ENSURING THE NEXT GENERATION GREEN AIRCRAFT' SUSTAINABILITY FROM THE DESIGN PHASE VIA A LIFE CYCLE COST ANALYSIS

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Abstract

Sustainable development should be a core principle for current aviation industry, aiming to design aircraft with alternative energy sources and/or innovative configuration solutions. To ensure sustainable aircraft, Life Cycle Cost (LCC) analysis becomes paramount since the early phase of a design process. Among the possible approaches for the LCC analysis, the top-down ones produce Cost Estimation Relationships (CERs) correlating costs, technical information, and system parameters, while the bottom-up ones (i.e., "engineering approaches") allow obtaining accurate cost estimates relying on the collection of detailed information on a product and its associated life cycle processes. Since the adoption of a top-down approach is not recommended for estimating the cost of products utilizing novel technologies, this paper proposes a hybrid LCC / CER model for next generation green aircraft. The approach is meant to be used starting from the design phase, which is based on an engineering-based approach that is integrated with CERs when needed, i.e., parameters with no chance to access physical data. To account for any uncertainty sources related to the use of CERs and of data not specifically suited for next-generation green aircraft, the parameters of the CERs are described by means of probability density functions to investigate uncertainty in different scenarios. The model is applied via the design process of a 50-seat regional aircraft composed of aluminum and composites. The results and model could be integrated in a Multi-Disciplinary Optimization framework for facing the design challenges of next-generation green aircraft.

Keywords: cost management; Multi-Disciplinary Design Optimization; Reduced Order Model; Monte Carlo simulation; sustainable mobility

1. Introduction

Nowadays, the concept of "sustainable development" is key and fundamental for system design, intended as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainable development principles should guide every industry, by stimulating the simultaneous enhancement of environmental, social, and economic performance.

This appears extremely relevant for the aviation industry, being characterized by rapid expansion [2], generation of emissions and environmental impacts along the entire life cycle of aircraft [3], and the need to ensure a high general level of safety to reduce accidents and incidents rate [4]. Different research directions reflect this priority, i.e., energy-efficient aircraft design, sustainable aircraft production, exploitation of alternative energy sources, among others [3]. The design of an aircraft is a complex, iterative, and multi-disciplinary process that requires several phases (e.g., requirement definition, conceptual design, preliminary design, detail design, manufacturing, and testing) to provide a certifiable and operating vehicle. To obtain an aircraft that is also efficient, cost modeling should be integrated into the design process [6]: the cost estimation in the early phase of the design cycle is crucial [7]. Asiedu and Gu [8] emphasize that, in general, during the design stage, most (between 70-85%) of the total Life Cycle Cost (LCC) of a product is committed, and this can be reduced by properly considering the LCC issues early in the design. Indeed, LCC analysis provides the framework for specifying the estimated total incremental costs of developing, producing, using, and retiring a particular item [8].

An LCC analysis can be based on top-down and/or bottom-up approaches [8]. The former, also known as parametric modelling, is based on the application of equations that correlate costs and technical information with parameters describing the system (e.g., weight and performance) and results in sets of formulae, which are called Cost Estimation Relationships (CERs) [8]. A well-known example of top-down approaches for aircraft LCC estimation is given by Gudmundsson [5], whose work has been adapted and adjusted over the years for capturing any changes on aircraft (cf. [9]). On the contrary, a bottom-up approach (also known as “engineering approach” [10]) represents a detailed model requiring information and knowledge on the product and associated processes (e.g., labor time and rates, quantity material) [8]. Therefore, this view demands for an expert designer for the estimation [10]. Examples of such approaches employ physics-based and simulation models (e.g., [6], [11]). The literature does not reach a consensus on the most suitable approach to be used for estimating the LCC in the aircraft design stage: Asiedu and Gu [8] highlight that top-down approaches are not a good methodology for estimating the cost of products utilizing novel technologies, while bottom-up ones are time consuming and costly although they produce the most accurate cost estimates. This is also valid for next generation green aircraft, i.e., vehicles that are characterized by novel propulsion systems, sustainable aviation fuels, and/or innovative configuration solutions able to reduce greenhouse gas and carbon dioxide emissions, and consumptions.

For these reasons, this paper aims to develop a hybrid LCC / CER model for next generation green aircraft, to be used in the design phase. The proposed approach is based on an engineering-based approach in turn integrated with CERs when some data are unavailable or not easily assessable. Since the CERs are based on historical data, they are introduced in the model by assigning proper probability distributions to their parameters in order to take into account the different uncertainty sources related to the data.

The remainder of the paper is organized as follows. Section 2 describes the methodology to develop and apply the hybrid LCC / CER model. Its application and validity to a next-generation green aircraft is presented in Section 3 and discussed in Section 4. Concluding remarks are provided in the final section.

2. Methodology

To achieve the objective of this paper, we employed the methodology represented in Figure 1.

Figure 1 – Methodology for the hybrid LCC / CER model development and application.

Such methodology is composed of the following five steps.

