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Environmental Life Cycle Assessments for the Design Exploration of Electric UAVs

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Abstract

As the use and applications of Unmanned Aerial Vehicles (UAVs) continue to grow, it becomes essential to assess their environmental impacts throughout their life cycle. Such assessment would be particularly interesting when the specifications and the technologies of the UAV are not yet frozen. This article aims to address this need by introducing a novel approach that integrates Life Cycle Assessment (LCA) with an existing design framework for sizing electric UAVs. The results show that the production and renewal of batteries is the main contributor to environmental impacts, together with electricity consumption during operation. Several scenarios are presented to explore the sensitivity of the environmental impacts to mission requirements and technological assumptions. The findings provide valuable insights to guide future developments and mitigate environmental impacts from the earliest design stages.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have emerged as a promising alternative to conventional aircraft due to their versatility and cost-effectiveness. While these novel aircraft concepts claim no direct emissions during flight owing to their electric propulsion, they are responsible for other environmental issues through the rest of the value chain, such as manufacturing and disposal. As the market for UAVs grows rapidly, it is important to assess the environmental impacts of these systems. Life Cycle Assessment (LCA) has proven to be a valuable tool for quantifying the environmental impacts of products throughout their entire life cycle and across a range of indicators.

Although the literature reviews show increasing interest in LCA in the aviation industry [1, 2], its application to UAVs is sparse. In particular, the integration of LCA into the design process of UAVs has not been explored. Stolaroff pointed out the need for a life cycle assessment to evaluate the potential impacts of UAVs for package delivery [3]. Some studies addressed this aspect with a focus on energy demand and CO_2 equivalent (CO_{2e}) emissions related to the operating phase [4–6]. Goodchild and Toy [4] compared the CO_{2e} emissions of multirotor UAVs with those of conventional trucks to deliver parcels. It was established that a drone-based delivery system can emit less CO_{2e} than diesel trucks when the customer density is low and the distance is short. Chiang *et al.* [5] proposed an optimal routing model that would reduce the use of energy and CO_{2e} emissions when coordinating conventional vehicles and UAVs for deliveries. Kirschstein [6] further compared the energy demand and CO_{2e} emissions with electric trucks. The study shows that switching to an entirely drone-based system for deliveries in most situations is not desirable. However, none of the aforementioned studies has addressed the emissions related to the production stage of UAVs. Rodrigues *et al.* [7] and Stolaroff *et al.* [8] extended the scope to battery life cycle emissions, although other components (e.g. airframe) are not considered. Figliozzi [9] was the first to adopt a cradle-to-grave approach for comparing the CO_{2e} emissions of multirotor UAVs with ground vehicles. It is shown that UAV emissions per delivery can increase by up to 50% when the production stage is taken into account. Consequently, if customers can be grouped in a route, CO_{2e} emissions of UAVs are higher than those of tricycles and electric vans. Yet, the study from Figliozzi is limited to the impact on climate change. The production of batteries to power drones will likely put significant pressure on the supply of materials, resulting in various additional impacts. The environmental assessment should cover different impact categories to mitigate the risk of environmental burdens shifting. Recently, academic studies have adopted a multi-criteria approach to address this risk [10–13]. Yowtak *et al.* conducted a life cycle assessment on multiple impact categories such as global warming potential, photochemical oxidant formation potential, and respiratory effects [13]. For grocery deliveries, the authors conclude that UAVs have less impact on climate change than conventional vehicles,

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but greater than battery electric vehicles. However, respiratory effects can be much higher for UAVs than conventional vehicles, especially if the electricity mix is based on coal.

A critical element of environmental assessment is the adequacy of the data used in the life cycle inventory. As pointed out by Kirschstein [6], the results of an LCA are based on several assumptions restricting their credibility and their domain of validity. Most of the works mentioned above use an average value for estimating the energy consumption per flight distance [4, 5, 11, 13]. However, using an average value does not capture the effects of varying UAV designs and flight conditions. Some authors have proposed models to describe the energy demand as a function of the UAV's mass and the flight path [6–9]. The models are fitted with either real-world data of existing UAVs or generic values. In both cases, the energy consumption models do not take into account the individual characteristics of the components, which may vary from one design to another. Consequently, it does not allow for investigating the effects of future technologies. The constitution of a bill of materials for exploring the production and end-of-life impacts of UAVs is even more case-specific. It is systematically based on data from existing UAVs. Therefore, current research is not capable of exploring the environmental impacts of specific UAV designs that are not yet developed.

The present work introduces a design exploration of multirotor UAVs with a focus on environmental impacts, using a life cycle and multi-criteria approach. For this purpose, a parametric model for describing the LCA of multirotor UAVs is introduced. The LCA model is linked to a Life Cycle Inventory (LCI) database providing essential processes for the production and operation stages. Additionally, the model parameters, such as component masses and electricity consumption, are assigned based on the outputs of an existing sizing tool. This novelty allows for the assessment of environmental impacts right from the preliminary design phase, enabling designers to evaluate the sensitivities of these impacts to mission requirements and technology assumptions and, ultimately, identify areas for improvement. The effectiveness of the proposed methodology is demonstrated through a case study involving a package delivery mission.

The article is organized as follows. First, the scope of the life cycle assessment is defined in Section 2. The data collection and implementation of the environmental module are presented in Section 3. Results for a reference delivery mission are provided in Section 4. The sensitivity of the environmental impacts to mission requirements and battery technologies are discussed in Section 5 and Section 6, respectively. Finally, Section 7 concludes the article.

2. Scope definition of the LCA

The LCA approach is a widely used methodology for quantifying the environmental impacts of products, processes or services. It is standardized in the International Standards Organization (ISO) 14040 series [14, 15], and follows a four-step approach that includes goal and scope definition, inventory analysis, impact assessment and interpretation. This section introduces the LCA scope definition. First, the goal of the study and the functional unit are detailed. Then, the UAV modeling and the associated technological assumptions are presented. Finally, further information on the LCA is provided, including the process tree, system boundaries, and the environmental impacts considered for analysis.

2.1 Goal of the study

The goal of this study is to evaluate the environmental impacts associated with the entire life cycle of a multirotor UAV designed for a typical delivery mission. Specifically, the study focuses on identifying the main contributors to environmental burdens and assessing the sensitivity of the drone's environmental performance to mission requirements and technological choices. Therefore, the study aims to provide a quantitative basis for decision-making on how to improve the sustainability of multirotor UAVs.

2.2 Functional unit

In the context of LCA, the functional unit represents a quantified description of the system and its performance. It provides a reference unit for the reporting of environmental impacts. In this study, the functional unit is intended to represent a typical UAV delivery application. The reference application, from which the functional unit is derived, is defined as follows:

> *Deliver a 2 kg payload within a 7.5 km radius, at the rate of 5 deliveries per day, 260 days per year, for a period of 2 years.*

However, where comparison with alternative scenarios is required, the results will be expressed per kilogram.kilometer (kg.km), representing the transportation of 1 kg of payload over 1 km.

