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Assessing the Technical–Economic Feasibility of Low-Altitude Unmanned Airships: Methodology and Comparative Case Studies

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Abstract: The current growing interest in lighter-than-air platforms (LTA) has been fueled by the significant development of some enabling technologies, in particular electric motors and on-board electronics. The localization of multiple thrust forces in the layout of the airship, as well as the ability to manage them through automatic control, promises to mitigate the controllability issues connatural to this type of flying craft. Employed on unmanned missions and close to the ground, LTA vehicles now appear to be a technically viable alternative to other unmanned aerial vehicles (UAVs) or low-flying manned machines and are similarly capable of effectively achieving the corresponding mission goals. A key step in establishing the credibility of LTA vehicles as industrial solutions for an end user is an assessment of the economic effort required for producing and operating them. This study presents an analytic approach for evaluating these costs, based on the data available at a preliminary design level for an airship. Three missions currently flown by other types of flying machines were considered, and for each mission the sizing and preliminary design of a LTA platform capable of providing the same mission performance was carried out. Correspondingly, a newly introduced method for the estimation of the cost of a LTA platform was applied. Also, an estimation of the costs currently sustained by operators for each mission was obtained from the available data and with the support of relevant companies, who currently do not fly LTA platforms but operate with more standard flying machines (in particular, multicopter or fixed-wing UAVs or manned helicopters). Finally, the costs corresponding to both currently flying non-LTA vehicles and suitably designed LTA solutions were compared, yielding indications of the emerging economic trade-offs.

Keywords: airship; design; unmanned; economics; feasibility; cost; scenario; trade-off; opportunity; comparison; multicopter; LTA; LCC; UAV

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1. Introduction

The recent development of lighter-than-air (LTA) platforms for low-altitude missions, evidenced by the growing number of new companies offering services based on this type of machine (like Kelluu [1], HyLight [2], Roboloon [3] or FloFleet [4] in Europe; see Figure 1), has been fueled by the advancement of some key enabling technologies.

Among them, electric motors for powering propellers offer a higher power-to-weight ratio compared to internal combustion engines. The adoption of these motors is especially advantageous on airships, since they can supply thrust for both propulsion and attitude control when suitably positioned in a distributed fashion at multiple locations in the layout of an airship [5–9]. Additionally, the comparatively low expenditure of energy for propulsion and the reduced peak power required even in terminal maneuvers, compared to either fixed-wing aircraft [10] or rotorcraft [11], make the sizing of the batteries far less penalizing than in heavier-than-air platforms, both in terms of the battery mass for the mission and the corresponding battery volume.

Figure 1. Examples of unmanned commercially available airships. (**Top left**): Kelluu [1]. (**Top right**): HyLight [2]. (**Bottom left**): Roboloon *Squid* [3]. (**Bottom right**): FloFleet *Polar Owl* [4].

Similarly relevant has been the advancement of on-board electronics, not just in terms of the weight to computational power or weight to accuracy, respectively, of the electronic components and sensors required for automatic control, but also in terms of the absolute computational power and protocol standardization. The state of the art in the field allows one to affordably and efficiently program and physically implement a reliable and safe flight control system [12], coping with the specific features of a non-standard flying machine like a LTA platform governed by differential thrust as well as aerodynamic surfaces [7]. Fueled by the boom in the multicopter UAV market over the past decade, effective on-board electronics constitute a key enabler for unmanned LTA platforms as well, especially since the removal of the crew and crew-related masses (e.g., a cockpit, physical control stick, related power lines, etc.) from an airship significantly saves on its buoyant volume as well.

The combined use of these technologies is producing technically viable LTA solutions, with clear performance advantages, especially in terms of endurance in forward flight and the time over target in hovering or station-keeping phases, compared to other flying machines like fixed-wing aircraft (incapable of hovering) and rotorcraft (dramatically limited in terms of their endurance and time over target). Clearly, on the other hand, their volume creates control challenges (mostly a tendency to drift in an air stream) and logistical difficulties (especially regarding a suitable ground infrastructure), which intrinsically limit their adoption. However, even for those missions where LTA platforms could be employed from a technical standpoint, their consideration by a potential industrial end user is still hindered by uncertainty in the costs associated with acquisition and operation and maintenance (O&M).

In this regard, the present work aims to shed some light on these, by firstly introducing a simple analytic method for the most relevant components of the life cycle cost of a LTA platform for low-altitude use. As is typical in the field of aeronautics, these components are associated with design and production, which are jointly the major drivers of the acquisition cost for an end user, as well as with O&M. Secondarily, this work provides a detailed analysis of three case studies, where the costs associated with flying machines currently operating a mission, namely a quadcopter UAV, a fixed-wing UAV and a manned helicopter, obtained as much as possible by processing relevant company data from actual operators, are compared to a cost prediction made for a LTA platform capable of achieving the same mission target.

1.1. Cost Prediction Approach

Among the many available cost prediction methods [13], for the scenario at hand, where there are still not many practical realizations, a parametric estimation (PE) method [14] based on cost-estimating relationships (CERs) for the sub-components of each major cost component was adopted, trying to capture all major potential contributions to a specific cost. The advantage of a PE approach is that for cost estimation it uses only data typically available at a preliminary design stage, like the breakdown of the take-off mass, the installed thrust, etc. A primary example of this approach is the DAPCA-IV model [15], established in the 1970s–1980s and still largely employed in the baseline approach for cost estimation in the field of aviation [16–18]. According to this class of cost estimation methods, in order to feed CERs in the case of a LTA platform and obtain a cost prediction, it is possible to employ data on a LTA design solution obtained from a suitable preliminary design exercise (like the volume, mass, etc.), considering a specific target mission. Such a design exercise can be carried out in a largely automated fashion, thanks to consolidated procedures available in the literature bearing credible results once values pertaining to the mission at hand have been assigned [8,16,19,20].

Among the disadvantages of a PE method is the reliance on statistical data in most CER expressions. Of course, besides carrying out the due actualization of some of the financial coefficients, for some components of the cost, good commonality with respect to other applications in the industrial field can be expected (e.g., the cost of engineering). For components more typical to the LTA case, the building up of simple CERs has been attempted (especially for the material cost), mostly based on current industrial datasheets. Furthermore, CERs for research, development, testing and engineering (RDTE) costs, as well as manufacturing, have been considered for LTA platforms. However, the estimation of the O&M cost was treated in a slightly different way for each case study at hand, on account of some specific features of each of the missions analyzed, yielding the need for such customization (this will be illustrated in detail in each case study). Finally, in order to cope with the unavoidable inaccuracy in the cost estimation method, a perturbation analysis was carried out, checking the effects of perturbations to some of the data involved in cost estimation on the corresponding cost predictions. The intensity of the perturbations was assumed based on an autonomous judgment by the authors, based on the perceived reliability of the corresponding nominal value of each considered parameter (i.e., when greater uncertainty was present in the nominal value of a parameter, a broader perturbation range was considered).

1.2. Considered Case Studies

Three missions were considered among those currently flown by either UAVs or manned machines which could be flown by a low-altitude LTA platform at the current level of technology and without the need for an unrealistically big size of the envelope. These are listed below:

1. *Solar power plant inspection*. This mission is currently frequently carried out using multicopter UAVs, which accurately overfly the plant from a close distance with visual and infrared sensors, looking for debris, dust accumulation and wear or damage to the cells. As a reference case for a quantitative analysis, the 87 MW plant of Trino Vercellese (VC) in northern Italy was selected.
2. *Sea life monitoring*. This type of mission is currently flown with a fixed-wing UAV, which takes off from a nearby airstrip and flies to a monitoring area over high waters, where it spends most of the mission in a loiter pattern, observing sea life using electro-optical, infrared or mirrorless digital camera sensors. As a reference case, the cetacean study mission carried out by a joint group including the Italian Coast Guard near the Pelagos sanctuary in the Ligurian Sea in northern Italy was considered.
3. *Pipeline inspection*. This mission is typically currently flown with manned helicopters, often crewed by technicians with manual cameras, who inspect the pipeline in search of leaks and wear of the pipeline structure, while also checking the safety of the surroundings close to the pipeline. The practical case of the Italian section of the Transalpine Oil Pipeline (TAL), linking Trieste (IT) to Ingolstadt (DE), was considered for this analysis.

None of these missions are associated with significant restrictions impacting volume, thus enhancing the relevance and credibility of this study. In comparison, a mission like roof inspections for tall buildings, currently flown with multicopters and totally compatible with the performance and lifting ability of a dedicated LTA platform, was not considered, on account of the likely excessive volume of a LTA platform when operating in crowded and narrow town streets (in other words, a LTA platform would be technically feasible and possibly even economically advantageous in theory in that case, but the LTA solution would likely be less acceptable for the public and for potential end users as well, due to exogenous constraints). Additionally, none of these missions is performed in adverse meteorological conditions, including in the presence of significant wind. Actually, the controllability of LTA platforms, despite being technically achievable today even in the presence of wind [5,6], would come with a reduced level of accuracy in overflights and hence reduced mission efficacy for LTA platforms. However, since the other considered flying platforms, albeit less prone to being affected by wind disturbances, are also not operated in adverse meteorological conditions on account of their reduced efficacy, the presented comparisons are deemed sufficiently fair in this respect as well.

1.3. Structure of the Work

The next sections will cover the proposed cost estimation models for the RDTE and manufacturing costs for a LTA platform. Then, the basics of a preliminary sizing method for airships, mostly taken from other work, will be reviewed. Subsequently, the focus will be moved to the three proposed scenarios for comparison, considered one by one, where the mission will be quantitatively defined, and the cost pertaining to the current flying solution—from now on, defined with the tag AS-IS—will be evaluated from the available data and models, both in terms of the production (or acquisition, for an end user) and O&M

costs. For each case study, a LTA platform will be preliminarily sized for the mission—a solution from now on associated with the tag TO-BE. Finally, the acquisition and O&M costs for an operator, pertaining to the AS-IS vs. TO-BE flying solutions, will be compared. In their respective sections and in the Conclusions, indications from the three test cases will be summarized and synthesized.

Cost predictions for the TO-BE LTA solutions and the various flying vehicles in the respective AS-IS configurations were sometimes supported or fed by information provided by Entities or industrial subjects relevant to the field. Some of this information is publicly available, where other was obtained from direct contact with the respective representatives through dedicated interviews.

2. Estimation of Production Cost for Low-Altitude Airships

As stated in the Introduction (Section 1.1), cost estimation relationships (CERs) were considered for the forecast of the cost associated with the production of an airship. Some of the CERs were obtained from existing general models originally developed for fixed-wing aviation [14,15], on account of the similarity between the corresponding processes and those implemented or required for the manufacture of a lighter-than-air platform.