1. **System definition and data collection.** The system (i.e., the aircraft) under investigation should be preliminarily defined. This requires the characterization of technical details (e.g., weights of the components, materials), desired performance (e.g., cruise speed, fuel flow at cruise speed), qualitative information on the processes needed for certifying and producing the aircraft. This step should be conducted by involving primarily Original Equipment Manufacturers (OEMs), and authorities. These latter represent the main data source providers in terms of requirements and performance. Further data can be gathered from the scientific literature, technical reports about similar products, analyses and simulations on structure, aerodynamics, and propulsion features.
2. **Assumption definition.** The system definition and data collection stimulate the identification of significant assumptions to be defined in the LCC analysis. For instance, the costs not included in the overall LCC should be made explicit, the processes required to obtain a part of the aircraft should be identified, the location where the manufacturing and final assembly

of the aircraft will take place should be clear, and the various possible suppliers and their locations should be stated.

3. **Engineering-based approach definition.** To define the engineering-based approach for the LCC analysis, we identified and analyzed the different costs that occur in the life cycle stages of next-generation green aircraft. The relevant cost types and items, classified according to the stage, are summarized in Figure 2. In the design stage, we considered the costs related to the engineering, tooling, prototype construction, test crew and pilots, and fuel. In the manufacturing process, we modelled the costs related to the materials (i.e., aluminum, Carbon Fiber-Reinforced Polymer - CFRP, and Kevlar), the components purchased by vendors (i.e., engines, propellers, avionics), their transportations from the vendor sites, and the consumptions of electricity, natural gas, and heat for obtaining the aircraft structure, and the manufacturing labor needed for assembling the different parts. Finally, the operations cost is related to the maintenance and inspections performed across the aircraft lifetime, the fuel and crew used for conducting flights, the storage at a main base. The insurance and taxes in the operations stage are not considered in our approach. We neglected the costs in the decommissioning phase (cf. grey box in Figure 2) being this an early modelling attempt.

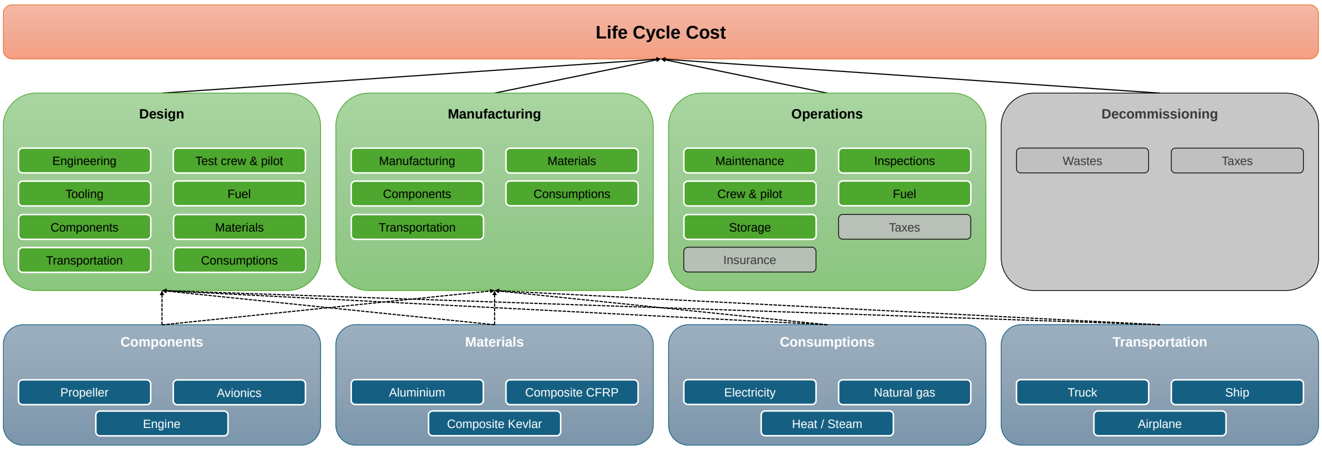

Figure 2 – Cost types and items to estimate LCC.

In general, each equation composing the engineering-based approach can be defined as reported in Eq. (1):

$$C_{i,j} = f(\overline{x_{i,j}}) \tag{1}$$

where $C_{i,j}$ is the cost related to a specific factor i (e.g., cost of the fuel) incurred in the life cycle stage j (e.g., operations), and $x_{i,j}$ represents the set of parameters required for estimating the cost i in the same stage j. For instance, the cost of fuel in the operations phase can be estimated through Eq. (2):

$$C_{fuel,operations} = \left(\frac{c_{fuel}}{\rho_{fuel}}\right) \dot{m}_{fuel}\, n_{flight}\, L\, d_{flight} \tag{2}$$

where:

- c_{fuel} is the unitary cost (i.e., price) of the fuel used by the aircraft (in €/l);
- ρ_{fuel} is the fuel density (in kg/l);
- $\dot{m}_{fuel}$ is the fuel flow per hour during cruise (in kg/h);
- n_{flight} is the number of annual flights (in flight/year);
- L is the entire lifetime of the aircraft (in year);
- d_{flight} is the duration of one flight (in h/flight).

The entire set of equations composing the engineering-based approach can be found in Table A1, Table A2, and Table A3 in Appendix. Note that the LCC is equal to the sum of the costs incurred in the design, manufacturing, and operations phase, as reported in Eq. (3):

$$C_{i,j} = \sum_j \sum_i C_{i,j} = C_{design} + C_{manufacturing} + C_{operations} \quad (3)$$

The implementation of the approach has been portrayed in the SimaPro software (version 9.5). Such software is a commonly employed worldwide tool for Life Cycle Assessment (LCA) and sustainability analysis, which permits considering several cost categories (e.g., acquisition, maintenance) in the various life cycle stages (e.g., manufacturing, operations) from different perspectives (e.g., manufacturer) [12]. In particular, the costs in the different life cycle stages were defined in the SimaPro software by creating a new assessment method and populating it with substances (i.e., cost items or economic issues), impact categories (i.e., cost types), and damage categories. An overview of the LCC method as being implemented is provided in Table 1. We set the currency as €, and we assigned an equal factor (i.e., 1) to all the impact categories in the damage assessment. Finally, the different economic issues were assigned to the related product stages, as suggested in [12].