Specifically, a mission starts with a take-off before initiating a vertical climb at a rate of 3 m/s to an altitude of 120 meters, which is the maximum flight height generally authorized by EASA [16]. It is followed by a level

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flight over a distance of 7.5 km to the delivery area. This is slightly higher than Matternet's five-kilometer delivery route launched in 2022 [17], but below the announced maximum radius of 10 km (20 km total distance) for their M2 quadcopter [18, 19], which received FAA type certification in 2022 [20]. The choice of cruising speed typically depends on optimum energy consumption, which is linked to parameters such as the drone's weight and aerodynamic performance [21]. However, more stringent considerations could be considered for deliveries, such as safety, cost, and the ability to deliver quickly [22]. In the present work, the cruising speed is assumed to be fixed at 15 m/s. The cruise phase is followed by a hover phase to deliver the parcel. A hover time of 5 minutes is chosen, including a safety margin. Finally, the 7.5 km return flight is performed empty, without the parcel. It is assumed that the drone makes an average of 5 deliveries a day, throughout the 260 working days of a year. The 2-year lifespan of the UAV is in line with the arrival of the next generation of UAVs every two years, leading to the retirement of older models [23]. In total, the delivery rate represents a lifetime of 2,600 missions, also referred to as cycles in the following. Table 1 summarises the main choices for the functional unit. Given the wide variability of values found in the literature [9, 10, 13, 22], ranges of variation used for subsequent sensitivity analyses are also presented.

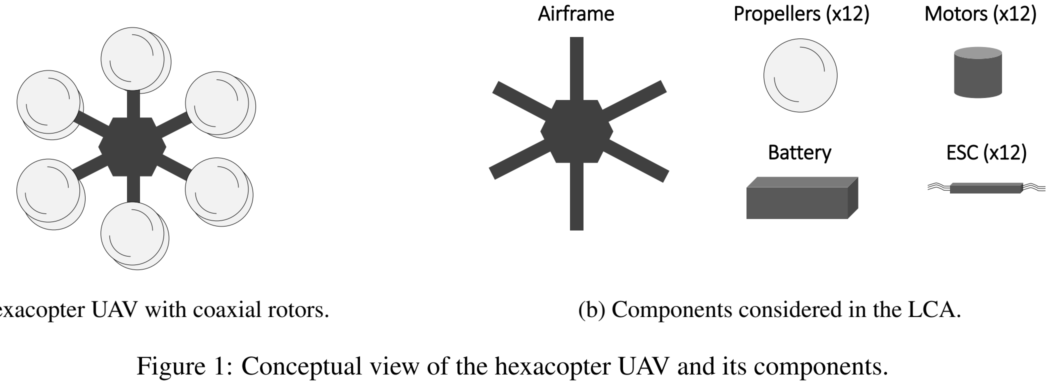
Table 1: Assumptions and sensitivity analysis ranges for the functional unit definition

Functional unit parameter	**Reference value**	**Range of variation**
Payload mass	2 kg	[0.5 - 5] kg
Delivery radius	7.5 km	[5 - 12.5] km
Cruise speed	15 m/s	-
Cruise altitude	120 m	-
Lifespan	2,600 cycles	[0 - 10,000] cycles

2.3 System modeling and assumptions

The system consists of a hexacopter UAV with coaxial rotors. This choice is consistent with the results of the controllability assessment of safety-critical UAVs presented by Liscoüet *et al.* [24]. Indeed, the coaxial hexacopter concept was shown to be robust to double rotor failures while maintaining a reasonable mass compared to other concepts of multirotor UAVs (e.g. octocopters). This is of major importance as the delivery mission may occur in densely populated areas.

The sizing of the UAV and its components is obtained using the methodology presented by Delbecq and Pollet [21, 25, 26]. The sizing process relies on analytical models [27] and Multidisciplinary Design Analysis and Optimization (MDAO) techniques to efficiently optimize a UAV with respect to mission requirements and technology assumptions (e.g. battery energy density) while minimizing its mass. In this paper, the mission requirements correspond to the operational mission defined by the functional unit. This is an optimistic case, as in practice UAVs are oversized compared to the actual missions they perform. Appendix A lists the technology assumptions used for fitting the models representing the main components. In addition to the airframe and propulsion system components, an additional 1 kg of mass is included to model the payload attachment and release mechanism but is not considered in the life cycle inventory. The reference lithium-ion battery features NMC chemistry for the cathode — a mix of lithium, nickel, manganese and cobalt. It is expected to last 400 cycles before replacement [28, 29], and its combined charge-discharge efficiency caused by internal inefficiencies is assumed to be 85%.



(a) Hexacopter UAV with coaxial rotors.

(b) Components considered in the LCA.

Figure 1: Conceptual view of the hexacopter UAV and its components.

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2.4 Sensitivity scenarios

The reference scenario, described by the reference values in Table 1 and the above system definition, is complemented by alternative scenarios for the purposes of sensitivity analyses and robustness of the results. First, the robustness of the results to the assumptions underlying the functional unit are studied. Both UAV's lifespan and mission requirements are varied to assess their influence on environmental performance. Specifically, for the mission requirements, the payload mass and delivery radius are varied in accordance with Table 1. By applying the optimal sizing methodology [21, 25, 26], the variation of these parameters induces different design alternatives, thereby influencing the environmental impacts. The results are provided in Section 5. Then, two additional scenarios are introduced to allow comparison of alternative battery chemistries with varying energy densities and lifetimes. The results, presented in Section 6, allow identifying the most promising areas for future technological developments.

2.5 Process tree

In LCA, a process tree is a hierarchical representation of the processes and flows required to fulfil the functional unit being assessed. Figure 2 provides an overview of the materials and energy required to fulfil the delivery application. The foreground and background processes are distinguished. Foreground processes refer to the processes within the scope of the UAV's design phase (e.g. the components' masses). On the other hand, background processes include processes that are not under the direct control of the designer and which precede or follow the sizing process. For example, the propeller manufacturing process is beyond the designer's control. The background processes are defined by generic data obtained directly from the EcoInvent 3.9 database [30]. Detailed information on the EcoInvent processes used in this study is provided in Section 3. The achievement of the functional unit requires a UAV and electricity from the grid to ensure its operation. The UAV is composed of several components, each of which has a mass determined by the sizing methodology [21, 25, 26]. In addition, the cumulative mass of batteries required to fulfil the functional unit depends on their replacement rate, which is defined by their specific lifetime and the number of mission executions. All these quantities, known as reference flows, differ according to the scenarios previously introduced. Indeed, the flows quantifying the amount of components and electricity depend on the assumptions underlying the delivery mission, the UAV's lifespan and the battery chemistry used in the design. The parameters used for building the process tree are described in Table 2.