2.1. Cost Estimation Relationships

A first set of CERs, all associated with recurring costs (i.e., costs proportional to the production volume), allowed us to estimate the time required for completing a task. This time could be multiplied by a suitable hourly rate to obtain the actual corresponding recurring cost. This set was as follows:

- *Airframe engineering*. Engineering activities include design studies, the design of testing facilities, laboratory work and the creation of technical documentation. The number of engineering hours, T_E, can be computed as

$$T_E = 4.86 W_e^{0.777} V^{0.894} Q^{0.163}, \tag{1}$$

  where W_e is the empty weight of the craft (in pounds), V is the maximum speed at altitude (in knots), and Q is the cumulative quantity of the items produced (i.e., the number of LTA platforms leaving the production line, in the case at hand).
- *Tooling*. This includes tool design and manufacturing and the manufacturing of test rigs, as well as the checking and maintenance of production tools. The corresponding time (in hours) for tooling, T_T, is computed as

$$T_T = 5.99 W_e^{0.777} V^{0.696} Q^{0.263}. \tag{2}$$

- *Manufacturing labor*. This includes the manufacturing processes and the assembly or installation of the parts composing the production item. The corresponding time (in hours) is obtained as

$$T_L = 7.37 W_e^{0.82} V^{0.484} Q^{0.641}. \tag{3}$$

- *Quality control*. This includes all quality control processes at all levels of the design, testing and production of the item, and it can be computed as a proportion of T_L as

$$T_Q = 0.13 T_L. \tag{4}$$

Another set of CERs allowed us to compute a cost value directly, in US Dollars of 1998 (USD_{1998}). These cost components were either non-recurring (see Equation (5)) or recurring. This set was composed of the following:

- *Development support*. This is the non-recurring component of the engineering cost, and it is essentially modeled to measure the cost of engineering which is not proportional to the volume of production. This cost can be obtained (in USD_{1998}) as

$$C_D = 66.0 W_e^{0.63} V^{1.3}. \tag{5}$$

- *Flight test operations*. This cost is that of all flight test operations, excluding the cost of the test exemplars of the produced item. It can be obtained as

$$C_F = 1852.0 W_e^{0.325} V^{0.822} Q_D^{1.21}, \tag{6}$$

  where Q_D is the number of items employed for testing.

The hourly rate considered in this work as a multiplier for the time estimations provided by Equations (1)–(4) was taken from Italian statistics for an average-sized industry carrying out technical activities in the aeronautical field, and it was equal to $HR = 80.0$ EUR/h [21]. Costs expressed in USD_{1998} were actualized with reference to the same date according to the economic escalation factor $EF = 1.654$ from 1998 and were converted to Euros according to the rate in August 2024 (1 USD = 0.92 EUR).

Concerning the manufacturing material and equipment costs, LTA platforms differ significantly from other flying craft. Therefore, an estimation of this cost was built up from scratch by conceptually considering the major components of the LTA platform and introducing corresponding CERs for each of them. Notably, a non-rigid construction paradigm was considered (oftentimes referred to as a *blimp*), which is the most widespread construction solution for smaller-scale airships designed to sustain limited loads [1–4]. Furthermore, since electric propulsion with batteries was considered as an enabling technology, as stated in the Introduction (Section 1), it was assumed to work with this type of propulsion. The following list of additional CERs was therefore created:

- *Envelope*. Considering a non-rigid structure, the material of the envelope is typically manufactured in sheets, for which the cost per unit of surface is typically available from the material providers. Therefore, the corresponding cost C_{env} is defined by the CER as

$$C_{env} = A_{env} f_{env}, \tag{7}$$

  where A_{env} is the surface of the envelope, and f_{env} is the envelope pricing factor. For the latter, for representative polyurethane employed for low-volume machines, the value is $f_{env} = 3.50$ EUR/m^2 [22] (whereas by comparison, for material for an airship featuring a bigger size and load like Tedlar, it is $f_{env} = 28.57$ EUR/m^2 [23]).
- *Structural components and systems*. In the case of a non-rigid airship, this includes the nacelle (typically hosting the payload, on-board computers, energy storage or power signal conditioning systems) and notably excludes the payload. Similarly to aircraft, it is assumed that this cost is proportional to the mass, yielding the CER

$$C_{str} = W_{str} f_{str}, \tag{8}$$

  where W_{str} is the structure and system mass, and f_{str} the corresponding pricing factor. A value for the latter was obtained starting from a basic estimation of the system cost by RAND for high-tech aeronautical applications [24], expressed in USD_{2005}, actualized to August 2024 using an escalation factor of $EF = 1.40$ and converted to EUR/kg, yielding $f_{str} = 2844$ EUR/kg.
- *Battery*. For batteries, a major driver in defining the cost is the amount of energy stored. Of course, depending on the chemistry of the battery, the pricing factor may change

significantly. Standard batteries employed for multicopter UAVs were considered, for which the CER can be expressed as

$$C_{bat} = W_{bat} e_{bat} f_{bat}. \tag{9}$$

where W_{bat} is the weight of the batteries, e_{bat} is the specific energy, and the battery pricing factor can be estimated as $f_{bat} = 2000$ EUR/kWh for the technology level of professional electrically propelled UAVs [25].

- *Lifting gas*. The prediction of the lifting gas cost is simply proportional to the gas volume V_{gas}:

  $$C_{gas} = Vol_{gas} f_{gas}, \tag{10}$$

  since the pricing factor is typically expressed in terms of the price per unit volume. The considered lifting gas was Helium 4.6, and its pricing factor fluctuates on a daily basis. An average representative value for 2024 was $f_{gas} = 110$ EUR/m^3 [26].

A final cost was associated with the payload, labeled C_{pl}. For this, a generally valid CER could not be found, since the nature, and hence the value, of the payload can change completely from one mission to another. Considering the applications at hand (see Section 1.2), the value of the characteristics and value of the corresponding payload will be discussed in the sections dedicated to each case study.

2.2. Prediction of Total Production Cost

According to the relationships introduced in Section 2.1, it is possible to predict the overall production cost of a single manufactured item by employing the following built-up equation:

$$\begin{aligned} C_{item} = \frac{1}{Q} \big[& (T_E + T_T + T_L + T_Q) HR + \\ & C_D + C_F \big] + \\ & C_{env} + C_{str} + C_{bat} + C_{gas} + \\ & C_{pl} \end{aligned} \tag{11}$$

where on the first line are the costs proportional to the man-hours (Equations (1)–(4)), on the second are the costs estimated directly from models for the aeronautical field (Equations (5)–(6)), on the third are the costs estimated specifically for the production of a LTA platform (Equations (7)–(10)), and on the last is the payload cost, which will be discussed case by case.

In Equation (11), all the costs appearing on the first line are recurring costs, depending on the production volume (represented by Q), whereas those on the second line are fixed costs for the program. All these costs are therefore divided by the production volume Q to yield the unitary production cost of an item. Conversely, costs appearing on the third and fourth lines were defined from the start as unitary costs per single item. Clearly, from Equation (11), it is evident that the cost, C_{item}, of a single item changes depending on the production volume, and the expected value of the latter should be planned based on the market demand. Guessing the market demand is typically one of the most complex managerial tasks, often requiring dedicated and expensive market studies, which are not within the scope of the present work. In the following case studies, the effect of a different production volume will be addressed to some extent through a parameterized analysis where multiple values are considered for Q.

3. Preliminary Sizing Methodology for Low-Altitude Unmanned LTA Platform

In order to carry out a sufficiently credible analysis of a LTA solution for each case study, a preliminary sizing technique capable of coping with the details of a specific mission and accounting for realistic assumptions specifically regarding the adopted technology (e.g., the materials employed, the general arrangement and layout of the airship, etc.) was employed. Indeed, some of the CERs introduced in the previous section (Section 2) similarly required a design problem to be solved to a certain level of detail (e.g., a breakdown of the take-off weight was required, not just its assembled value). Preliminary sizing techniques for airships offering a suitable level of detail are well documented in the literature [8,16,19,20]. A high-level description of the one adopted here, constituting the core routine of the `Morning Star` algorithm introduced elsewhere [8,20], is portrayed in Figure 2.

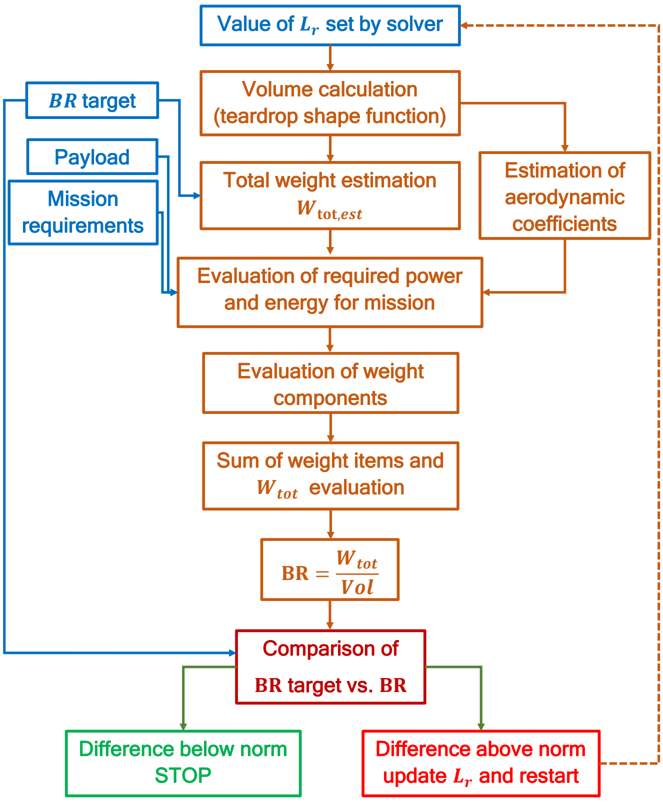

Figure 2. Flowchart of the airship sizing algorithm.

Some assumptions allowed us to actually simplify the more general design approach underlining `Morning Star` for the case studies at hand. Conceptually, for a low-altitude unmanned LTA platform featuring the low volume required to carry a limited payload, the naturally sustaining effect of buoyancy allowed us to cut down significantly on the energy requirement of the airship. Therefore, even for missions largely exceeding the values of endurance and the time over target typically set for AS-IS flying solutions, a TO-BE airship designed for the same mission parameters does not need to rely on solar cells or innovative propulsion systems to meet the mission energy requirement. Conversely, it shall feature a standard battery, capable of sustaining it for the entire mission without recharging, both in terms of the payload power and propulsion power. Additionally, even with a non-rigid airship, when only flying close to the ground, the use of ballonets or sophisticated pressure management systems to guarantee envelope integrity can be avoided.

