautical Sciences*, 2014.
- [16] João Lopes. Life Cycle Assessment of the Airbus A330-200 Aircraft. Master’s thesis, Universidade Técnica de Lisboa, Nov. 2010.
- [17] C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos. Life Cycle Assessment of Kerosene Used in Aviation (8 pp). *The International Journal of Life Cycle Assessment*, 10(6):417–424, Nov. 2005. ISSN 1614-7502. doi:10.1065/lca2004.12.191. URL <https://doi.org/10.1065/lca2004.12.191>.

- [18] H. Nojoumi, I. Dincer, and G. F. Naterer. Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft propulsion. *International Journal of Hydrogen Energy*, 34(3):1363–1369, Feb. 2009. ISSN 0360-3199. doi:10.1016/j.ijhydene.2008.11.017. URL <https://www.sciencedirect.com/science/article/pii/S0360319908015048>.
- [19] J. Ribeiro, F. Afonso, I. Ribeiro, B. Ferreira, H. Policarpo, P. Peças, and F. Lau. Environmental assessment of hybrid-electric propulsion in conceptual aircraft design. *Journal of Cleaner Production*, 247:119477, Feb. 2020. ISSN 0959-6526. doi:10.1016/j.jclepro.2019.119477. URL <https://www.sciencedirect.com/science/article/pii/S0959652619343471>.
- [20] T. Maury, P. Loubet, S. M. Serrano, A. Gallice, and G. Sonnemann. Application of environmental life cycle assessment (LCA) within the space sector: A state of the art. *Acta Astronautica*, 170:122–135, May 2020. ISSN 00945765. doi:10.1016/j.actaastro.2020.01.035. URL <https://linkinghub.elsevier.com/retrieve/pii/S0094576520300552>.
- [21] S. S. Neumann. *Environmental Life Cycle Assessment of Commercial Space Transportation Activities in the United States*. Thesis, Apr. 2018. URL <https://rc.library.uta.edu/uta-ir/handle/10106/27352>. Accepted: 2018-06-05T15:57:18Z.
- [22] T. V. Koroleva, P. P. Krechetov, I. N. Semenov, A. V. Sharapova, S. A. Lednev, A. M. Karpachevskiy, A. D. Kondratyev, and N. S. Kasimov. The environmental impact of space transport. *Transportation Research Part D: Transport and Environment*, 58:54–69, Jan. 2018. ISSN 1361-9209. doi:10.1016/j.trd.2017.10.013. URL <https://www.sciencedirect.com/science/article/pii/S1361920917303115>.
- [23] ESA LCA Working Group. Space system Life Cycle Assessment (LCA) guidelines. Handbook ESSB-HB-U-005, ESA, Oct. 2016.
- [24] A. R. Wilson, M. Vasile, C. A. Maddock, and K. J. Baker. Ecospheric life cycle impacts of annual global space activities. *Science of The Total Environment*, 834:155305, Aug. 2022. ISSN 0048-9697. doi:10.1016/j.scitotenv.2022.155305. URL <https://www.sciencedirect.com/science/article/pii/S0048969722023981>.
- [25] J. D. DeSain, B. B. Brady, and A. F. S. Command. Potential Atmospheric Impact Generated by Space Launches Worldwide—Update for Emission Estimates from 1985 to 2013. 2014.
- [26] A. R. Wilson. Estimating the CO₂ intensity of the space sector. *Nature Astronomy*, 6(4):417–418, Apr. 2022. ISSN 2397-3366. doi:10.1038/s41550-022-01639-6. URL <https://www.nature.com/articles/s41550-022-01639-6>.
- [27] M. Ross, D. Toohey, M. Peinemann, and P. Ross. Limits on the Space Launch Market Related to Stratospheric Ozone Depletion. *Astropolitics*, 7(1): 50–82, Mar. 2009. ISSN 1477-7622. doi:10.1080/14777620902768867. URL <https://doi.org/10.1080/14777620902768867>. Publisher: Routledge eprint: <https://doi.org/10.1080/14777620902768867>.