Table 1 - LCC method in SimaPro.

Impact categories	**Cost item**	**Unit of cost item**
Personnel	Engineering labor	€/h
Personnel	Tooling labor	€/h
Personnel	Test crew & pilot	€/h
Personnel	Manufacturing labor	€/h
Personnel	Maintenance labor	€/h
Personnel	Crew & Pilot	€/h
Material	Propeller	€/item
Material	Avionics	€/item
Material	Engine	€/item
Material	Inspection	€/year
Material	Fuel	€/h
Material	Aluminum	€/kg
Material	CFRP	€/kg
Material	Kevlar	€/kg
Material	Electricity	€/kWh
Material	Natural gas	€/kWh
Material	Heat / Steam	€/kWh
Overhead	Storage	€/year
Transport	Transport by truck	€/kg
Transport	Transport by ship	€/kg
Transport	Transport by airplane	€/kg

4. **Integration with CERs.** Despite all attempts, it might be possible that data and information about certain costs are not available in the design stage. In these cases, a top-down approach could represent a valid support for such cost estimations. Among the different top-down approaches available in the literature for the LCC analysis, we recognized the CERs proposed by Gudmundsson [5] as the most suitable ones for the next-generation green aircraft. These CERs are defined in accordance with Eq. (1): this permits a feasible hybridization of the proposed approach. To consider potential uncertainty sources due to the use of relationships defined for other aircraft and based on correlations with historical data, we have assigned proper probability density functions, managed via Monte Carlo simulations.
5. **Application and validation of the model.** The proposed hybrid LCC / CER model can be applied by introducing the data collected in the first step of the methodology. The obtained results, in terms of the total LCC and costs for each life cycle stage, allow identifying those parameters having a higher impact on the aircraft LCC. Furthermore, the uncertainty analyses about the data obtained through the CERs provide insights into the degree of

confidence of the different costs.

3. Case Study

The methodology described in Section 2 was applied to a 50-seat regional aircraft, which is powered with the fuel jet A1, and composed of aluminum and composites (CFRP and Kevlar). The relevant results are described in the following paragraphs.

3.1 System Definition and Data Collection

The investigated next-generation green aircraft is a regional turboprop aircraft currently under design. Similar aircraft is the Italian Regional Transport Airplanes (in Italy: Aerei da Trasporto Regionale, ATR) and, in particular, ATR 42 (versions 300 and 500). We analyzed the desired technical requirements and performance of the aircraft, and we collected data from the scientific literature, technical reports about the reference aircraft, analyses and simulations on structure, aerodynamics, and propulsion features. We also collaborated with OEMs and aircraft manufacturers for gathering other useful data. The aircraft is characterized by two engines (Pratt & Whitney, model PW127) and two propellers (Collins, model 568F).

Table 2 summarizes the technical requirements, data, and performance of the aircraft, Table 3 the parameters related to the design and manufacturing processes, and Table 4 the economic parameters. Note that the data about electricity, natural gas, and heat / steam consumptions are taken from [13].

Table 2 – Technical requirements, data, and performance of the aircraft.

Parameter	Symbol	Unit	Value
Lifetime	L	year	30
Passengers	pax	pax	48
Typical mission	mission	km	370.4
Cruise speed	s_{cruise}	km/h	493
Maximum cruise speed	s_{max}	km/h	555.6
Flights per year	n_{flight}	flight/year	1800
Flight duration	d_{flight}	h/flight	0.75
Typical horsepower during cruise	P_{HPC}	kW	1207.28
Fuel flow per hour during cruise	$\dot{m}_{fuel}$	kg/h	414.08
Propeller weight	$W_{propeller}$	kg/item	160
Number of propellers	$n_{propeller}$	item	2
Engine weight	W_{engine}	kg/item	481.7
Number of engines	n_{engine}	item	2
Fuselage structural weight	$W_{fuselage}$	kg	2800
Wing weight	W_{wing}	kg	1496
Tail weight	W_{tail}	kg	422
Total structural weight	$W_{structure}$	kg	4718
Aluminum percentage in the structure	$\%_{aluminum}$	%	80
CFRP percentage in the structure	$\%_{CFRP}$	%	15
Kevlar percentage in the structure	$\%_{Kevlar}$	%	5
Crew members required to test the prototypes	$n_{testcrew}$	person	2
Crew members required to operate the airplane	n_{crew}	person	2
Flight test hours	H_{test}	h	2600
Density of the fuel	ρ_{fuel}	kg/l	0.81

Table 3 – Parameters about the design and manufacturing processes.

Parameter	Symbol	Unit	Value
Planned aircraft to be produced over a 5-years period	Q_{5years}	item	120
Production rate	$Q_{production}$	item/month	2
Prototypes	$n_{prototype}$	item	4
Electricity consumption	$Q_{electricity}$	kWh/kg	40.022
Natural gas consumption	Q_{gas}	kWh/kg	40.244
Heat / steam consumption	Q_{heat}	kWh/kg	5.023

Table 4 – Economic parameters.