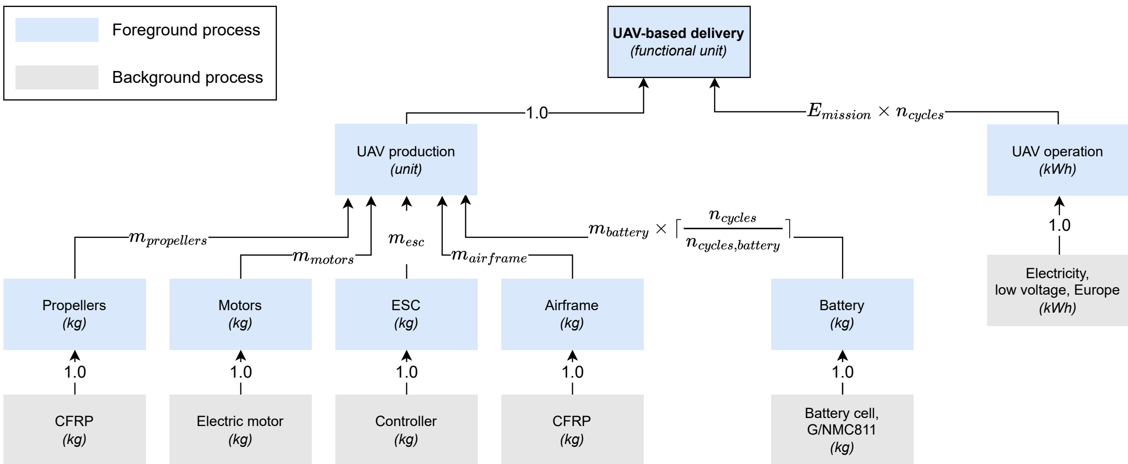

Figure 2: Process tree for the delivery application, over the entire lifecycle of the UAV.

2.6 System boundaries

The study's scope encompasses the production and operation (or, use) stages of the UAV. The production stage includes processes such as materials extraction and processing, components manufacturing, and transport of the components to the assembly facility. Additionally, the study considers the electricity consumed during the use stage, specifically the energy required for the flights. However, certain aspects are excluded from the assessment due to limited data availability and challenges with allocation rules. These exclusions include the assembly of the components, the delivery or transport of the UAV to the operating area, and the end-of-life treatment of the components. Furthermore, the study

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Table 2: Parameters for modeling the reference flows

Parameter	Unit	Description
$m_{propellers}$	kg	Mass of propellers
m_{motors}	kg	Mass of motors
m_{esc}	kg	Mass of electronic speed controllers
$m_{battery}$	kg	Mass of battery
$m_{airframe}$	kg	Mass of airframe
$E_{mission}$	kWh	Energy from electrical grid consumed over a single mission
n_{cycles}	-	Number of times the mission is performed
$n_{cycles,battery}$	-	Number of charge-discharge cycles before replacing battery

does not include ground infrastructure and ancillary systems such as battery chargers, nor the parcel and its release mechanism.

2.7 Environmental impact categories

The phase of the LCA that aims to evaluate the magnitude and significance of the environmental impacts is called the Life Cycle Impact Assessment (LCIA). Numerous methods for assessing the impacts are available in the scientific literature, including ReCiPe 2016 [31] or IMPACT World+ [32]. In this paper, the impact assessment relies on the recent EU Environmental Footprint (EF) methods [33] which cover 16 environmental impacts, including but not limited to climate change, resource depletion, and human toxicity. The EF provides a set of characterization factors for each impact, allowing the Life Cycle Inventory, described in the following section, to be mapped to each specific environmental impact. Following EF's recommendations, the impacts are then normalized against reference values to better reflect their relative importance. The reference values used in the EF consider the average environmental pressures of one person over one year [34]. Finally, the results are weighted and aggregated to obtain a single score [35]. This facilitates comparison of the results, for example when assessing different scenarios.

3. Data collection and implementation

3.1 Life Cycle Inventory

The Life Cycle Inventory (LCI) collects all the information needed to perform the LCA. In this study, data collection for processes supporting the LCI is based exclusively on the EcoInvent database version 3.9 [30], although the lack of specific data for UAVs requires some simplifying assumptions. The main choices that were made for building the LCI are provided here. The propellers are assumed to be made entirely of Carbon Fiber Reinforced Plastic (CFRP), similar to the carbon propellers manufactured by APC [36]. The composition of the brushless motors used in the UAV is assumed to be equivalent to that of electric scooter motors. Similarly, the electronic speed controller (ESC) is represented by an electric scooter controller. The airframe, which consists essentially of the body and the arms supporting the rotors, is made entirely of CFRP. The battery technology chosen for the reference scenario is based on a G/NMC811 chemistry, with a graphite anode and a lithium-based cathode containing nickel, manganese and cobalt in an 8:1:1 ratio. Additional battery chemistries are introduced in Section 6. The manufacturing processes for all these components include the extraction, transport and transformation of raw materials as well as the delivery of the manufactured component. The average global production (denoted by *GLO*) is chosen for the production of the components. This ensures general applicability and best reflects the current market. However, future research could explore the possibility of providing region-specific results. Finally, operations at the European level are considered. The UAV's battery is therefore powered by the European electricity mix. Table 3 provides the EcoInvent processes corresponding to these assumptions. From the process tree shown in Figure 2 and the EcoInvent processes listed in Table 3, it is possible to build the LCI and to determine the quantities of emissions to and extractions from the environment for each scenario. These cumulative exchanges are essential for evaluating the damages across the 16 impact categories using the characterization factors supplied by the EF methods.

3.2 Implementation

For the purpose of this study, a specific environmental module was developed and linked to the design optimization framework introduced by the authors in previous work [21, 25, 26]. By efficiently sizing the UAV from a set of spec-

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Table 3: EcoInvent 3.9 processes for the LCI.

Component	Unit	EcoInvent processes
Propeller	kg	Market for carbon fibre reinforced plastic, injection moulded [GLO]
Motor	kg	Market for electric motor, for electric scooter [GLO]
ESC	kg	Market for controller, for electric scooter [GLO]
Battery	kg	Market for battery cell, Li-ion, NMC811 [GLO]
Airframe	kg	Market for carbon fibre reinforced plastic, injection moulded [GLO]
Energy consumption	kWh	Market group for electricity, low voltage [EU]

Note: Terminology [*LOC*] refers to the geographic location: Europe without Switzerland (EU) and Global (GLO).

ifications, the process yields key component characteristics, such as mass, along with in-flight energy consumption. These outputs, which are essential for conducting the LCA, link the design process to the environmental module. Figure 3 represents the integration of the environmental module with the sizing optimization, using the eXtended Design Structure Matrix (XDSM) notation [37]. The sizing framework and the environmental module are depicted as green boxes, while parallelograms represent data inputs and outputs. Data connections are represented by vertical lines for inputs and horizontal lines for outputs. The environmental module consists of a 3-step procedure, as shown in Figure 4.