With these simplifications, it was possible to employ a sizing algorithm not relying on any optimization, as illustrated in Figure 2 (and differently from the more general `Morning Star` approach). It was assumed that the shape of the envelope could be assigned through a shape function, basically producing a certain longitudinal distribution of the cross-sectional radii for a nominal length (an example of the application of a teardrop function as adopted in this work is presented in Figure 3). The radii scaled dimensionally with the length, L_r, of the airship envelope, through the multiplication of the length with the shape function. This allowed us to bind the geometrical sizing of the envelope to the single parameter L_r. The latter is first guessed by the user then manipulated by the algorithm as an iteration variable to bear the final sizing solution.

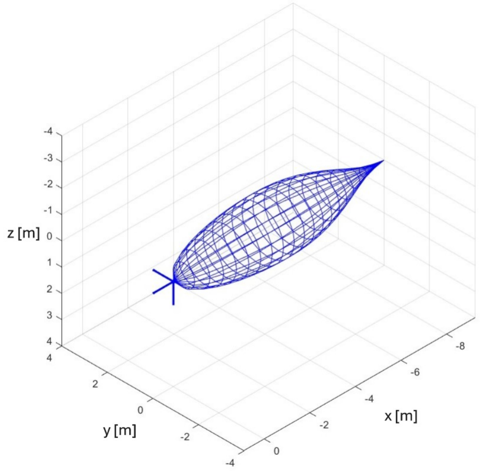

Figure 3. Example sizing solution for the envelope, showing the features of the teardrop shape function assumed for sizing in the procedure adopted in this work.

The automatic search for a sizing solution is fueled by user-defined data including the following data clusters:

- *Requirements of the mission to fly*. The mission profile is set according to the user's need, specifying the origin and target altitudes for climbs and descents, the time duration or range for the loiter or cruise phases, respectively, and the velocity to maintain on any leg.
- *Aerodynamic characteristics*. Reference values of the drag and lift coefficients are set by the user for any of the legs in the considered mission profile (ideally, a polar estimated from the current value of the geometry can be employed, provided that a corresponding parameterized description is available).
- *Values of relevant technology parameters*. Firstly, the estimation of the breakdown of the take-off mass requires models linking the mass of any component to other parameters, changed by the sizing algorithm as it progresses towards a solution. These models need to be provided by the user. Furthermore, the density of the envelope material and lifting gas, the energy and power densities of the battery and the power density of the electric motors need to be provided.
- *Target buoyancy ratio*. The convergence norm employed within the sizing algorithm is based on the buoyancy ratio $BR = \frac{W_{tot}}{\rho_{air} Vol}$, where ρ_{air} is the density of air. A target value is specified by the user and employed to trigger the sizing algorithm (see Figure 2). At the end of any iteration, the algorithm allows the user to compute a value of the buoyancy ratio among the other results, and by comparing this to the user-defined set point, the convergence is assessed, and a new iteration is started or the algorithm is arrested based on that.

The values of interest for the computation of the cost, among those obtained from the sizing algorithm, include those in Table 1. These allow us to employ the CERs in Section 2.1 and estimate C_{item} according to Equation (11) (the only remaining parameter being the volume of production Q, which needs to be assigned).

Table 1. Output of the sizing algorithm. Highlighted parameters are those of direct interest for the application of cost estimation models (Section 2.1).

Parameter	Unit	Symbol
Nacelle mass	[kg]	
Stabilizers mass	[kg]	
Movable control surfaces mass	[kg]	
Actuators mass	[kg]	
Electric motors mass	[kg]	
Propellers mass	[kg]	
Motor mountings mass	[kg]	
Motor cables mass	[kg]	
Signal conditioning mass	[kg]	
Miscellaneous systems mass	[kg]	
Structural components and systems mass (sum of the above)	[kg]	W_{str}
Battery mass	[kg]	W_{bat}
Envelope mass (external and septa)	[kg]	
Empty mass (sum of the above)	[kg]	W_e
Lifting gas mass	[kg]	
Envelope volume	[m^3]	Vol
Envelope external surface	[m^2]	A_{env}

4. Case Study A: Solar Plant Monitoring Mission

As mentioned in the Introduction, Section 1.2, the first case study is represented by the monitoring of a solar power plant.

4.1. Mission Requirements

The 87 MW plant in Trino Vercellese (VC) in northern Italy (Figure 4) features an almost rectangular shape and an area of 130 hectares (with sides of $s_1 = 1000$ m and $s_2 = 1300$ m).

From interviews with an Italian operator running similar monitoring missions [27], it was assumed that two cameras are required for this inspection mission, an infrared (IR) camera and a visual (RGB) camera, respectively. The former is employed for the detection of defective bypass diodes, weak connections or generically hot spots, which indicate defects in the cell components. The latter is employed for visual damage assessments, as well as for checking the level of accumulated debris and dirt on the panels. To reduce the duration of the mission, a single inspecting drone should simultaneously carry both cameras. Considering two cameras typically employed for this type of mission, the DJI Zenmuse XT (IR) and DJI Zenmuse Z30 (RGB), respectively [25], the optimal altitude for employment is $h_{cr} = 60$ m, which defines the cruising altitude of the UAV. Among those, the IR camera has the smallest inspection angle (32° by 26°), from which a transect width of $d_{tr} = 34.4$ m is obtained at an altitude of h_{cr}. This is the ground width of the scanned corridor when the inspecting UAV is moving forward. Assuming the UAV covers the plant area using a simple multi-transect trajectory, the number of transects can be estimated as $N_{tr} = s_1/d_{tr} = 29.07$. Finally, the total length of the trajectory to cover the field, i.e., the mission range R, is estimated as $R = N_{tr}s_2 = 37.7$ km.

Figure 4. Left: Solar plant at Trino Vercellese (VC) [28]. **Right**: DJI Matrice 210 RTK quadcopter [25].

4.2. Cost Analysis of AS-IS Mission: Quadcopter UAV

The quadcopter UAV considered for this case study was the DJI Matrice 210 RTK [25] (Figure 4), among the most commonly employed for monitoring tasks [27], capable of transporting two cameras at the same time. In order to estimate the acquisition cost for a potential operator, it was assumed that, besides the UAV and payload, a set of batteries is purchased. In particular, the DJI Matrice 200-TB55 Intelligent Flight Battery [25] was considered, for which the unit cost is $C_{bat,unit} = 351.64$ EUR, the nominal flight time is $T_{flight} = 24$ min and the recharge time is $T_{rec} = 2$ h 24 min. Assuming the need for a ready-to-fly UAV around the clock, a set of 12 batteries would be needed, yielding a battery cost of $C_{bat} = 12 \cdot C_{bat,unit} = 4219.67$ EUR. Table 2 reports the components of the purchase cost of a quadcopter UAV according to the assumptions of this case study. Additionally, on account of uncertainty in the price of components (especially batteries), and to extend the validity of the study when small changes in the identity of the components are considered, values corresponding to a flat perturbation of +/−15% of each value were considered.

Table 2. Components of acquisition cost for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
UAV [EUR]	8360.66	9836.07	11,311.48
IR camera [EUR]	4528.68	5327.86	6127.04
RGB camera [EUR]	2228.81	2622.13	3015.45
Batteries [EUR]	3586.72	4219.67	4852.62
Total acquisition cost [EUR]	**18,704**	**22,005**	**25,306**
Difference	−15%	-	+15%

The operating and maintenance (O&M) cost is made of four components, bound to the pilot’s salary, insurance, energy for recharging, and maintenance, respectively. All of these were computed for a single mission. In order to estimate the time taken for a mission, it was assumed that the time taken for inspecting 1 hectare of land is roughly 15 min/hectare [27]. Considering a working day composed of 8 h, and an area of 130 hectares, it was possible to firstly compute the total time taken for an inspection ($T_{mission} = 1950$ min) and finally the equivalent number of working days required for covering the entire site, equal to slightly more than 4 and increased here for safety (e.g., on account of the downtime for the UAV or payload) to 5 days. The pilot’s daily salary was computed starting from the Italian average value for an averagely skilled professional [21] and taking into account +/−50 EUR/day perturbations as in Table 3.

Table 3. Cost of pilot for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Pilot's daily salary [EUR]	350	400	450
Working days per mission	5	5	5
Cost of pilot per mission [EUR]	**1750**	**2000**	**2250**
Difference	−12.5%	-	+12.5%

The cost of insurance per mission was estimated through a similar procedure to that for the cost of the pilot. The annual insurance fee, estimated according to a national Italian average [21] and considering values perturbed by +/−20% as well, was scaled to the duration of a single mission, i.e., 5 days (as was just estimated). The results are presented in Table 4.

Table 4. Insurance cost for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Insurance cost per year [EUR]	640	800	960
Working days per mission	5	5	5
Insurance cost per mission [EUR]	**8.80**	**11.00**	**13.20**
Difference	−20%	-	+20%

The cost of energy associated with one mission was estimated according to the following model:

$$C_{rec} = E_{bat} f_e N_r, \tag{12}$$

where E_{bat} is the energy stored in a single battery, N_r is the number of single batteries recharged during a mission, and f_e is the unit price of energy. For the latter, an Italian average for 2024 for small businesses was employed, equal to $f_e = 0.26$ EUR/kWh [29]. A fluctuation of +/−5% was applied to this value as well. The number of recharges was obtained by dividing the duration of a mission, $T_{mission}$, by the time taken for a flight, T_{flight}, yielding a nominal value of $N_r = 164$. The latter was perturbed by +/−20% on account of a potentially changing battery performance (and rounded to the closest integer). Table 5 summarizes the results for nominal, minimum and maximum cost cases.

Table 5. Energy cost for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Nominal battery energy E_{bat} [kWh]	174.6	174.6	174.6
Energy unit price f_e [EUR/kWh]	0.247	0.26	0.273
Number of recharges N_r	131	164	197
Energy cost per mission [EUR]	**5.66**	**7.45**	**9.38**
Difference	−24.0%	-	+25.9%

Finally, the maintenance cost per mission was estimated from its yearly value, taken as a value of 10% of the nominal UAV purchase cost. Again, in Table 6, a perturbation of +/−10% is considered to cope with uncertainties.