Parameter	Symbol	Unit	Value
Rate of engineering labor	$R_{engineering}$	€/h	117.55
Rate of tooling labor	$R_{tooling}$	€/h	77.94
Rate of test crew & pilot labor	$R_{testcrew}$	€/h	102
Rate of manufacturing labor	$R_{manufacturing}$	€/h	67.72
Rate of certified airframe and powerplant mechanic (i.e., maintenance) labor	$R_{maintenance}$	€/h	55.55
Rate of crew & pilot labor	R_{crew}	€/h	92.59
Propeller cost	$c_{propeller}$	€/item	138326.25
Avionics cost	$c_{avionics}$	€/item	2089814.81
Engine cost	c_{engine}	€/item	849799.40
Inspection cost	$c_{inspections}$	€/year	7440
Fuel price	c_{fuel}	€/l	1.9
Aluminum cost	$c_{aluminum}$	€/kg	2.016
CFRP cost	c_{CFRP}	€/kg	378.88
Kevlar cost	c_{Kevlar}	€/kg	26.68
Electricity cost	$c_{electricity}$	€/kWh	0.361
Natural gas cost	c_{gas}	€/kWh	0.093
Heat / steam cost	c_{heat}	€/kWh	0.055
Storage rate	$c_{storage}$	€/year	19530
Truck transport cost	c_{truck}	€/kg	1.5
Ship transport cost	c_{ship}	€/kg	1
Airplane transport cost	$c_{airplane}$	€/kg	5.5

3.2 Assumption Definition

For the estimation of the LCC of the next-generation green aircraft under investigation, we did not consider the costs related to the following aspects:

- training for the personnel dedicated to test crew and pilots, to the manufacturing and maintenance of the aircraft, to the flights (i.e., pilots);
- machinery and equipment required for the manufacturing and assembly of the aircraft;
- specific parts of the aircraft (e.g., nacelle, canopy, interiors);
- transportation between the manufacturing site to the user site;
- flight attendants and ground personnel during the operations phase;
- building rental;
- taxes (e.g., landing and navigation fees) and insurance;
- decommissioning of the aircraft.

The fuselage manufacturing site and final assembly line are hypothesized to be located in Naples (Italy), where the vendor supplied components and materials arrive. In particular, we assumed that the engines are assumed to be moving from Quebec to Naples via air, the wings from Bordeaux to Naples via truck and ship, and the propellers and tails from Figeac to Naples via truck and ship. The fuselage and avionics are assumed to be built in Naples.

We assumed that these movements of components and materials also occur for the realization of the prototypes. In addition, we supposed that the prototypes are similar to the manufactured aircraft in terms of components, weights, fuel consumption, materials composing the structure, resources needed for building the aircraft (e.g., electricity, natural gas, heat / steam). Finally, the design cost of the entire program is only allocated to the first aircraft produced: we hypothesized that this cost is spread over 5 years of production.

3.3 Engineering-Based Approach Definition

We applied the engineering-based approach by considering the collected data and employing the set of equations (cf. Table A1, Table A2, and Table A3 in Appendix).

3.4 Integration with CERs

The definition of the engineering-based approach highlighted the need to estimate the engineering, tooling, manufacturing, and maintenance workhours related to the next-generation green aircraft. The engineering is the process required to design the aircraft and perform the necessary Research, Development, Testing, and Evaluation (RDT&E), the tooling is the process required to design and build tools, fixtures, jigs, and molds, the manufacturing is the process to build the aircraft, and the maintenance encompasses both preventative and restorative strategies for maintaining the aircraft operating [5]. The lack of data and not feasible generation of assumptions on them for the next-generation green aircraft was overcome by using the CERs for the engineering, tooling, manufacturing, and maintenance workhours suggested by Gudmundsson [5]. These CERs are summarized in Eq. (4), Eq. (5), Eq. (6), and Eq. (7) respectively. Note that Eq. (6) is slightly different from the original CER by Gudmundsson [5] since our focus was the calculation of the number of workhours to manufacture one aircraft.

$$H_{engineering} = 4.86\, {W_{structure}}^{0.777}\, {s_{max}}^{0.894}\, {Q_{5years}}^{0.163}\, F_{CERT1}\, F_{CF1} F_{COMP1} F_{PRESS1} \quad (4)$$

$$H_{tooling} = 5.99\, {W_{structure}}^{0.777}\, {s_{max}}^{0.696}\, {Q_{5years}}^{0.263}\, F_{CERT2}\, F_{TAPER2}\, F_{CF2} F_{COMP2} F_{PRESS2} \quad (5)$$

$$H_{manufacturing} = \frac{7.33\, {W_{structure}}^{0.82}\, {s_{max}}^{0.484}\, {Q_{5years}}^{0.641}\, F_{CERT3}\, F_{CF3} F_{COMP3}}{Q_{5years}} \quad (6)$$

$$H_{maintenance} = (2.00 + F_1 + F_2 + F_3 + F_4 + F_5 + F_6)\, n_{flight}\, L\, d_{flight} \quad (7)$$

where:

- $H_{engineering}$ is the engineering workhours (in h);
- F_{CERT1} is the certification factor related to engineering labor (equal to 1.15);
- F_{CF1} is the flap system factor related to engineering labor (equal to 1.03);
- F_{COMP1} is the composite factor related to engineering labor (equal to 1.2);
- F_{PRESS1} is the pressurization factor related to engineering labor (equal to 1.03);
- $H_{tooling}$ is the tooling workhours (in h);
- F_{CERT2} is the certification factor related to tooling labor (equal to 1.05);
- F_{TAPER2} is the wing factor related to tooling labor (equal to 1);
- F_{CF2} is the flap system factor related to tooling labor (equal to 1.02);
- F_{COMP2} is the composite factor related to tooling labor (equal to 1.2);
- F_{PRESS2} is the pressurization factor related to tooling labor (equal to 1.01);
- $H_{manufacturing}$ is the manufacturing workhours (in h);
- F_{CERT3} is the certification factor related to manufacturing labor (equal to 1.05);
- F_{CF3} is the flap system factor related to manufacturing labor (equal to 1.01);
- F_{COMP3} is the composite factor related to manufacturing labor (equal to 1.5);
- $H_{maintenance}$ is the maintenance workhours (in h);
- F_1 is the factor depending on the ease of engine access (equal to 0.2);
- F_2 is the factor depending on the landing gear system (equal to 0.2);
- F_3 is the factor depending on the avionics system (equal to 0.2);
- F_4 is the factor depending on the fuel tanks (equal to 0.1);

- F_5 is the factor depending on the flap system (equal to 0.2);
- F_6 is the factor depending on certification (equal to 0.5).

The values of the several factors above were assigned based on the considerations available in [5]. Among the parameters in the selected CERs, the number of aircraft planned to be produced over a 5-years period (Q_{5years}) is particularly affected by uncertainty, as highlighted by the different subject-matter experts involved in the data elicitation phase. As a consequence, we replaced its static value (equal to 120) with a normal distribution having a mean value equal to 120 and a standard deviation value equal to 12. We performed the CER calculations via Monte Carlo simulations in MATLAB (version R2023b), setting the number of iterations equal to 1000. Table 5 summarizes the results (in hours) obtained through such simulations, in terms of the 5th percentile, 50th percentile (mean), and 95th percentile values.

Table 5 – Engineering, tooling, and manufacturing workhours (in hours).

Parameter	**5th percentile**	**Mean**	**95th percentile**
Engineering workhours	3,267,400	3,362,100	3,448,900
Tooling workhours	1,912,100	2,005,300	2,092,200
Manufacturing workhours	43,300	45,900	48,800

The number of aircraft planned to be produced over a 5-years period is equal to 100 at the 5th percentile of the engineering, tooling, and manufacturing workhours, to 120 at the mean value, and to 140 at the 95th percentile.

3.5 Application and Validation of the Model

The hybrid LCC / CER model permitted obtaining the overall LCC of the next-generation green aircraft and the costs for each stage of its life cycle.

For instance, considering the most credible scenario (i.e., the mean values for the engineering, tooling, and manufacturing workhours in Table 5), we obtained a LCC equal to 67,820,537 €/aircraft, which is mainly caused by the operations phase (Figure 3). This result is mostly associated to the costs of the fuel employed for the flights over the aircraft lifetime (i.e., 58.1%). This is, in turn, related to the fuel price: by assuming a fuel price equal to 1 €/l, the cost of the flights over the aircraft lifetime decreases, accounting for the 42.2% of the LCC. In the manufacturing phase, relevant costs are linked to the manufacturing labor, avionics, and engines that represent about the 41%, 28%, and 22.5% of the total manufacturing cost, respectively. The costs that occur in the design phase are responsible for the 7.19% of the entire LCC: this is related to the engineering labor and tooling labor required for producing the prototypes, which account for the 67.58% and the 26.73% of the total design cost, respectively. Such results are also emphasized in Figure 4, which provides an overview of the costs incurred in designing (i.e., the prototype realization) and manufacturing the aircraft.