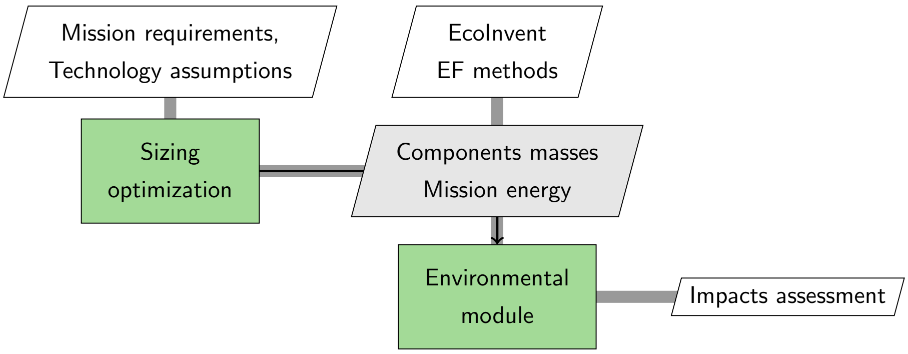

Figure 3: Overview of the methodology using the XDSM notation [37].

The first step consists of building a parametric model for the life cycle inventory, as represented by the process tree in Figure 2. For this purpose, the background processes are imported from the EcoInvent database, and the parameters for modeling the reference flows are created. The functional unit is defined as a parameterized combination of the foreground processes, which are themselves expressed by the background processes. In this approach, the inventory can be expressed in the form of a symbolic expression referring to the background processes:

$$
\begin{aligned}
\text{Inventory} =& f(P_i, B_j) \\
=& m_{propellers} \times B_{propeller} + m_{motors} \times B_{motor} + m_{esc} \times B_{controller} + m_{airframe} \times B_{airframe} \\
&+ m_{battery} \times \lceil \frac{n_{cycles}}{n_{cycles,battery}} \rceil \times B_{battery} + E_{mission} \times n_{cycles} \times B_{electricity}
\end{aligned}
$$

where P_i are the parameters from Table 2, and B_j are the background processes introduced in Table 3. The parametric inventory is created once and for all, and is common to all life cycle assessments carried in this study.

In the second step, the parameters' values are assigned from the outputs of the sizing optimization, which differ depending on the mission requirements and technology assumptions. Additionally, LCA-specific variables (e.g. UAV lifespan) are introduced. This second step is crucial in linking the LCA to the design framework.

Finally, the parametric inventory and the assigned parameters are fed into the sub-module for impact assessment. The impacts are calculated in two stages, as proposed by Jolivet [38]. During instantiation, i.e. the first time the sub-module is called, the impacts of each background process are computed. This initial calculation is time-consuming due to the extensive data associated with the background processes [39]. The impacts are then substituted into the parametric inventory, allowing the creation of algebraic formulas for each impact that involve only the parameters P_i [38]:

$$\text{Impact}_k = f_k(P_i)$$

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Therefore, the subsequent evaluations of the impacts are processed in a very short time. This is important when evaluating a large number of scenarios, e.g. for sensitivity analyses. Lastly, the results for each impact category are normalized and weighted on the basis of the factors introduced by the EF [33]. As recommended by the EF, a single score aggregating all the impacts is also returned.

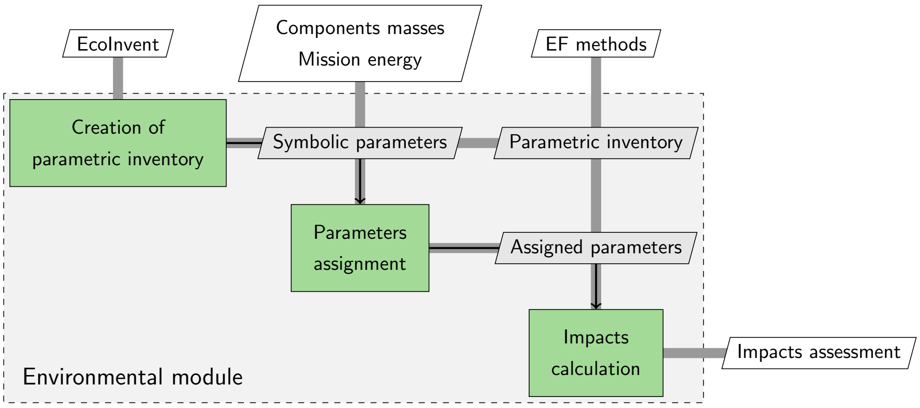

Figure 4: Representation of the environmental module using the XDSM notation [37].

The environmental module is fully integrated with the design framework [26], which relies on FAST-OAD [40] and the *OpenMDAO* platform [41]. It leverages the capabilities of *Brightway* for performing LCA in the Python programming language [42]. The implementation of parameterized models for the LCA is enabled by the *lca_algebraic* library [38]. This layer on top of *Brightway* brings symbolic calculus to LCA, which is essential for building the parametric inventory and supporting fast processing speeds of the impacts assessment.

4. Results for the reference scenario

The main results of the environmental study for the reference scenario are presented here. The main design parameters of the UAV, obtained from the specifications through the sizing optimization, are provided in Table 4. The single score for the design thus obtained is equal to 0.095 points over the entire life cycle, or 2.4 $\times 10^{-6}$ points/kg.km.

Figure 5 provides more information on the contributions to this single score. The most critical stage is the production of the components, which accounts for 65% of the total environmental footprint. For this stage, battery production represents more than 90% of the impacts. This is due to the battery being replaced every 400 cycles, i.e. 6 times during the 2 years of use. The contributions of the airframe, propellers, motors and electronic speed controllers are negligible, particularly due to their low mass. Early replacement of these components, for example in the event of a malfunction, would not significantly affect the results.

Table 4: Results of the sizing optimization for the coaxial hexacopter, for the reference scenario.

UAV total mass *	5.62 kg	Battery mass	1.69 kg
Motors mass	0.42 kg	Airframe mass	0.35 kg
Propellers mass	0.08 kg	Arms length	0.21 m
Propellers diameter	0.21 m	Mission energy	257 Wh
ESC mass	0.08 kg	Mission duration	23 min

* including payload mass.