Table 6. Maintenance cost for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Yearly cost of maintenance [EUR]	885.25	983.61	1081.97
Working days per mission	5	5	5
Maintenance cost per mission [EUR]	**12.12**	**13.47**	**14.82**
Difference	−10%	-	+10%

The cost analysis just shown yielded the nominal, lowest and top cost figures for the O&M cost reported in Table 7.

Table 7. Operation and maintenance cost per mission for AS-IS UAV (quadcopter) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Pilot's salary [EUR]	1750	2000	2250
Insurance [EUR]	8.80	11.00	13.20
Energy [EUR]	5.66	7.45	9.38
Maintenance [EUR]	12.12	13.47	14.82
O&M cost per mission [EUR]	**1776**	**2031**	**2287**
Difference	−12.55%	-	+12.6%

4.3. Cost Analysis of TO-BE Mission: Unmanned Airship for Solar Plant Monitoring

In order to estimate the purchase cost of an unmanned airship completing the same mission as the quadcopter UAV considered in this study, a preliminary sizing of the airship was carried out as outlined in Section 3. The data for the sizing mission are reported in Table 8. The range R for the design was slightly increased for safety with respect to the requirement for the Trino Vercellese plant. The payload weight and payload required power were obtained from the payload datasheet [25], whereas an indication of a plausible speed for this type of mission was obtained from airship operators working with LTA platforms in a similar scenario [2].

Table 8. Mission design data for a TO-BE LTA platform for solar plant monitoring.

Parameter	Value
Range R [km]	40
Altitude h_{cr} [m]	60
Cruising speed V_{cr} [km/h]	20
Payload mass W_{pl} [kg]	1
Payload power [W]	14

The main features of the sizing solution are reported in Table 9, whereas the components of the corresponding analytic cost of manufacturing are shown in Table 10.

Figure 5 allows us to better appreciate the ratio among the components of the production cost reported in Table 10. Notably, in Table 10, costs with an asterisk (*) were obtained as explained in Section 2.1, employing a reference number of items produced of $Q = 50$. Figure 5 makes the same assumption.

Table 9. Main sizing results for a TO-BE LTA platform for solar plant monitoring.

Parameter	Value
Volume Vol [m^3]	20.74
Length L_r [m]	9.24
Fineness ratio [-]	4.02
Battery mass W_{bat} [kg]	1.55
Battery energy E_{bat} [Wh]	209.25
Total mass W_{tot} [kg]	25.66

Table 10. Production cost for a TO-BE LTA platform for solar plant monitoring.

Parameter	Value
Airframe engineering cost * [EUR]	2846.38
Tooling cost * [EUR]	3245.77
Manufacturing labor cost * [EUR]	12,682.26
Quality control cost * [EUR]	963.85
Development support cost C_D [EUR]	664.16
Flight test operations cost C_F [EUR]	1746.17
Envelope cost C_{env} [EUR]	1490.94
Structural components and systems cost C_{str} [EUR]	4308.09
Battery cost C_{bat} [EUR]	426.13
Gas cost C_{gas} [EUR]	2347.81
Payload cost C_{pl} [EUR]	8109.00

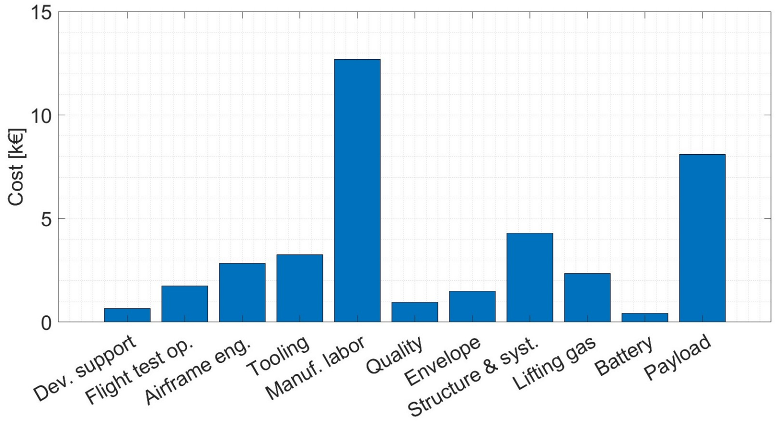

Figure 5. Components of production cost per item ($Q = 50$) for LTA platform for solar plant monitoring (nominal condition).

Since the actual production run is clearly difficult to forecast, a study of its effect on the production cost per item (i.e., per single LTA platform) was carried out, and the result is shown in Figure 6.

As is typical, the effect of parameter Q was non-linear, yielding significant sensitivity of the cost per item produced, especially for a more limited (i.e., below the reference value) production run. On the other hand, for a production run over the reference value, a significant decrease in the cost could be achieved (for instance, at $Q = 100$ items produced, the cost per item would be roughly 20% less than at $Q = 50$).

Considering the relevance of the labor cost to the total unitary cost of production (Figure 5), a sensitivity study was conducted on the nominal value of the corresponding hourly cost figure of 80 EUR/h. Changing this parameter by $+/-10$ EUR/h already produced a significant perturbation of the reference unitary production cost per item, as shown in Table 11.

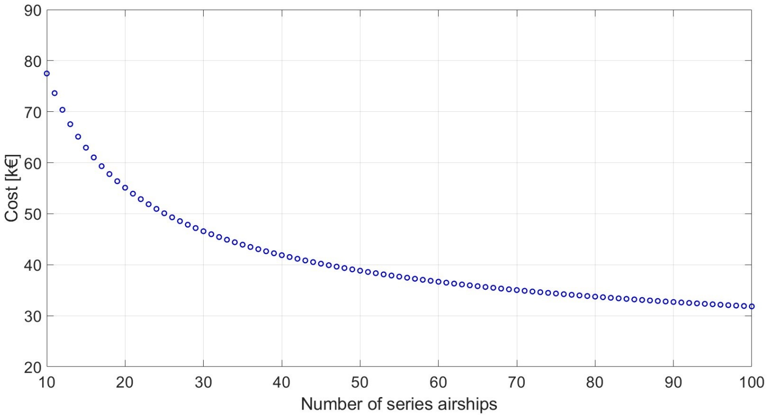

Figure 6. Production cost per item for LTA platform for solar plant monitoring (nominal), as function of production yield.

Table 11. Effect of a change in the hourly labor cost on the production cost of a TO-BE LTA platform for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Labor cost [EUR/h]	70	80	90
Production cost per item [EUR]	**36,363**	**38,831**	**41,298**
Difference	−6.36%	-	+6.35%

Another parameter found to bear a significant role was the inspection speed, which constituted an input for the sizing of the airship (i.e., the cruise velocity, V_{cr}) besides entering some CERs directly (see Section 2.1). Considering a +/−10% change in this parameter, the results shown in Table 12 were obtained. These were obtained by resizing the airship for the corresponding perturbed values of V_{cr}. Qualitatively, an increase in V_{cr} produces a higher drag, which in turns requires more energy to be stored in the battery for covering the same flight range. This increases the weight of the batteries and correspondingly the volume of the machine and in turn the drag again in a detrimental recursive loop.

Table 12. Effect of a change in the target inspection velocity V_{cr} on the production cost of a TO-BE LTA platform for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Inspection speed, V_{cr} [km/h]	18	20	22
Production cost per item [EUR]	**36,543**	**38,831**	**41,442**
Difference	−5.89%	-	+6.72%

Considering the O&M cost associated with the TO-BE airship, two differences with respect to the AS-IS multicopter were considered. Firstly, the range of the airship was such as to cover the entire mission with a single flight. The range and especially endurance are the performance indices where an airship is naturally at an advantage with respect to other flying machines (since no energy is spent for staying aloft). At a cost analysis level, the number of days required for an inspection was correspondingly reduced to 1 (from 5 for the AS-IS mission), which was sufficient to cover the entire inspection mission in the considered case. The second difference was in the relative novelty of the platform, which requires a highly skilled professional to fly it (whereas by comparison an averagely skilled professional was considered for the AS-IS mission). A nominal daily cost for the pilot for the TO-BE mission was taken to be 800 EUR/day [27], doubling the nominal value for the AS-IS mission (intended for a professional pilot of UAVs based on more widespread technology [21]), considering changes of +/−100 EUR/day for checking the sensitivity of the resulting cost. These numerical values constituted the cost for the mission as well, since it would last 1 day.

The insurance cost was estimated considering as extremes the insurance for a multicopter (i.e., the same as in the AS-IS mission) and for a manned ultra-light aircraft (single-propeller two-seater). The latter was likely an overshoot, but considering the relative novelty of the LTA platform and the connected uncertainty in the insurance risk class, it was preferred to lean towards a robust assumption with this cost component. The resulting yearly rate was assumed as 1000 EUR/year, with an adopted +/−200 EUR/year margin employed for checking the sensitivity. This yearly cost, divided by 365, provided the mission cost of insurance for a 1-day mission.

Concerning the cost of energy for battery charging, the same parameters employed for the AS-IS mission were adopted (Table 5). The battery energy E_{bat} obtained from the LTA design tool is reported in Table 9. Equation (12) was employed, assuming only one recharge ($N_r = 1$, consistent with the hypothesis employed for the sizing algorithm of the LTA platform, where the battery was sized to cover the entire mission profile), but again changing the overall cost by +/−20%, on account of uncertainties, for instance, in the actual recharging time (bound to the degradation state of the battery or the residual charge in it). The summary of the energy cost for the TO-BE mission is reported in Table 13.

Table 13. Energy cost for TO-BE LTA platform for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Nominal battery energy E_{bat} [kWh]	209.25	209.25	209.25
Energy unit price f_e [EUR/kWh]	0.247	0.26	0.273
Perturbation factor	0.80	1.00	1.20
Energy cost per mission [EUR]	**0.04**	**0.05**	**0.07**

Finally, the maintenance cost was estimated according to indications from LTA platform operators in the field [2], yielding a yearly value of 10% of the purchase cost in the case of regular maintenance only (i.e., excluding accidents and condition-induced repairs). Notably, this is in line with similar assumptions in the fixed-wing aircraft design field [17]. The estimated value for the maintenance cost was therefore nominally 3883 EUR/year, and a +/−10% perturbation was applied to check the sensitivity of the O&M cost to this parameter. From this, the cost per 1-day mission was obtained through a mere division by 365.

Table 14 summarizes the O&M cost for the TO-BE mission with a LTA platform for solar plant monitoring.