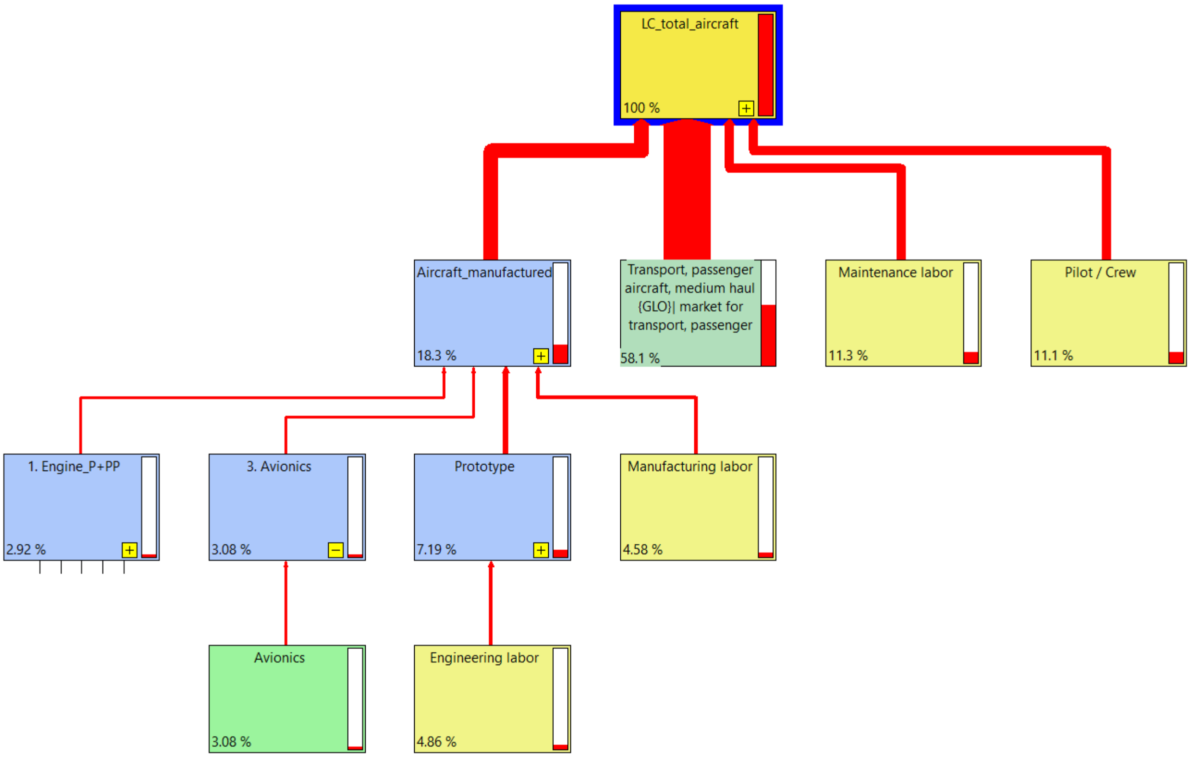

Figure 3 – LCC results (tree diagram), considering the most credible scenario.

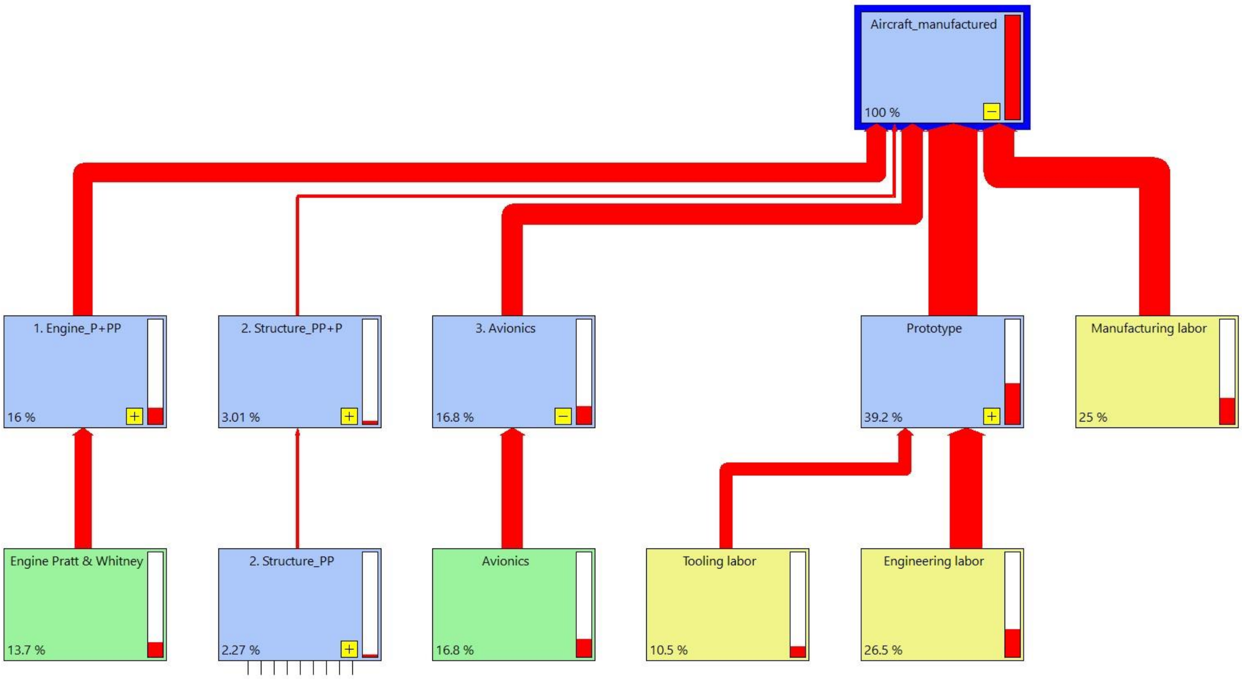

Figure 4 – Design and manufacturing costs (tree diagram), considering the most credible scenario.

In addition to the most credible scenario, it is possible estimating the LCC in the worst and best credible scenarios by considering the 5^{th} and 95^{th} percentile values for engineering, tooling, and manufacturing workhours (Table 5), respectively. As can be shown in Figure 5, the operations cost does not vary across the three scenarios, and remains the stage accounting for the majority of the costs: in the worst credible scenario, the operations cost is about 80.95% of the total LCC, while in the best credible scenario, it is about 82.13%. On the contrary, the three scenarios are characterized by different values for the design and manufacturing costs. This causes a change in the relative contributions that each phase has in the LCC:

- in the worst credible scenario, the contribution of the design cost to the LCC is higher than the one in the most credible scenario (i.e., accounting for about 10.78% in comparison to 7.19%);
- in the best credible scenario, the contribution of the manufacturing cost to the LCC is higher than the one in the most credible scenario (i.e., accounting for about 11.49% in comparison to 11.14%).