As shown in Figure 6, the most relevant impact categories are resource use — both metals and minerals, and non-renewable energy — and climate change. These categories account for 37%, 13%, and 14% of the total impacts, respectively. The operation stage is particularly important regarding climate change and non-renewable energy use, as it represents more than half of the impacts in these categories (Figure 7). The consequences are twofold. Firstly, the transition to a low-carbon electricity mix is essential for operating UAVs. Secondly, reducing energy consumption is a key factor for mitigating the impact on climate change, provided that it is not accompanied by a transfer of the impact to the production stage. Future work should assess the sensitivity of environmental impacts to the efficiency of the propulsion chain, the aerodynamics of the airframe and the mass of the UAV. Finally, reducing the depletion of

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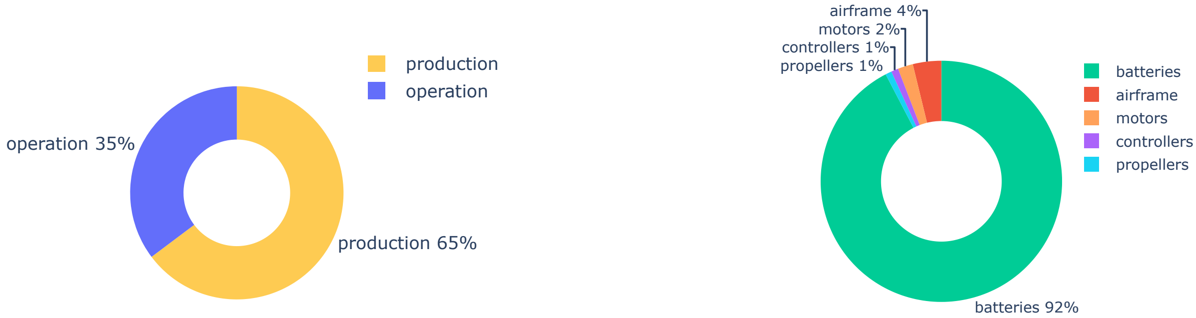

(a) Production and operation stages.

(b) Components production and renewal.

Figure 5: Contributions to the single overall score for the reference scenario.

metals and minerals requires batteries that consume fewer critical compounds, last longer so they have to be replaced less frequently, or can be easily recycled. Again, particular attention must be paid to the transfer of impacts between the production and operation stages due to changes in battery technology. This point is covered in Section 6.

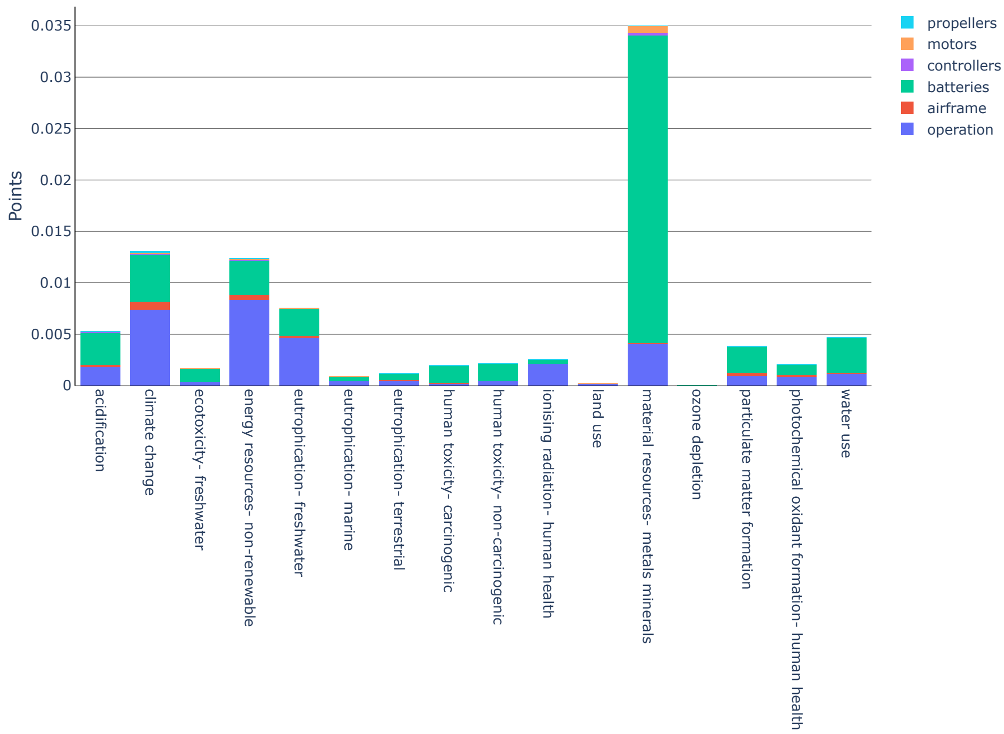

Figure 6: Normalized and weighted scores for the reference scenario.

5. Sensitivity to UAV’s lifespan and mission requirements

Alternative scenarios are assessed to investigate the effects of a change in the assumptions underlying the functional unit.

First, the UAV’s lifespan is varied. In practice, this means using the UAV more intensively, flying more missions per day or using the UAV for a longer period of time before replacing it. Figure 8 provides the evolution of the single overall score with the total number of cycles, or missions, in the functional unit. Battery replacement every 400 cycles is responsible for the steps observed in the plots. The proportion of impacts caused by the operation and production

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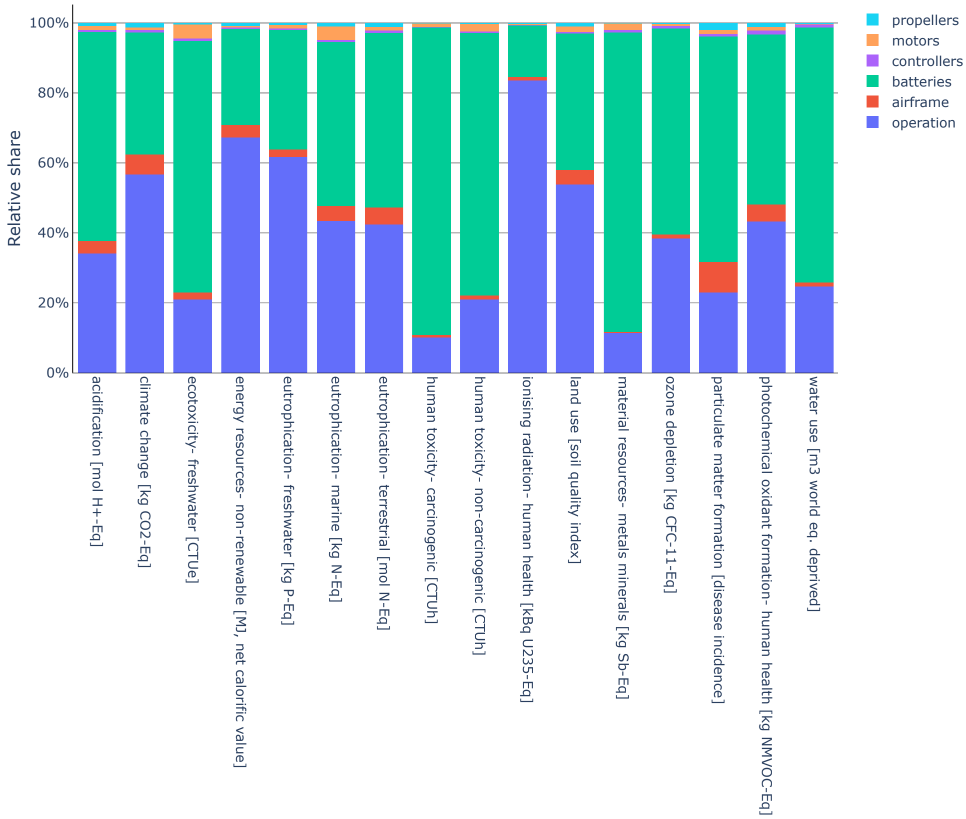