-
- [28] J. Dallas, S. Raval, J. Alvarez Gaitan, S. Saydam, and A. Dempster. The environmental impact of emissions from space launches: A comprehensive review. *Journal of Cleaner Production*, 255:120209, May 2020. ISSN 09596526. doi:10.1016/j.jclepro.2020.120209. URL <https://linkinghub.elsevier.com/retrieve/pii/S0959652620302560>.
- [29] I. W. Kokkinakis and D. Drikakis. Atmospheric pollution from rockets. *Physics of Fluids*, 34(5):056107, May 2022. ISSN 1070-6631. doi:10.1063/5.0090017. URL <https://aip.scitation.org/doi/10.1063/5.0090017>.
- [30] E. J. L. Larson, R. W. Portmann, K. H. Rosenlof, D. W. Fahey, J. S. Daniel, and M. N. Ross. Global atmospheric response to emissions from a proposed reusable space launch system. *Earth's Future*, 5(1):37–48, 2017. ISSN 2328-4277. doi:10.1002/2016EF000399. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/2016EF000399>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/2016EF000399>.
- [31] M. N. Ross and P. M. Sheaffer. Radiative forcing caused by rocket engine emissions. *Earth's Future*, 2(4):177–196, 2014. ISSN 2328-4277. doi:10.1002/2013EF000160. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/2013EF000160>.
- [32] M. Ross, M. Mills, and D. Toohey. Potential climate impact of black carbon emitted by rockets. *Geophysical Research Letters*, 37(24), 2010. ISSN 1944-8007. doi:10.1029/2010GL044548. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2010GL044548>.
- [33] A. Poubeau. *Simulation des émissions d'un moteur à propergol solide : vers une modélisation multi-échelle de l'impact atmosphérique des lanceurs*. phd, Université de Toulouse, Université Toulouse III - Paul Sabatier, Feb. 2015. URL <http://thesesups.ups-tlse.fr/2742/>.
- [34] L. DeLuca, L. Galfetti, F. Maggi, G. Colombo, L. Merotto, M. Boiocchi, C. Paravan, A. Reina, P. Tadini, and L. Fanton. Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution. *Acta Astronautica*, 92:150–162, Dec. 2013. doi:10.1016/j.actaastro.2012.05.002.
- [35] M. R. Denison, J. J. Lamb, W. D. Bjorndahl, E. Y. Wong, and P. D. Lohn. Solid rocket exhaust in the stratosphere - Plume diffusion and chemical reactions. *Journal of Spacecraft and Rockets*, 31(3):435–442, May 1994. ISSN 0022-4650. doi:10.2514/3.26457. URL <https://arc.aiaa.org/doi/10.2514/3.26457>. Publisher: American Institute of Aeronautics and Astronautics.
- [36] C. Mutel. Brightway: An open source framework for Life Cycle Assessment. *Journal of Open Source Software*, 2(12):236, Apr. 2017. ISSN 2475-9066. doi:10.21105/joss.00236. URL <https://joss.theoj.org/papers/10.21105/joss.00236>.
- [37] J. S. Gray, J. T. Hwang, J. R. R. A. Martins, K. T. Moore, and B. A. Naylor. OpenMDAO: an open-source framework for multidisciplinary design, analysis, and

- optimization. *Structural and Multidisciplinary Optimization*, 59(4):1075–1104, Apr. 2019. ISSN 1615-1488. doi:10.1007/s00158-019-02211-z. URL <https://doi.org/10.1007/s00158-019-02211-z>.
- [38] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. D. M. Vieira, A. Hollander, M. Zijp, and R. van Zelm. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. 2016.
- [39] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2):182–197, 2002. doi:10.1109/4235.996017.
- [40] J. Blank and K. Deb. pymoo: Multi-Objective Optimization in Python. *IEEE Access*, 8:89497–89509, 2020.
- [41] M. J. D. Powell. A Direct Search Optimization Method That Models the Objective and Constraint Functions by Linear Interpolation. In S. Gomez and J.-P. Hennart, editors, *Advances in Optimization and Numerical Analysis*, pages 51–67. Springer Netherlands, Dordrecht, 1994. ISBN 978-94-015-8330-5. doi:10.1007/978-94-015-8330-5_4. URL https://doi.org/10.1007/978-94-015-8330-5_4.
- [42] E. J. Adler and J. R. R. A. Martins. Efficient Aerostructural Wing Optimization Considering Mission Analysis. *Journal of Aircraft*, Dec. 2022. ISSN 1533-3868. doi:10.2514/1.c037096. Publisher: American Institute of Aeronautics and Astronautics.
- [43] B. J. Brelje and J. R. R. A. Martins. Development of a Conceptual Design Model for Aircraft Electric Propulsion with Efficient Gradients. In *Proceedings of the AIAA/IEEE Electric Aircraft Technologies Symposium*, Cincinnati, OH, July 2018. doi:10.2514/6.2018-4979.