Since these changes are particularly limited, they impact the total LCC marginally. Indeed, in the worst credible scenario the LCC is equal to 68,428,114 €/aircraft, whereas in the best credible scenario it is equal to 67,447,616 €/aircraft. This provides insights into potential minimum and maximum estimates about the aircraft costs, due to the uncertainty on the engineering, tooling, and manufacturing labor workhours.

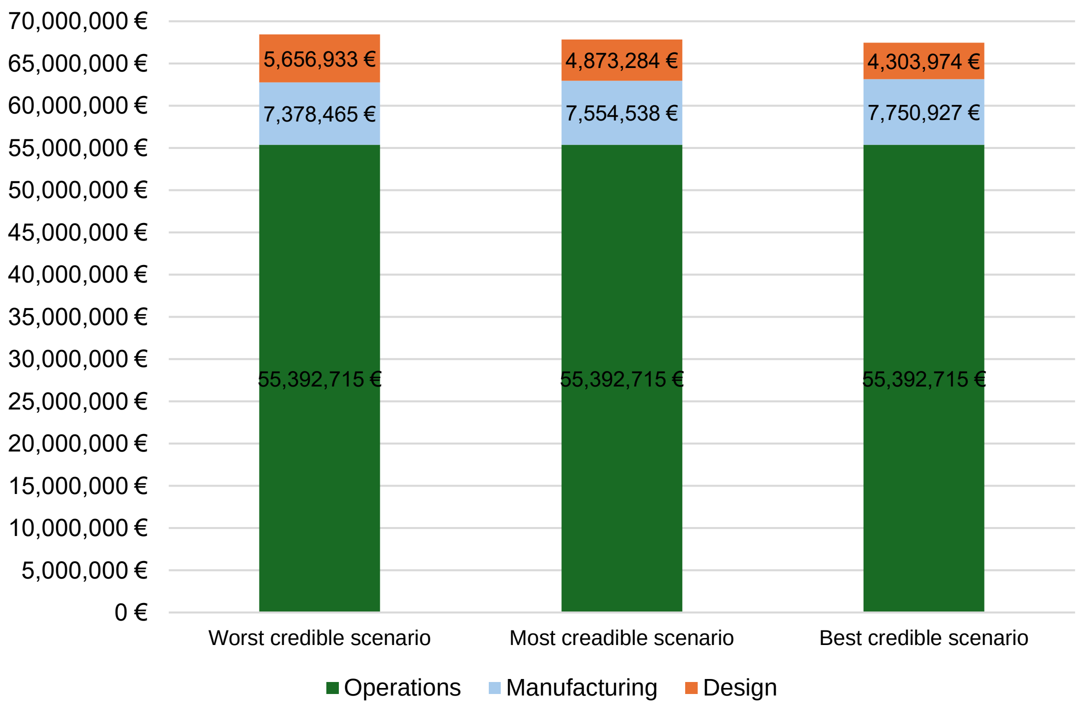

Figure 5 – LCC and costs for each life cycle phase in the worst, most, and best credible scenarios.

4. Discussion

The proposed hybrid LCC / CER model provides insights into the different cost types incurred in the various life cycle stages of a next-generation green aircraft. By adopting an engineering-based approach, such costs can be detailed in terms of technical data and performance of the aircraft, processes and resources required for its design, production, and use, and economic issues. This permits having a clear and transparent overview of the cost breakdown structure that takes into account the peculiarities of next-generation green aircraft. However, it requires gathering specific data in order to accurately model and determine such kind of costs. It represents one of the main drawbacks of the engineering-based approach for aircraft at the design phase: it is necessary involving various subject-matter experts and practitioners for defining the system and the associated processes, and it is challenging to obtain precise quantitative values. Moreover, in terms of the software used in this paper, the SimaPro and ecoinvent databases lack data on economic issues, calling for significant efforts for developing accurate cost inventories.

The complete lack of data on specific parameters of the model (i.e., engineering, tooling, manufacturing, and maintenance workhours) was managed in this study through the usage of existing CERs. Indeed, the CERs proposed by Gudmundsson [5] provide relationships estimating costs based on historical data of similar systems (i.e., aircraft) that can be adjusted for taking into account the features of the product under investigation. However, the adjustments may not be able to capture both the challenges of the design for the aircraft at hand, and all the differences existing between it and previous similar ones. The introduction of probability density functions for describing some parameters in the CERs and the associated uncertainty analysis can overcome this issue only partially. Additionally, since several CERs are currently available for various kind of aircraft (e.g., business, general), it is necessary to properly select the most suitable set of relationships that best suited the features of the next-generation green aircraft under investigation. When new data become available, it will be possible to reduce the use of CERs in the model, updating the LCC estimation with more precise information. In fact, the methodology for the hybrid LCC / CER model development and application should not be conceived as a linear process, but it is actually a loop with continuous feedback and iterations that allow for the refinement of the model and its results.

The hybrid LCC / CER model proposed in this paper is intended to be fully integrated in a Multi-Disciplinary Optimization (MDO) framework that considers the interactions among the system's disciplines and permits facing the design challenges of next-generation green aircraft [14]. Indeed, the outcomes derived from different disciplines (e.g., structural analysis, aerodynamics, propulsion systems) are used as inputs for the cost model to solve complex decisions about the aircraft design by considering conflicting objectives (e.g., minimization of material costs, maximization of performance). In this regard, in addition to the traditional configuration variables (e.g., structures, aerodynamics, propulsion), the various dimensions of costs represent a strategic leverage to ensure both the true MDO and the economic sustainability of aircraft.