Figure 7: Relative contributions to each impact category for the reference scenario.

stages varies only slightly. For 1000 cycles, 38% of the total environmental footprint is attributed to operation, and 62% to production. At 10,000 cycles these figures are 31% and 69% respectively. This result contrasts with life cycle analyses of conventional kerosene-fueled aircraft where the manufacturing stage quickly becomes negligible compared to the kerosene life cycle [43]. However, if attributing the impacts of the batteries to the operating stage rather than the production stage, as André and Hajek propose [44], similar results to those for conventional aircraft are obtained. With this approach, the system comprising the batteries and the energy supply (i.e. electricity from the grid) accounts for up to 98% of the total environmental footprint when the number of cycles increases to 10,000. This is in the same order of magnitude as the production and combustion of jet fuel for conventional aircraft. Finally, Table 5 provides the single scores for different numbers of cycles. The results are expressed for the entire life cycle, per cycle and per kilogram of payload transported per kilometer. The results show little change in the score per kg.km with usage intensity.

Table 5: Single overall score for different numbers of cycles.

Number of cycles	**Single score (points)**			
	Total	**Per cycle**	**Per kg.km**	**Relative change per kg.km**
1,000	0.042	4.18×10^{-5}	2.78×10^{-6}	+ 15 %
2,600 (reference)	0.095	3.64×10^{-5}	2.43×10^{-6}	—
10,000	0.335	3.35×10^{-5}	2.23×10^{-6}	- 8 %

Secondly, the main design-related parameters of the functional unit are varied. In this study, the two parameters of interest are the payload mass and the delivery distance. These parameters define the delivery mission, which in turn affects the sizing of the UAV through design optimization. Indeed, as stated in Section 2.3, the UAV is minimally sized for achieving the mission specified by the functional unit. According to Table 1, the payload mass is varied in the range [0.5 - 5] kg, and the delivery distance in the range [5 - 12.5] km. The payload attachment and release mechanism is assumed to be unchanged regardless of the payload mass. Figure 9 shows the results of the design process in terms of both UAV mass and environmental single score, for a fixed number of 2,600 cycles. The environmental score is

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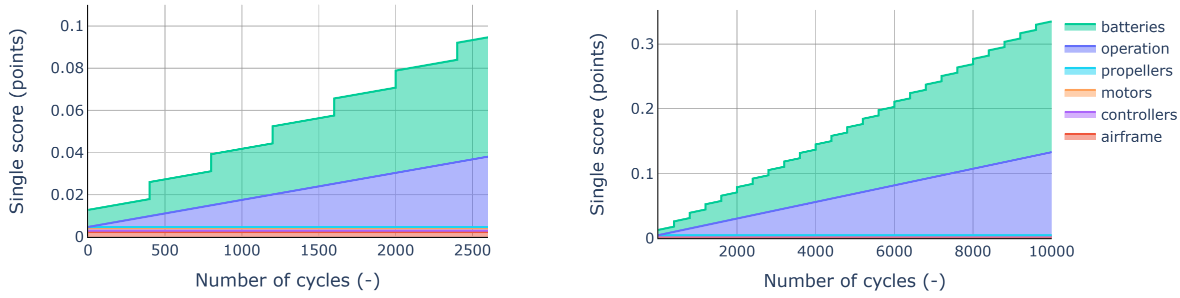
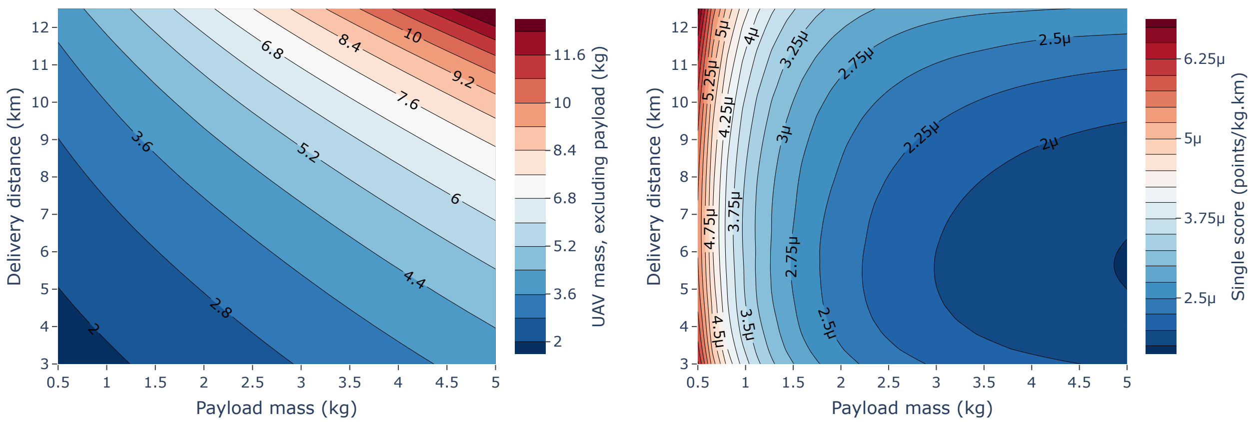


(a) Range [0 - 2,600] cycles.

(b) Range [0 - 10,000] cycles.

Figure 8: Variation of the single overall score with the number of cycles.

expressed in points/kg.km to allow comparison on a common basis.



(a) UAV mass, excluding payload.

(b) Environmental single score.

Figure 9: Results of the design optimization for various payload masses and delivery distances.