4.4. Comparison of Overall Cost for AS-IS and TO-BE Missions: Multicopter vs. LTA Platform

Summarizing the findings of this case study from Sections 4.2 and 4.3, it can firstly be observed in Table 15 that the purchase price of the LTA solution (nominal) is significantly higher than that of the quadcopter. The former was increased by a factor of 15% for a fair comparison, on account of the fact that the nominal cost per item reported in Tables 10 and 11 is the bare cost, without a profit margin for the manufacturer of the LTA platform. Conversely, for the multicopter, public catalogs for end users have been employed, and the corresponding cost is the direct acquisition cost for the operator. It should be recalled that the production run for the TO-BE LTA solution providing the nominal cost of the airship was $Q = 50$, and as shown in Figure 6, this cost may change significantly for an increased production run, getting closer to that of the AS-IS multicopter solution.

Table 14. Operation and maintenance cost per mission for TO-BE UAV (LTA platform) for solar plant monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Pilot's salary [EUR]	700	800	900
Insurance [EUR]	2.19	2.74	3.29
Energy [EUR]	0.04	0.05	0.07
Maintenance [EUR]	9.47	10.64	11.70
O&M cost per mission [EUR]	**712**	**813**	**915**
Difference	−12.4%	-	+12.5%

Table 15. Comparison of global costs per mission for AS-IS and TO-BE solutions considering solar plant monitoring mission.

	Acquisition Cost [EUR]	O&M Cost [EUR]	Overall Cost [EUR]
Quadcopter (AS-IS)	22,005	2031	2091
LTA Platform (TO-BE)	44,655	813	825

Considering the O&M cost instead, the comparison in Table 15 shows the opposite result, where the TO-BE LTA platform is apparently cheaper than the AS-IS multicopter. The major driver in favor of the LTA solution in this case is mostly the substantially lower time required to complete the mission, which is a direct result of the cut in the battery charging time. The lower time required primarily reduces the cost of the pilot, with a positive effect on the global cost. Notably, this is true even though the analysis was carried out considering the cost of a TO-BE pilot doubled with respect to the AS-IS mission. Furthermore, the effect of multiple interruptions of the missions for getting back to the docking station for recharging, and the corresponding additional travel distances, typical only to the AS-IS multicopter solution, were considered. This would further slightly increase the estimated cost of operation for the AS-IS mission.

Comparatively much less relevant effects were obtained regarding the direct energy or insurance costs.

The overall mission cost (last column in Table 15) could be estimated based on an assumed depreciation scheme. For the AS-IS multicopter, a rather favorable depreciation period of 5 years was assumed. As is typical for relatively novel technology, this parameter ranges significantly depending on the source, and it also depends on the actual type of machine and on-board equipment. For professional multicopters in the purchase price range of the one considered here, considering official sources, the depreciation time may vary between 2 and 3 years [30]. For the TO-BE LTA platform, a time span of 10 years was considered, since this is the life span of the typical envelope material for an airship in this weight and size category (materials employed for larger LTA platforms typically have a longer life span [16]). Spreading the acquisition cost across the respective depreciation time span, a yearly cost was obtained. This was divided by the duration of the mission (5 days or 1 day, respectively, for the AS-IS and TO-BE missions) and added to the O&M cost per mission to yield the overall mission cost, reported in Table 15.

It can be concluded that, according to these data, an operator of UAVs may obtain a significantly reduced cost per mission by employing a LTA platform instead of a multicopter for this type of mission. The driver of the mission cost reduction is mostly the time length of the mission. Therefore, a similar advantage may be obtained for similar inspection missions, where the time taken by a multicopter is significantly higher than that taken by a LTA platform (the larger the area to be monitored, the greater the likely saving). The advantage at the operations level comes at the price of a significantly higher upfront cost of procurement for the LTA vehicle compared to the multicopter. Despite an obvious fluctuation in the margins, the general picture does not change substantially even when comparing perturbed results, yielding the minimum cost and maximum cost scenarios presented in this case study. This further strengthens the conclusions just given.

5. Case Study B: Sea Life Monitoring Mission

The second considered case study is represented by a mission where a prescribed sea area is monitored for studying the behavior of marine mammals.

5.1. Mission Requirements

The target of the mission is the Pelagos sanctuary, a 40-by-37 km rectangular area located close to the western boundary of the Ligurian Sea. The monitoring mission has been carried out with a fixed-wing UAV in a multi-year project by the Tethys Research Institute [31]. On a single flight, only partial coverage of the overall area of the sanctuary is achieved, overflying it for a total trajectory length of 100 km. This value is assumed to be the same for the AS-IS and TO-BE (LTA) missions. However, the actual flight plan of the AS-IS mission requires the fixed-wing UAV to cover the distance from the Italian Naval Air Station of Luni-Sarzana, located a further 100 km away from the access point to the sanctuary area, yielding a total flight range of $R_{AS-IS} = 300$ km considering the inbound and outbound legs to and from the base (Figure 7). Conversely, assuming that a TO-BE airship can operate away from any significant airport infrastructure (an assumption validated a posteriori by the outcome of the airship design phase, since the resulting airship is rather compact), the access point to the target area closest to the coast is 5 km away from it. Therefore, the range for the TO-BE mission can be set to a total of $R_{TO-BE} = 110$ km.

Figure 7. Left: Mission structure for AS-IS fixed-wing UAV, position of Pelagos sanctuary (survey area) [31]. **Right**: Tekever AR5 Evolution fixed-wing UAV [32].

Another difference between the specifications of the AS-IS and TO-BE missions is in the payload characteristics. The mission payload of the AS-IS mission is composed of three cameras, an electro-optical (EO) camera, an infrared (IR) camera and a mirrorless camera for manual operation. This system is flown at an altitude of $h_{cr,AS-IS} = 245$ m, which is constrained by the need to avoid any significant noise reaching the ground (to avoid interference with the normal habits of the marine mammals). Noise from this class of machine is mostly due to the highly loaded propellers, as well as to high values of dynamic pressure in the flow investing the airframe, both typical of a winged aircraft in the category of UAV at hand [33]. Correspondingly, since this distance from the ground is relatively high for monitoring purposes with optical systems, the cameras need to be high-end technology in order to grant a sufficient quality of the collected imagery. Conversely, thanks to the lower noise likely produced by the TO-BE airship platform, the constraint on the altitude from ground can be substantially reduced to a value of $h_{cr,TO-BE} = 100$ m, in turn allowing us to obtain good-quality results even when employing more standard technology for the sensor suite (details on the payload will be given in the next paragraphs).

5.2. Cost Analysis of AS-IS Mission: Fixed-Wing UAV

The fixed-wing UAV employed for the mission was a Tekever AR5 Evolution, with a maximum take-off mass (MTOM) of 180 kg and an available payload mass of 50 kg. The actual payload (not available from the data gathered from the involved subjects) was estimated considering the usual provision for this particular UAV and the target of the mission at hand. The specifications for the WESCAM MX-10 imagery system were considered, which, besides covering the requirements for the sensors mentioned in the mission description (Section 5.1), resulted in a payload weight of 18 kg, compatible with the aircraft specifications. Clearly, given the relevant uncertainty in the identity of the payload, a perturbation analysis was carried out considering a +/−15% change in the purchase cost for the UAV and payload, summarized in Table 16.

Table 16. Components of acquisition cost for AS-IS UAV (fixed-wing) for sea life monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
UAV [EUR]	850,000	1,000,000	1,150,000
Payload [EUR]	391,000	460,000	529,000
Total acquisition cost [EUR]	**1,241,000**	**1,460,000**	**1,679,000**
Difference	−15%	-	+15%

Concerning the O&M cost, the staff required for carrying out the mission and managing the UAV during the monitoring program (during the mission and on the ground) are 3 technicians (pilot, safety pilot and maintenance technician). A calculated value of the cost of this staff and of the fuel for the entire campaign is available [31], equal to 250,000 EUR, where 16,786 km are covered. This allows us to compute the cost per mission, assuming, as previously stated, a mission range of $R_{AS-IS} = 300$ km. The corresponding part of the O&M cost, considering a +/−10% range of uncertainty, is reported in Table 17.

Table 17. Components of operation and maintenance cost for AS-IS UAV (fixed-wing) for sea life monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Technical staff and fuel [EUR]	4021.34	4468.15	4914.97
Maintenance [EUR]	161	179	197
Airport taxes [EUR]	13.50	15	16.50
O&M cost per mission [EUR]	**4203**	**4671**	**5139**
Difference	−10%	-	+10%

The regular yearly cost of maintenance was computed as a 3% portion of the purchase price for this type of UAV [31]. Additionally, the surveillance mission takes only one-third of the year, thus allowing us to compute the cost of maintenance per mission, as reported in Table 17 for a nominal case and perturbed cases (+/−10%).

Finally, the insurance and airport operation costs were assessed. A projection for the former was obtained considering the insurance cost of a general aviation single-propeller four-seater for sport flights in Italy in 2024 as the top value and a quadcopter drone like in Case Study A (Section 4.2) as the bottom limit. An intermediate value of 1500 EUR/year was considered for computations, yielding a corresponding 500 EUR for 1/3 of the year. For the airport cost, again an estimation was made considering the same general aviation aircraft just mentioned, yielding on average 15 EUR per mission (depending on the airport). Both the insurance and airport management costs are reported in Table 17 (including +/−10% perturbation cases), where it can be perceived that they make for negligible components compared to the other factors (similarly to in Case Study A, Table 7).

5.3. Cost Analysis of TO-BE Mission: Unmanned Airship for Sea Life Monitoring

Similarly to in Case Study A (Section 4.3), and as described in the Introduction (Section 1.3), an unmanned LTA vehicle was preliminarily sized according to the requirements of the mission at hand. The major sizing parameters pertaining to the mission are reported in Table 18. In particular, the payload data refer to a camera system offering the same output quality as that considered for the fixed-wing UAV but from a closer inspection distance. This is the DJI Zenmuse H20T, which is required to reduce the altitude to the value reported in Table 18 (made possible by the lower noise of the airship compared to the fixed-wing aircraft). Furthermore, the field of view of this system is smaller than that envisaged for the fixed-wing platform; hence, two systems are employed on the LTA platform instead of one, so as to be able to monitor the same surface area as the winged UAV at any given time.

Table 18. Mission design data for a LTA platform for sea life monitoring.

Parameter	Value
Range, R [km]	110
Altitude, h_{cr} [m]	100
Cruising speed, V_{cr} [km/h]	20
Payload mass, W_{pl} [kg]	1.7
Payload power [W]	20

The resulting main features of the airship obtained using the sizing method outlined in Section 3 are reported in Table 19. As previously pointed out, the resulting LTA platform is not exceedingly long for operation from a non-specific open field, thus validating the assumption of a reduced need for ground infrastructure.

Table 19. Main sizing results for a LTA platform for sea life monitoring.