5. Conclusions

This paper proposes a hybrid LCC / CER model for next-generation green aircraft at the design phase. Such a model is based on an engineering-based approach to estimate the costs, which is integrated with CERs when some data are completely lacking. To consider potential uncertainty sources due to the use of CERs and historical data not specifically suited for the aircraft under investigation, we also performed uncertainty analyses and Monte Carlo simulations. This permitted obtaining the worst, most, and best credible results for LCC.

The proposed model is applied and demonstrated via the design process of a 50-seat regional aircraft, powered with fuel jet A1, and composed of aluminum and composites. Such application highlights that most of the costs occur in the operations phase due to the fuel consumed during the flights over the entire lifetime. Other significant costs in the overall LCC are associated with engineering and manufacturing labor, needed for its design and production, respectively. These results remain valid regardless of the uncertainty surrounding the engineering, tooling, and manufacturing labor workhours.

Future research activities could be focused on refining the preliminary results obtained in this study: this could be stimulated by collaborating with further subject-matter experts, designers, and manufacturers and collecting other useful data and information. It could also allow revising the current assumptions. Furthermore, Monte Carlo simulations and uncertainty analyses could be introduced in the entire hybrid LCC / CER model by assigning other probability distributions to a wide set of parameters and by establishing a proper number of iterations to obtain a desired results' accuracy. Finally, the LCC of other next-generation green aircraft could be examined to further test the validity of the model.

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8. Copyright Statement

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Appendix

This appendix contains the entire set of equations composing the hybrid LCC / CER model to estimate the different costs associated with the design (Table A1), manufacturing (Table A2), and operations (Table A3) of next-generation green aircraft. The symbols of the equations are reported in the text of the article.

Table A1 – Equations for the costs in the design phase of the hybrid LCC / CER model.

Cost type	Equation
Engineering labor	$C_{engineering,design} = \frac{R_{engineering}\, H_{engineering}}{Q_{5years}}$
Tooling labor	$C_{tooling,design} = \frac{R_{tooling}\, H_{tooling}}{Q_{5years}}$
Components	$C_{components,design} = \left(n_{engine} c_{engine} + n_{propeller} c_{propeller} + c_{avionics}\right) \frac{n_{prototype}}{Q_{5years}}$
Transportation	$C_{transportation,design} = \left[W_{engine} n_{engine} c_{airplane} + W_{propeller} n_{propeller}\left(c_{truck} + c_{ship}\right) + W_{wing}\left(c_{truck} + c_{ship}\right) + W_{tail}\left(c_{truck} + c_{ship}\right)\right] \frac{n_{prototype}}{Q_{5years}}$
Test crew & pilot	$C_{testcrew,design} = \frac{R_{testcrew}\, n_{testcrew}\, H_{test}}{Q_{5years}}$
Fuel	$C_{fuel,design} = \left(\frac{c_{fuel}}{\rho_{fuel}}\right) \dot{m}_{fuel}\, H_{test}\, \frac{1}{Q_{5years}}$
Materials	$C_{materials,design} = [W_{structure}\, \%_{aluminum}\, c_{aluminum} + W_{structure}\, \%_{CFRP}\, c_{CFRP} + W_{structure}\, \%_{Kevlar}\, c_{Kevlar}] \frac{n_{prototype}}{Q_{5years}}$
Consumptions	$C_{consumptions,design} = \frac{\left(Q_{electricity} + Q_{gas} + Q_{heat}\right) W_{structure} n_{prototype}}{Q_{5years}}$

Table A2 – Equations for the costs in the manufacturing phase of the hybrid LCC / CER model.

Cost type	Equation
Manufacturing labor	$C_{manufacturing,manufacturing} = R_{manufacturing}\, H_{manufacturing}$
Components	$C_{components,manufacturing} = n_{engine} c_{engine} + n_{propeller} c_{propeller} + c_{avionics}$
Transportation	$C_{transportation,manufacturing} = W_{engine} n_{engine} c_{airplane} + W_{propeller} n_{propeller}\left(c_{truck} + c_{ship}\right) + W_{wing}\left(c_{truck} + c_{ship}\right) + W_{tail}\left(c_{truck} + c_{ship}\right)$
Materials	$C_{materials,manufacturing} = W_{structure}\, \%_{aluminum}\, c_{aluminum} + W_{structure}\, \%_{CFRP}\, c_{CFRP} + W_{structure}\, \%_{Kevlar}\, c_{Kevlar}$
Consumptions	$C_{consumptions,manufacturing} = \left(Q_{electricity} + Q_{gas} + Q_{heat}\right) W_{structure}$

Table A3 – Equations for the costs in the operations phase of the hybrid LCC / CER model.

Cost type	Equation
Maintenance labor	$C_{maintenance,operations} = R_{maintenance}\, H_{maintenance}$
Crew & pilot	$C_{crew,operations} = R_{crew}\, n_{crew}\, n_{flight}\, L\, d_{flight}$
Storage	$C_{storage,operations} = c_{storage}\, L$
Inspections	$C_{inspections,operations} = c_{inspections}\, L$
Fuel	$C_{fuel,operations} = \left(\frac{c_{fuel}}{\rho_{fuel}}\right) \dot{m}_{fuel}\, n_{flight}\, L\, d_{flight}$