It is observed that UAVs designed for carrying heavy loads on short distances yield lower impact than their counterparts. This design area puts the emphasis on power-related criteria (e.g. to achieve take-off with a heavy payload) rather than endurance. Since battery sizing is primarily influenced by endurance criteria, this domain allows the battery to be lighter, thereby reducing its environmental impact. The increase in mass of the propellers, motors, speed controller and airframe, which are primarily sized from power requirements, does not outweigh the savings offered by the reduced battery mass. Indeed, the single overall score is more sensitive to the battery mass than that of the other components. This mechanism also explains why the environmental score is almost independent of the total mass of the UAV. In fact, a long endurance, low carrying capacity UAV may have the same mass as a UAV carrying heavy loads over short distances. For the same total mass, the different mass distribution of the components results in different environmental impacts. The inverse effects observed for very short distances, that is, an increase of environmental impacts for distances below 5 km, coincide with a tipping point for the sensitivity of battery sizing to the mission distance. For these distances, the take-off and the payload drop-off phases, whose duration is incompressible, are no longer negligible compared to the cruising phase. As a result, a reduction in the delivery distance no longer makes it possible to reduce in the same proportions the energy consumed over the mission, and ultimately the size of the battery and its impact.

6. Comparative analysis of different battery chemistries

The findings in Section 4 demonstrate that the environmental impacts of the UAV are primarily attributed to batteries, specifically due to depletion of metals and minerals. Therefore, the consequences of modifying the battery chemistry employed in the UAV design are investigated. To this end, two alternative battery chemistries are introduced alongside

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the reference battery, which utilizes G/NMC811 chemistry. The first alternative battery uses lithium iron phosphate (*LFP*) as the cathode material and graphite as the anode. Despite LFP batteries having lower energy density compared to NMC batteries, they provide a significantly longer cycle life, reaching several thousand cycles. The present study considers a conservative value of 1,500 cycles [45], along with an energy density of 119 Wh/kg [46]. The second alternative battery replaces the conventional graphite anode with a silicon nanowire anode (referred as *Si*), as proposed by Amprius [47, 48]. Although the anode can be paired with various cathode materials, an NMC811 chemistry is selected in this study. This technology allows for achieving high energy densities at the expense of reduced battery lifespan. For the specific application under study, an energy density of 360 Wh/kg is assumed, corresponding to a C-rate of 3C for balance between power and energy [47]. Although Amprius claims a cycle life of 325 cycles for a C/5 battery, which corresponds to very high endurance applications [47], an increased charge-discharge rate is likely to reduce this specification [49]. Consequently, a conservative value of 150 cycles is assumed for the Si/NMC chemistry. Table 6 provides a summary of the characteristics of the three battery chemistries. Detailed information on the life cycle inventory, more specifically the process tree and the EcoInvent processes related to the batteries, is provided in Appendix B.

Table 6: Assumptions for the three battery chemistries used in this study.

Battery chemistry	**Energy density (Wh/kg)**	**Proposed lifespan (cycles)**
G/NMC (reference)	191 [28]	400 [29]
G/LFP	119 [46]	1500 [45]
Si/NMC	360 [47]	150 [47]

Table 7 shows the results for the UAV designs obtained with the three battery chemistries. The single overall score is provided for the transport of a 2 kg payload over a distance of 7.5 km during 2,600 cycles. The differences observed in the total mass of the UAVs are due to the lighter (or heavier) batteries, which in turn lead to the oversizing (or undersizing) of the other components to accommodate the extra mass.

Table 7: Sizing results and environmental scores for the UAV designs obtained with the three battery chemistries.

Battery chemistry	**UAV design**		**Environmental single score**			
	Total mass* (kg)	Battery mass (kg)	Points**	Relative variation	Share production	Share operation
G/NMC (reference)	5.62	1.69	0.095	—	65 %	35 %
G/LFP	9.73	4.40	0.093	- 2 %	41 %	59 %
Si/NMC	4.48	0.80	0.156	+ 65 %	83 %	17 %

* including payload mass.

** over the entire life cycle.

On the one hand, the design based on the Si/NMC chemistry requires a significantly lower battery mass to fulfil the delivery mission. However, despite the mass reduction, the Si/NMC battery does not decrease any of the environmental impacts compared to the G/NMC reference battery, as shown in Figure 10. Specifically, the single overall score is increased by +65% compared to the reference chemistry. This is primarily due to the additional processing required to produce the silicon nanowire used in the anode, as detailed by Li *et al.* [50], and the very short lifespan of the battery, resulting in frequent replacement. Indeed, 18 batteries must be produced to fulfil the application over the two-year period. The impact of this can be seen in the proportion of the single score attributed to the production stage, which accounts for 83% for the Si/NMC battery. In other words, although the Si/NMC chemistry offers energy savings due to its lighter weight, these savings are outweighed by the significant battery production required for the UAV's continuous operation.

On the other hand, the design involving G/LFP chemistry is considerably heavier than its counterparts due to its lower energy density. However, the increase in mass is offset by the battery's long lifetime, which is almost four times that of the G/NMC chemistry and ten times that of the Si/NMC chemistry. By increasing the weight of the UAV while reducing the number of replacements, the G/LFP battery shifts the environmental burdens to the operation stage. With this technology, the use of a low-carbon electricity mix becomes critical to minimize the impacts on global warming and the consumption of non-renewable energy resources. Overall, G/NMC and G/LFP batteries have similar environmental single scores.

Interestingly, the usage intensity does not significantly affect the results, as shown in Figure 11, which illustrates the change in the single score with the total number of cycles for the application.

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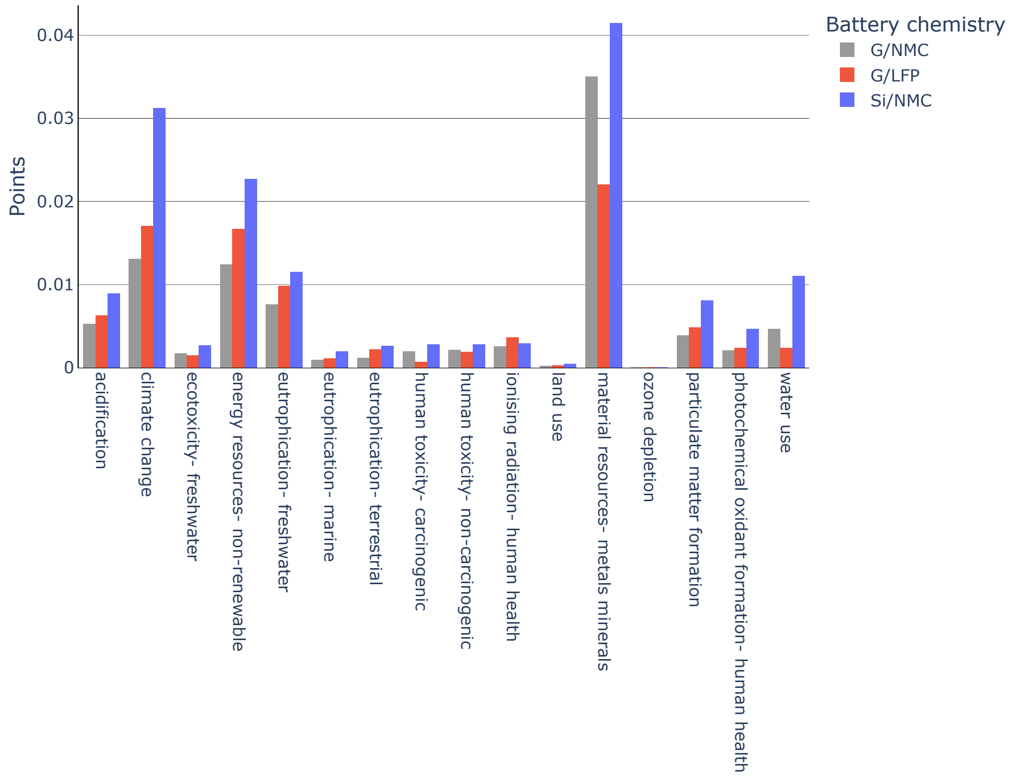

Figure 10: Normalized and weighted results for the UAV designs obtained with the three battery chemistries.