Parameter	Value
Volume Vol [m^3]	49.36
Length L_r [m]	12.34
Fineness ratio [-]	4.02
Battery mass W_{bat} [kg]	6.24
Battery energy E_{bat} [Wh]	805.95
Total mass W_{tot} [kg]	61.08

Correspondingly, the breakdown of the production cost obtained using the method introduced in Section 2 is reported in Table 20.

Similarly to Case Study A (Section 4.3), values with an asterisk (*) in Table 20 were obtained considering a production run of $Q = 50$ items. The plots in Figure 8 show visually a comparison of the components of the cost of manufacturing for $Q = 50$ and the effect of a change in the number of items in the production batch, respectively.

A comparison of the production cost per item for changing values of the labor cost, under the same perturbations as in Table 11, produced qualitatively similar results with respect to Case Study A, with a minimum cost and maximum cost reduced or increased, respectively, by +/−5.93% compared to the nominal cost.

Table 20. Production cost for a LTA platform for sea life monitoring.

Parameter	Value
Airframe engineering cost * [EUR]	5584.10
Tooling cost * [EUR]	6367.62
Manufacturing labor cost * [EUR]	25,825.71
Quality control cost * [EUR]	1962.75
Development support cost C_D [EUR]	1146.99
Flight test operations cost C_F [EUR]	2314.72
Envelope cost C_{env} [EUR]	2658.04
Structural components and systems cost C_{str} [EUR]	9936.22
Battery cost C_{bat} [EUR]	1719.04
Gas cost C_{gas} [EUR]	5588.77
Payload cost C_{pl} [EUR]	20,583.60

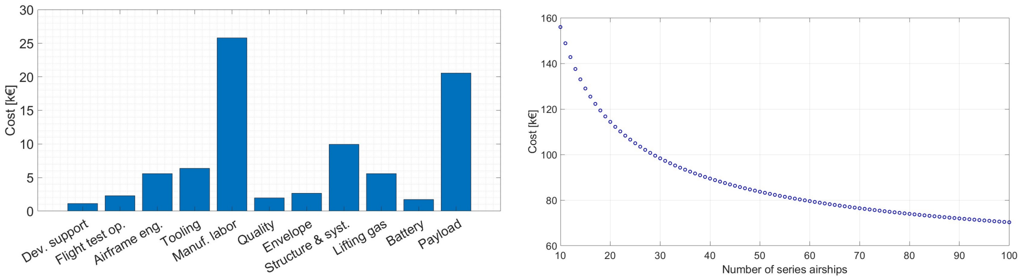

Figure 8. **Left**: Components of production cost per item ($Q = 50$) for LTA platform for sea life monitoring. **Right**: Production cost per item for LTA platform for sea life monitoring as function of production yield.

A parameter which was found to bear an interesting effect on the production cost was the payload power. Table 21 shows the effect of a change of only +/−2 W in the payload power. The corresponding sizing solutions for the airship feature significant differences. In particular, heavier batteries for the same mission duration, needed when the required payload power is increased, induce a bigger geometry, increased drag and hence increased propulsion power and energy in a detrimental recursive loop.

Table 21. Effect of a change in the payload power on the production cost of a LTA platform for sea life monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Payload power [W]	18	20	22
Production cost per item [EUR]	**81,777**	**83,688**	**85,571**
Difference	−2.28%	-	+2.25%

The O&M cost per mission for this case study was obtained with the same procedure as for the LTA platform designed in the former (Section 4.3). The mission was considered to take 1 day, which is compatible with the mission parameters employed for the sizing.

The contributors to the O&M cost are the pilot's salary, insurance, energy and maintenance. The same daily cost of the pilot (i.e., for a highly skilled pilot) and yearly insurance were employed. Also, the parameters for electric energy cost computations were the same, and a battery energy of $E_{bat} = 805.95$ Wh was employed (as in Table 19). The yearly value of the maintenance cost was estimated as 10% of the production cost, nominally 8369 EUR/year. This was spread over 365 days to yield the equivalent cost per mission. The generated breakdown of the O&M cost in Table 22 was correspondingly obtained, considering nominal and perturbed values of the cost estimation parameters.

Table 22. Operation and maintenance cost per mission for TO-BE UAV (LTA platform) for sea life monitoring.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Pilot's salary [EUR]	700	800	900
Insurance [EUR]	2.19	2.74	3.29
Energy [EUR]	0.16	0.21	0.26
Maintenance [EUR]	20.64	22.93	25.22
O&M cost per mission [EUR]	**723**	**826**	**929**
Difference	−12.5%	-	+12.5%

5.4. Comparison of Overall Cost for AS-IS and TO-BE Missions: Fixed-Wing vs. LTA Platforms

A comparison of the cost pertaining to the AS-IS and TO-BE missions within the case study analyzed in the present section is reported in Table 23. Considering the acquisition cost, similarly to in the previous case study, 15% profit was added to the nominal production cost. The difference between the two platforms for the sea life monitoring mission is extreme in this regard. Actually, the fixed-wing UAV selected for this operation is among the most expensive on the market in the medium-altitude, medium-range sector, offering great flexibility of employment seldom found in unmanned platforms. The camera system constituting its payload is similarly top-level, yielding a substantial overall cost for acquisition. Notwithstanding a stark increase for the LTA platform compared to Case Study A (Table 23), the LTA solution appears substantially cheaper than the fixed-wing solution in terms of the acquisition cost for an operator. Of course, the LTA platform does not come with the same flexibility as the fixed-wing UAV, and its reduced noise has been exploited to reduce the cruising altitude, hence the reduced required quality of the sensors.

Table 23. Comparison of global costs per mission for AS-IS and TO-BE solutions considering sea life monitoring mission.

	Acquisition Cost [EUR]	O&M Cost [EUR]	Overall Cost [EUR]
Fixed-wing (AS-IS)	1,460,000	4642	5042
LTA (TO-BE)	96,241	826	852

Considering O&M costs, the results are mostly different due to the staff salary and to a lesser extent to the energy supply. For the former, the operability of the fixed-wing UAV requires three staff members, whereas a single highly skilled pilot is required for the LTA platform. This unavoidably increases the cost per flight hour for the AS-IS solution. For the energy supply, the fixed-wing solution makes use of fuel and an internal combustion engine, whereas the LTA platform works on a purely electric power system. The latter appears to yield some advantages in this case. The result for the O&M cost is generally greatly in favor of the TO-BE solution.

Finally, assuming a depreciation scheme over 10 years, equal for both platforms, starting from the respective acquisition costs, the depreciation cost per year and the corresponding cost per mission could be computed. Summed with the O&M cost, this provided the overall cost per mission reported in Table 23 (last column). It should be mentioned that for a winged UAV the assumed depreciation scheme appears optimistic (official data cite 4 years for a 50% depreciation rate [34]). Yet, on account of the greater similarity of this type of UAV to a general aviation aircraft than a small-scale leisure machine, a more lenient assumption was made for the corresponding depreciation rate.

The reasons for the global advantage apparently provided in this case study, in terms of all cost components, by the LTA solution can be associated with the less numerous staff, as well as with advantages like the lower noise level, which allows for a lower flight altitude, and a very short take-off and landing (VSTOL) capability, which allows a potential user to make this platform independent of airport infrastructure, hence getting rid of non-essential relocation components of the flight profile, with a substantial saving regarding the travel distance. Of course, the winged solution is generally more versatile and less tailored to the mission and may allow for better robustness with respect to unfavorable weather, which in turn may increase its operability and efficiency of use with respect to the LTA platform.

6. Case Study C: Pipeline Inspection

The third and final case study is represented by the routine inspection of a pipeline.

6.1. Mission Requirements

This case study was carried out on the Italian track of the TAL pipeline linking Italy to Germany, extending for $R = 145$ km in northern Italy (Figure 9). The monitoring mission is currently carried out with a manned helicopter (AS-IS scenario), where a human crew visually inspects the status of the pipeline and its surroundings. In this specific mission, the same human crew takes occasional pictures with a personal camera (in other similar contexts, a dedicated camera is employed instead, which allows for flying faster and reducing the mission time). The helicopter remains at an average altitude of $h_{cr,AS-IS} = 100$ m, constrained by safety and noise pollution reasons [35,36] (a closer distance would conversely favor the quality of the imagery). The average inspection velocity is $V_{cr,AS-IS} = 120$ km/h [37].

Figure 9. Left: Scheme of TAL pipeline [38]. **Right**: Airbus AS350B3 helicopter [39].

The mission range R for the TO-BE LTA platform is the same as for the helicopter. However, the new machine will be unmanned, in a different weight category, and is expected to emit much less noise than a manned helicopter, allowing a potential user to reduce the cruising altitude to $h_{cr,TO-BE} = 60$ m. Furthermore, the cruising speed of the LTA platform is substantially reduced compared with the AS-IS mission, due to the intrinsically lower speed performance of a LTA platform. Clearly, to achieve the same speed as a helicopter, a LTA platform should deploy much propulsive power, yielding a higher battery energy (hence weight) requirement for the same range. This would require a hardly justifiable size for an airship carrying the small payload of interest here. To cope with this limitation, a speed of $V_{cr,TO-BE} = 20$ km/h was applied, similarly to in Case Study B. This allowed us to employ a standard camera device for taking pictures of acceptable quality for a visual inspection task. Additionally, in order for the LTA platform to still be capable of completing the planned mission within a single day, the use of a support truck to recover the airship at the end of the inspection and take it back to the origin of the flight was taken into account.

6.2. Cost Analysis of AS-IS Mission: Manned Helicopter

The helicopter currently employed for the monitoring of the considered pipeline is an Airbus AS350B3e. Employing a human technician instead of an automatic camera allows for a reduction in the purchase price, which is presented in Table 24 with $+/-15\%$ perturbations. The latter may model a change in the acquisition price for a different helicopter, for the same model in a condition different from brand-new, etc.

Table 24. Purchase cost for helicopter for AS-IS pipeline inspection mission.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Acquisition cost [EUR]	**2,770,626**	**3,259,560**	**3,748,494**
Difference	−15%	-	+15%

The O&M cost for the helicopter was estimated from data pertaining to the specific helicopter model at hand. The recurring share of the maintenance cost and its components are summarized in Table 25, assuming a yearly use of 200 h [40].

Table 25. Hourly recurring O&M cost for AS-IS solution (helicopter) for pipeline inspection mission (for 200 flight hours per year).

