A PROPOSAL TOWARDS A STEP CHANGE FROM ECO-DRIVEN TO SUSTAINABILITY-DRIVEN DESIGN OF AIRCRAFT COMPONENTS

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Abstract

Eco-design has emerged as a design methodology for aircraft structures aimed at mitigating the environmental impact of aviation, starting from the design phase and onward. In the current study, an approach is proposed to facilitate a transition from eco-driven to sustainability-driven design practices for aircraft components. In this method, sustainability is integrated as a fundamental design driver from the outset, expanding its interpretation beyond purely environmental concerns. The scope of this approach encompasses not only environmental impact and performance objectives related to safety requirements but also includes additional considerations such as costs, social, and circular economy aspects. These aspects are systematically quantified and optimized during the design process to deliver the most sustainable design that effectively balances structural and sustainability requirements. To demonstrate this approach, a typical component from the aviation industry, namely a hat stiffened panel, has been selected. The proposed approach allows for the comprehensive consideration of multiple sustainability aspects from the conceptual and basic design phase, thereby reducing risks and enabling engineers to address sustainability factors, when decisions are accountable for a great majority of the impact on sustainability.

Keywords: design for sustainability, sustainability-driven design, aircraft design, eco-design, hat stiffened panel

1. Introduction

Over the past few years, there has been an increasing focus on incorporating sustainability into product design [1]. However, despite the design stage possessing the greatest potential to influence the entire lifecycle of a product, this practice has not yet become widespread. Moreover, most approaches to design for sustainability (DfS) have primarily revolved around environmental concerns [2]. Within various DfS approaches, notable progress has been made in eco-design [3-7], also evident in initiatives within the aviation sector such as Clean Sky 2 and Clean Aviation [8, 9], which have emphasized this approach. However, the increasingly diverse landscape within aviation underscores the necessity for a broader approach to sustainability [10], demanding more comprehensive and adaptable strategies.

While other sectors like building and automotive industries have acknowledged the need to incorporate additional considerations beyond the environment, such as social criteria [11, 12], those approaches in aviation are seldom discussed. In the aviation research community, several works delve into considerations beyond environmental impact for design. These endeavors commonly focus on either conceptual aircraft or component levels.

At the conceptual aircraft level, multiple studies have expanded their scope beyond environmental impact assessment to include cost considerations, utilizing multi-objective optimization to optimize aircraft design based on these criteria, e.g. [7, 13-16]. Other aspects, such as social ones, are seldom taken into account, especially at the aircraft level [17]. At the aircraft component level, while the majority of design efforts have concentrated on optimizing performance enhancement and weight reduction, which are recognized as crucial for sustainability [18-21], only a subset of works have incorporated and optimized simultaneous considerations such as performance, weight, and costs [22], or environment and costs [23, 24], while social aspects are rarely being addressed and typically only advocated as a procedural step [25]. Finally, circularity aspects are rarely taken into account and are often linked to recyclability aspects, as also highlighted in previous studies by the authors [10, 26-27].

In the above, frame, the current work introduces a novel design methodology aimed at integrating sustainability considerations into the early stages of aviation component development. This approach involves simultaneous consideration of various sustainability-related factors including performance, environmental impact, costs, social implications, and circular economy principles. By exploring different material combinations and geometrical variations of a typical aviation component, namely a hat stiffened panel, the study employs multi-objective optimization (MOO) and multi-criteria decision-making (MCDM) techniques to identify optimal designs in terms of their sustainability. Through this process, a quantitative sustainability index is established, facilitating direct comparison and ranking of designs. This approach offers a swift evaluation tool for sustainability during the initial design phases, crucial for decision-making, particularly when faced with conflicting criteria for specific designs.

2. Methodology

2.1 Framework for sustainability-driven design and optimization

The proposed design methodology is rooted in the authors' understanding of sustainability as a design parameter, as demonstrated in previous works, e.g [10]. Central to this approach is the simultaneous evaluation of multiple sustainability-related factors, encompassing performance, environmental impact, costs, social implications, and circular economy principles. These aspects may present conflicts, necessitating a balanced trade-off among the criteria to attain the most sustainable solution between the alternatives (see Figure 1).