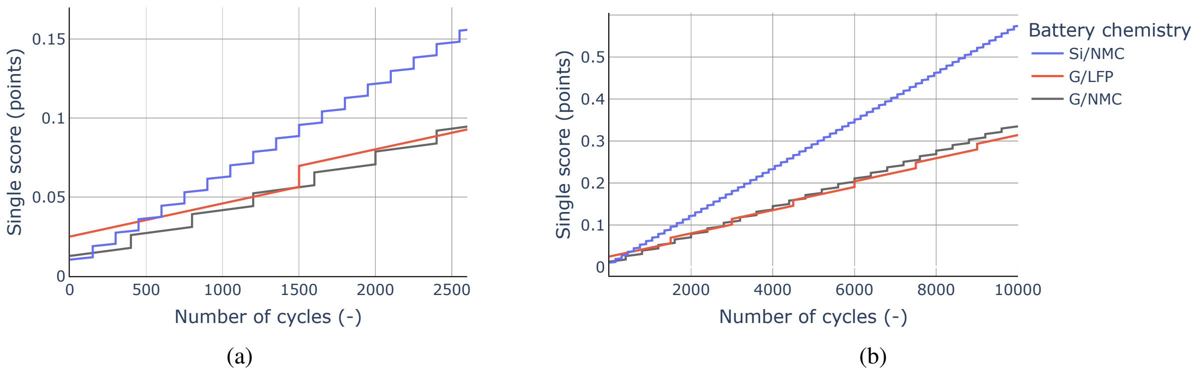

Figure 11: Variations of the single overall scores with the number of cycles, for the UAV designs obtained with the three battery chemistries.

7. Conclusions

This article presents the application of life cycle assessments to the early design of multirotor UAVs. In doing so, it provides insights for making the right design choices to mitigate the environmental impact of UAVs.

To this end, a new environmental module based on the LCA methodology is developed and integrated into an existing framework for the preliminary design of UAVs. The module uses the capabilities of the *Brightway* and *lca_algebraic* Python libraries to build a parametric LCA model for UAVs and relies on EcoInvent to collect inventory data. By directly linking the LCA to the outputs of the sizing process through the model's parameters, the environmental analysis efficiently calculates impacts for various design alternatives driven by mission requirements and technology assumptions. The results show that battery production and renewal contribute significantly to the environmental impact of UAVs. For this reason, UAVs designed to cover short distances have a better environmental score per kg.km of payload carried, as the size of the battery increases rapidly with range. Finally, it is shown that using batteries with a higher energy density does not necessarily reduce the impacts. In fact, battery lifespan is a key parameter and the frequent renewal of short-life batteries, such as Si/NMC chemistries, can largely outweigh the gains in mass and

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in-flight energy consumption.

Further research should focus on the evaluation of fixed-wing UAVs and hybrid vertical take-off and landing (VTOL) UAVs. Combined with existing studies on the environmental impact of ground vehicles, this could provide valuable information for comparing and selecting the most appropriate vehicle for a given application. In addition, the methodology could be improved with further integration of the environmental module into the design framework, allowing the UAV and its components to be sized for minimizing environmental impact. This shift from conventional practices, which are typically based on mass or energy consumption objectives, holds promise for advancing aerospace systems towards more environmentally conscious designs.

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Appendices

A. Reference technologies and assumptions for the design optimization

Table 8: Reference technologies and assumptions for the components' models used in the design optimization.

Component	**Reference technology / Assumptions**
Propeller	APC Propellers for Multi-Rotors
Motor	AXI 5325/16 GOLD LINE
Electronic Speed Controller	Turnigy K-Force 70HV
Battery	DJI TB30 Battery with NMC811 chemistry
	Energy density ρ = 191 Wh/kg,
	400 cycles lifetime,
	85% charge-discharge efficiency
Airframe	Carbon fibre-reinforced plastic
	Density ρ = 1700 kg/m^3,
	Allowable stress σ = 280 MPa,
	Drag coefficient C_D = 1.0

B. Process tree and EcoInvent processes for the batteries production

The production processes for the G/NMC and G/LFP batteries were taken from EcoInvent 3.9. In the case of the Si/NMC chemistry, the activity has been reconstructed using the data provided by Li *et al.* [50]. More specifically, the EcoInvent activity for the G/NMC battery is used as the basis, with the graphite component in the anode replaced by silicon nanowire.

Table 9: EcoInvent 3.9 processes for the different battery chemistries.

Battery chemistry	Unit	EcoInvent processes
G/NMC	kg	Market for battery cell, Li-ion, NMC811 [GLO]
G/LFP	kg	Market for battery cell, Li-ion, LFP [GLO]
Si/NMC	kg	Market for battery cell, Li-ion, NMC811 [GLO]
	kg	Market for silicon, solar grade [GLO]
	kWh	Market group for electricity, medium voltage [CN]

Note: [CN] refers to China geographical location.

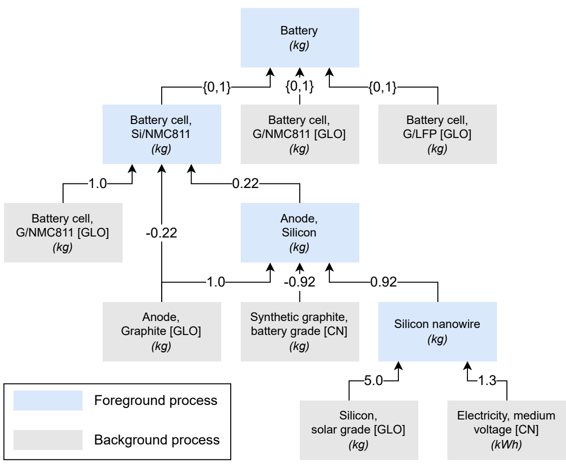

Figure 12: Process tree for the batteries production. {0, 1} represents a boolean option.