Item	Value
Fuel [EUR/h]	192.62
Lubricants [EUR/h]	5.78
Maintenance labor [EUR/h]	88.82
Replacement parts for airframe/engine/avionics [EUR/h]	74.66
Engine overhaul [EUR/h]	130.04
Periodic airframe maintenance [EUR/h]	82.65
Total recurring O&M cost [EUR/h]	**574.57**

In Table 25, the last two rows refer to periodic overhauls, which are spread across the hourly cost. To conclude regarding the O&M cost, the hourly cost due to non-recurring components (namely the crew's salary, insurance, cost of the operation bound to ground infrastructure) is not available by component, except through an aggregated value, which also includes depreciation [40]. The corresponding breakdown of the total O&M cost per hour and per mission, the latter assuming a duration of each mission of 2 h [37], is presented in Table 26, with the application of flat perturbation factors of $+/-10\%$.

Table 26. O&M cost for AS-IS solution (helicopter) for pipeline inspection mission (2 h mission duration).

Item	Minimum Cost	Nominal Cost	Maximum Cost
Recurring O&M cost [EUR/h]	517.05	574.57	632.03
Non-recurring O&M cost [EUR/h]	833.20	925.78	1018.36
Total O&M cost per mission [EUR]	**2700**	**3001**	**3301**
Difference	−10%	-	+10%

6.3. Cost Analysis of TO-BE Mission: Unmanned Airship for Pipeline Inspection

Prior to analyzing the cost pertaining to a TO-BE LTA vehicle, the latter was sized for the mission according to the procedure presented in Section 3. The mission is qualitatively similar to that of Case Study B (Section 5.1). Notably, the payload is a quality camera to substitute for the human operator. A DJI Zenmuse Z30 was selected, which provides quality photographs compatible with the altitude and speed of the airship [25]. The distance and speed employed for the sizing, mentioned in Section 6.1, are also reported in Table 27. The most relevant data for the corresponding sizing solution are reported in Table 28.

Table 27. Mission design data for a TO-BE LTA platform for pipeline inspection.

Parameter	Value
Inspection distance R_{cr} [km]	145
Inspection altitude h_{cr} [m]	60
Cruising speed V_{cr} [km/h]	20
Payload mass W_{pl} [kg]	0.6
Payload power [W]	9

Table 28. Mission design data for a TO-BE LTA platform for pipeline inspection.

Parameter	Value
Volume Vol [m^3]	46.98
Length L_r [m]	12.14
Fineness ratio [-]	4.02
Battery mass W_{bat} [kg]	6.07
Battery energy E_{bat} [Wh]	819.45
Total mass W_{tot} [kg]	58.13

The production cost according to the methods described in Section 2 yielded the results reported in Table 29, where the cost values with an asterisk (*) were obtained with a production run of $Q = 50$.

Similarly to in the previous case studies (Sections 4.3 and 5.3), Figure 10 displays the breakdown of the production cost and the effect of the production quantity. In this case study, the cost of manufacturing labor overshadows all other components of the production cost. The sensitivity to the number of items produced is rather high. Where the production cost per item for $Q = 50$ items is 62,983 EUR, considering, for instance, a total production quantity of $Q = 10$ items, the cost per item increases to 131,335 EUR, whereas for $Q = 100$ it is reduced to 50,239 EUR. Both values imply a significant alteration to the overall trade-off with respect to existing solutions (i.e., AS-IS vs. TO-BE).

Table 29. Production cost for a LTA platform for pipeline inspection.

Parameter	Value
Airframe engineering cost * [EUR]	5373.27
Tooling cost * [EUR]	6127.22
Manufacturing labor cost * [EUR]	24,797.80
Quality control cost * [EUR]	1884.63
Development support cost C_D [EUR]	1111.76
Flight test operations cost C_F [EUR]	2277.76
Envelope cost C_{env} [EUR]	2571.70
Structural components and systems cost C_{str} [EUR]	9172.92
Battery cost C_{bat} [EUR]	1672.98
Gas cost C_{gas} [EUR]	5318.69
Payload cost C_{pl} [EUR]	2674.44

Two sensitivity studies are presented in this case on two parameters with substantial effects, namely the hourly labor cost and the specific energy of the battery. For the former, Table 30 shows the significant effect of a change of only +/−10 EUR/h with respect to the nominal labor cost.

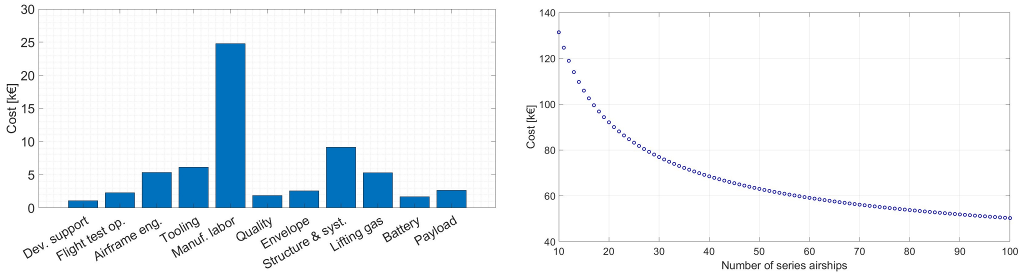

Figure 10. Left: Components of production cost per item ($Q = 50$) for LTA platform for pipeline inspection. **Right**: Production cost per item for LTA platform for pipeline inspection as function of production yield.

Table 30. Effect of a change in the hourly labor cost of manufacturing work on the production cost of a LTA platform for pipeline inspection.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Labor cost [EUR/h]	70	80	90
Production cost per item [EUR]	**58,210**	**62,983**	**67,756**
Difference	−7.58%	-	+7.58%

For the latter, the effect of a +/−10% change in the specific energy of the battery is presented in Table 31. A different sizing solution was obtained for each considered specific energy. A higher specific energy allows us to size up a smaller LTA platform, therefore resulting in a cheaper envelope, the size of which is also aerodynamically advantageous and requires less thrust and hence in turn less energy for the same speed and distance in a virtuous recursive loop.

Table 31. Effect of a change in the specific energy of the battery on the production cost of a LTA platform for pipeline inspection.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Battery specific energy [Wh/kg]	120	135	150
Production cost per item [EUR]	**70,783**	**62,983**	**57,206**
Difference	+12.38%	-	−9.17%

Concerning the operating cost, a major difference with respect to the mission covered with a helicopter is bound to the need to recover the airship at the end of the inspection trip instead of flying it back to the origin, which firstly would yield an exceedingly long mission to be completed within a working day. Therefore, a truck was envisaged for recovery. The sizing of the LTA platform is compatible with that of a large standard truck trailer (13.60–2.70–3 m). Therefore, it was not assumed that a dedicated truck needs to be purchased specifically for this task by the operator. However, the impact on the operating cost needs to be taken into account. According to the Italian data for 2024, the cost of operation for the end user for an average truck, including the driver, is 4.99 EUR/km [41]. By assuming a road distance to be covered per mission of 300 km, it was possible to obtain the value of the cost per mission for the support truck, which ended up being the most relevant component in the O&M cost for the TO-BE LTA platform mission. Table 32 displays all the components in the O&M cost per mission. For the truck cost, a +/−10% perturbation was considered to check the effect of this datum. The pilot's salary, insurance and energy cost computations were performed with the same data as for Case Study B (Section 5.3). Also, the maintenance cost was determined by assuming it was the same percentage of the production cost as for the previous case. The perturbation ranges were the same for these parameters.

Table 32. Operation and maintenance cost per mission for TO-BE UAV (LTA platform) for pipeline inspection.

Item	Minimum Cost	Nominal Cost	Maximum Cost
Pilot's salary [EUR]	700	800	900
Insurance [EUR]	2.19	2.74	3.29
Energy [EUR]	0.17	0.22	0.28
Maintenance [EUR]	15.53	17.26	18.98
Truck [EUR]	1348.20	1498.00	1647.80
O&M cost per mission [EUR]	**2066**	**2318**	**2570**
Difference	−10.8%	-	+10.8%

6.4. Comparison of Overall Cost for AS-IS and TO-BE Missions: Manned Helicopter vs. Unmanned LTA Platform

A comparison of the cost of acquisition, of the O&M cost per mission and of the overall cost for the AS-IS and TO-BE solutions for the mission considered in this case study is presented in Table 33. The acquisition cost is generally higher for the AS-IS helicopter than for the TO-BE LTA platform (the slight addition due to a good-quality camera in the latter case is not even appreciable). The acquisition cost prediction for the LTA platform is in line with current market values [2]. The operation and maintenance cost is much influenced by the need to have a recovery truck in the TO-BE mission, as has been observed (Section 6.3). However, taking into account a longer cruise for the LTA platform at the design level would produce a much bigger airship, generally more expensive and potentially producing hidden costs bound to logistics and management infrastructure (e.g., the need for a dedicated hangar for servicing, a large apron, a recovery pylon, etc.). Furthermore, the mission would not be feasible within a single day, which would be a hardly acceptable limitation compared to the AS-IS solution.

Table 33. Comparison of global costs per mission for AS-IS and TO-BE solutions considering pipeline inspection mission.

	Acquisition Cost [EUR]	O&M Cost [EUR]	Overall Cost [EUR]
Manned helicopter (AS-IS)	3,259,560	3000 [1]	3000
Unmanned LTA platform (TO-BE)	72,430	2318	2338

[1] Including depreciation.

The cost per mission was obtained including depreciation for the TO-BE LTA platform (in a 10-year time frame) and with no alteration to the O&M cost of the AS-IS helicopter solution, recalling that depreciation was already included in the cost per mission in this case due to the quality of the available data.

7. Conclusions

This paper tries to offer an insight on the feasibility and opportunity of LTA solutions to be used for missions currently flown by other types of flying machines. The feasibility was analyzed from a technical and economic standpoint, primarily considering three missions—solar plant monitoring, sea life monitoring and pipeline inspection—where a LTA solution could be reasonably manageable in terms of ground infrastructure and the ease of operation (e.g., not exceedingly big or technically demanding) compared to existing flying solutions. Furthermore, missions for which a LTA platform would constitute a theoretically feasible solution but soft constraints like social acceptance (e.g., overflight by a LTA platform in crowded areas) or a reduced ease of flight (e.g., close to buildings) would be comparatively higher were discarded.

The cost model adopted for the LTA platform was partly driven by estimation methods originally conceived for fixed-wing aircraft and complemented with estimation relationships based as much as possible on first-principle reasoning, i.e., making use of direct knowledge of the cost associated with a specific quantity (e.g., the unit cost of battery, envelope material, etc.). An estimation of the RDTE and production costs, and knowledge of the payload, allowed us to obtain a prediction of the acquisition cost for a potential operator. Furthermore, the analysis of the O&M cost allowed us to predict the cost that an operator should face for a mission.