To integrate sustainability as a design optimization criterion, Multi-Objective Optimization (MOO) and Multi-Criteria Decision-Making (MCDM) techniques can be employed to identify the optimal solution among designs that may feature different material combinations and varied geometrical characteristics.

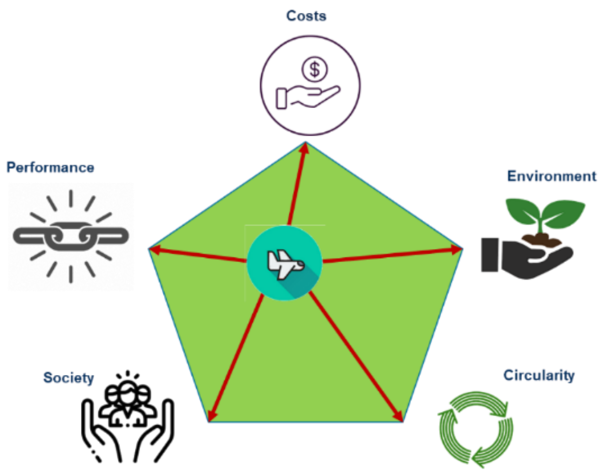

Figure 1 - Sustainability as trade-off between various parameters [10]

In the proposed design approach, multi-objective optimization (MOO) is used to optimize an aircraft component design characterized by distinct design geometrical variables with respect to the three pillars of sustainability: mechanical performance, environmental impact, costs. Following this, a post-optimization stage refines the design by considering social impact and circularity performance. Subsequently, multi-criteria decision-making (MCDM) techniques are employed to evaluate the most sustainable design, encompassing all five pillars of sustainability.

The method for optimizing the aircraft component design is illustrated in the flowchart of Figure 2, while the quantification and integration of each sustainability pillar into the design process are detailed in Section 2.2. Based on the flowchart of Figure 2, the process begins with the determination of the requirements, the selection of the reference case and the material or materials that will compose the aircraft component under consideration. Following the component's design, the geometrical parameters to be optimized are selected, leading to a multi-objective optimization (MOO) where the design is optimized regarding mechanical performance, environmental impact, and costs. Concurrently, based on the selected materials or material combinations, the social impact and circularity performance are assessed. Since these two aspects depend solely on the materials involved and not on the design's geometrical parameters, social impact and circularity performance are optimized independently. Once the optimized parameters for all aspects are derived, and all considered materials or material combinations are explored, a set of design alternatives associated to different materials or materials combinations emerge, demonstrating varying and potentially conflicting values within the sustainability Pillars. To compare and shortlist the available sustainable designs, a multi-criteria decision-making (MCDM) process takes place, assigning scores to the alternative designs and enabling the designer to determine which design or set of design alternatives excels in sustainability, compared to the alternatives explored.