In order to feed these models, basic sizing results for a LTA solution meeting the requirements for each considered mission were obtained from an accurate sizing algorithm developed in-house and largely validated in previous works. This makes use of realistic assumptions and data regarding the technology of the components of a LTA platform (e.g., batteries, motors, the envelope, etc.).

From the available data on the flying solutions currently adopted for the corresponding missions (again, both the acquisition and O&M costs were considered for a potential operator), it was possible to produce comparisons of the costs (including a per-mission cost) for AS-IS and TO-BE scenarios.

From these analyses and the corresponding assumptions, it appears that greater endurance of LTA platforms compared to their competitors, provided by the physical principle of buoyancy exploited by a LTA platform to fly, is especially advantageous compared to quadcopter UAVs, which are currently limited in weight and size (partly to fit within regulation categories) and hence cannot carry heavy batteries (Case Study A) and lose much performance to this effect. The ability to operate independently from significant ground infrastructure constitutes an advantage over fixed-wing machines (Case Study B), allowing one to cut out large parts of the mission profile employed for relocation to the target area. Conversely, the relatively low speed of overflight typical to LTA machines makes them less advantageous compared to manned helicopters on relatively long-range missions (Case Study C), implying the need for support infrastructure (a truck, in this case), which adds markedly to the operation cost. Therefore, for missions where the airspeed is very limited and endurance is at a premium, it appears that LTA solutions are potentially economically advantageous, even without implying any major technical shortcomings.

A parameterized analysis was carried out as much as possible, thus checking the robustness of the findings. Clearly, if major changes in the working hypotheses of the respective missions were applied (like the number of days required for a mission, the number of staff, the respective hourly cost, etc.), further perturbation effects would be obtained, potentially changing the outcome of the analysis. However, this study primarily provides a methodology for cost assessment, and it concurrently provides a detailed idea of the respective costs of AS-IS vs. TO-BE solutions for the missions at hand, highlighting the cost drivers in each case.

An even mildly positive trend in the technological evolution of batteries (in terms of the specific energy in particular) would further foster the advantage provided by a LTA solution. On the other hand, regulatory constraints concerning the employment of UAVs may also alter the balance in favor of AS-IS solutions, currently also limited by the regulatory framework.

Since high-altitude LTA platforms are currently the focus of some serious industrial evaluations, future work may try to explore the economic feasibility of these platforms compared to their competitors (e.g., space satellites and high-altitude reconnaissance platforms).

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References

1. Kelluu, O. Metallimiehentie 4, 80330 Reijola, Finland. Available online: https://kelluu.com/ (accessed on 1 January 2025).
2. HyLight. 91220 Brétigny-sur-Orge, France. Available online: www.hylight.aero (accessed on 1 January 2025).
3. Roboloon. Nobelstraße 15, 70569 Stuttgart, Germany. Available online: www.roboloon.com (accessed on 1 January 2025).
4. FloFleet. Via Sebenico 24, 20124 Milan, Italy. Available online: www.flofleet.com (accessed on 1 January 2025).

5. Riboldi, C.E.D.; Rolando, A. Layout Analysis and Optimization of Airships with Thrust-Based Stability Augmentation. *Aerospace* **2022**, *9*, 393. [CrossRef]
6. Riboldi, C.E.D.; Rolando, A. Thrust-based stabilization and guidance for airships without thrust-vectoring. *Aerospace* **2023**, *10*, 344. [CrossRef]
7. Riboldi, C.E.D.; Rolando, A. Autonomous flight in near hover and hover for thrust controlled unmanned airships. *Drones* **2023**, *7*, 545. [CrossRef]
8. Riboldi, C.E.D.; Belan, M.; Cacciola, S.; Terenzi, R.; Trovato, S.; Usuelli, D.; Familiari, G. Preliminary sizing of a low-altitude airship including ion-plasma thrusters. In Proceedings of the 34th Congress of the International Council of the Aeronautical Sciences (ICAS2024), Florence, Italy, 9–13 September 2024.
9. IPROP. Ionic Propulsion in the Atmosphere. Grant ID: HORIZON-EIC-2022-PATHFINDEROPEN-01, 2023–2027. Available online: www.iprop-project.eu (accessed on 1 September 2024).
10. Riboldi, C.E.D.; Gualdoni, F. An integrated approach to the preliminary weight sizing of small electric aircraft. *Aerosp. Sci. Technol.* **2016**, *58*, 134–149. [CrossRef]
11. Donateo, T.; Carlà, A.; Avanzini, G. Fuel consumption of rotorcrafts and potentiality for hybrid electric power systems. *Energy Convers. Manag.* **2018**, *164*, 429–442. [CrossRef]
12. Peksa, J.; Mamchur, D. A Review on the State of the Art in Copter Drones and Flight Control Systems. *Sensors* **2024**, *24*, 3349. [CrossRef] [PubMed]
13. Roy, R. *Cost Engineering: Why, What and How?* Technical Report; Cranfield University: Cranfield, UK, 2003.
14. *NASA Cost Estimating Handbook (v4.0)*; Technical Report; NASA Cost Analysis Division: Washington, DC, USA, 2015.
15. Large, J.P.; Campbell, H.G.; Cates, D. *Parametric Equations for Estimating Aircraft Airframe Costs*; Technical Report; The Rand Corporation: Santa Monica, CA, USA, 1976.
16. Carichner, G.E.; Nicolai, L.M. *Fundamentals of Aircraft and Airship Design*; AIAA Education Series; American Institute of Aeronautics and Astronautics, Inc.: Washington, DC, USA, 2013.
17. Raymer, D.P. *Aircraft Design: A Conceptual Approach*, 3rd ed.; AIAA Education Series; American Institute of Aeronautics and Astronautics: Washington, DC, USA, 1999.
18. Gudmundsson, S. *General Aviation Aircraft Design*; Butterworth-Heinemann: Oxford, UK, 2022.
19. Riboldi, C.E.D.; Rolando, A.; Regazzoni, G. On the feasibility of a launcher-deployable high-altitude airship: Effects of design constraints in an optimal sizing framework. *Aerospace* **2022**, *9*, 210. [CrossRef]
20. Riboldi, C.E.D.; Belan, M.; Cacciola, S.; Terenzi, R.; Trovato, S.; Usuelli, D.; Familiari, G. Preliminary Sizing of High-Altitude Airships Featuring Atmospheric Ionic Thrusters: An Initial Feasibility Assessment. *Aerospace* **2024**, *11*, 590. [CrossRef]
21. Istituto Nazionale di Statistica (ISTAT). Via Ercole Oldofredi 23, 20124 Milano, Italy. Available online: www.istat.it (accessed on 1 June 2024).
22. Permali. Gloucester GL1 5TT, UK. Quotation Autumn 2024. Available online: www.permali.co.uk (accessed on 1 November 2024).
23. American Durafilm. Holliston, MA 01746. Quotation Autumn 2024. Available online: https://americandurafilm.com (accessed on 1 November 2024).
24. Jamison, L.; Sommer, G.S.; Porche, I.R. *High-Altitude Airship for the Future Force Army*; Technical Report; RAND Corporation: Santa Monica, CA, USA, 2005.
25. DJI. Liuxiandong, Xili Subdistrict, Nanshan District, Shenzhen, Guangdong, China. Available online: www.dji.com (accessed on 1 November 2024).
26. Linde. Seitnerstraße 70, 82049 Pullach, Germany. Available online: www.linde-gas.de (accessed on 1 November 2024).
27. Eurodrone. Via Santuario 18/A, 12012 Boves, Italy. Available online: www.eurodrone.online (accessed on 1 September 2024).
28. Enel Green Power. Viale Regina Margherita 125, 00198 Roma, Italy. Available online: www.enelgreenpower.com (accessed on 1 October 2024).
29. Selectra Italia. Via Ombrone 2G, 00198 Roma, Italy. Available online: http://selectra.net (accessed on 1 September 2024).
30. *Taxation Ruling—Income Tax: Effective Life of Depreciating Assets*; Technical Report TR 2022/1; Australian Taxation Office: Sydney, NSW, Australia, 2022.
31. Costa, M.; Santis, V.D.; Lanfredi, C.; Airoldi, S. *Eye in the Sky, Technical Activities Report*; Phase I: July–November 2022, Phase II: March–June 2023; Technical Report; Tethys Research Institute: Milan, Italy, 2024.
32. Tekever. Heden Rossio Largo do Duque de Cadaval 17 Fracção I, 1200-160 Lisboa, Portugal. Available online: www.tekever.com (accessed on 1 September 2024).
33. Salucci, F.; Riboldi, C.E.D.; Trainelli, L.; Rolando, A.; Mariani, L. A noise estimation procedure for electric and hybrid-electric aircraft. In Proceedings of the AIAA SciTech 2021 Forum, Online, 11–15, 19–21 January 2021; p. 0258.
34. *General Depreciation Rates*; Technical Report IR265; New Zealand Government—Inland Revenue: Wellington, New Zealand, 2023.

35. Rolando, A.; Rossi, F.; Riboldi, C.E.D.; Trainelli, L.; Grassetti, R.; Leonello, D.; Redaelli, M. The pilot acoustic indicator: A novel cockpit instrument for the greener helicopter pilot. In Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, 1–4 September 2015.
36. Trainelli, L.; Gennaretti, M.; Bernardini, G.; Rolando, A.; Riboldi, C.E.D.; Redaelli, M.; Riviello, L.; Scandroglio, A. Innovative helicopter in-flight noise monitoring systems enabled by rotor-state measurements. *Noise Mapp.* **2016**, *3*, 190–215. [CrossRef]
37. EliFriulia. Piazzetta Luigi Coloatto 1, 34077 Ronchi dei Legionari, Italy. Available online: www.elifriulia.it (accessed on 1 September 2024).
38. Società Italiana per l'Oleodotto Transalpino S.p.A., via Muggia 1, 34018 San Dorligo della Valle, Italy. Available online: www.tal-oil.com (accessed on 1 September 2024).
39. Airbus Helicopters. Aeroport International Marseille Provence, 13725 Marignane Cedex, France. Available online: www.airbus.com/en/products-services/helicopters (accessed on 1 January 2025).
40. PhilJets Aero Services, G292+4G6, Airport Rd., Pasay, Metro Manila, Philippines. Available online: https://philjets.com (accessed on 1 September 2024).
41. Automobile Club d'Italia, Via Marsala 8, 00185 Roma, Italy. Available online: www.aci.it (accessed on 1 November 2024).