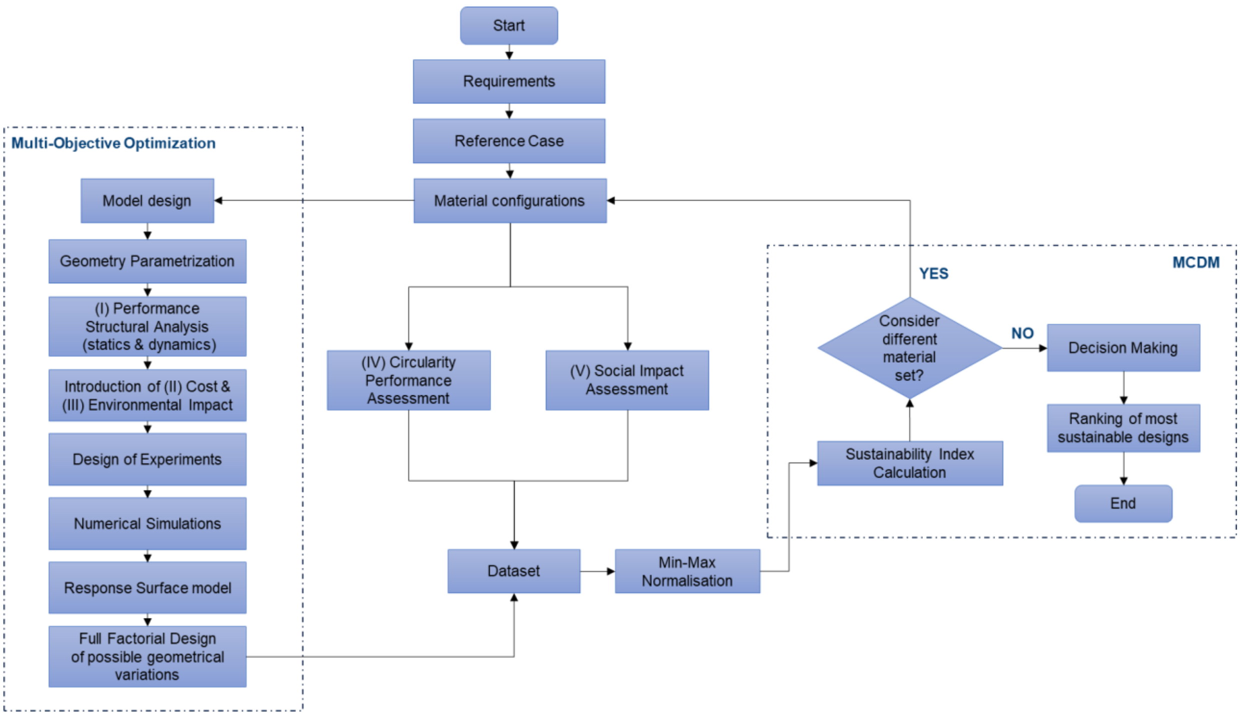

Figure 2 - Sustainability-driven design methodology including multi-objective optimization.

2.2 Integration of holistic sustainability assessment in the design process

To evaluate each design alternative in terms of sustainability and compare it with others, a multi-criteria decision-making (MCDM) approach is used to derive a quantified aggregate index for each design alternative. This index, initially presented by the authors in their earlier works [10, 26-29], considers stakeholder priorities across the five pillars of sustainability and potential trade-offs. The index is derived using normalized data for the five Pillars—Performance (P), Costs (C), Environmental Impact (E), Circularity Performance (CIRC), and Social Impact (SOC)—with normalization performed using the min-max method. These pillars are then combined using the Weighted Sum Method, where each pillar is multiplied by its respective weighting factor (Ki where i = P, C, E, CIRC, SOC), determined by the user.

$$SI = K_P \times P + K_C \times C + K_E \times E + K_{CIRC} \times CIRC + Ksoc \times SOC \quad (1)$$

This holistic index assesses the sustainability of a component design by assigning a value between zero (0) and one (1). A value of zero (0) indicates the lowest sustainability within the specific dataset, while a value of one (1) indicates the highest possible sustainability. It should be noted that sustainability in this context is relative to a reference, so we can only discuss degrees of sustainability rather than absolute measures.

2.3 Design Optimization Parameters

2.3.1 Mechanical performance and safety requirements

The structural integrity and durability of the structure as well as its functional needs must not be compromised when evaluating sustainability. Certain design constraints need to be set, such as establishing a threshold for the safety factor, to warrant an excellent mechanical performance. The considered component design is simultaneously optimized with respect to the desired mechanical properties.

2.3.2 Costs

The cost of a manufactured part must account for the entire processing chain, including material cost, part size and complexity, batch size, processing methods, recycling, and other factors. It is essential to consider all these factors when evaluating the cost of a component. By using the Part Cost Estimator Tool from ANSYS Granta [30], the cost parameter is calculated as the sum of each part's mass (m) multiplied by the part cost estimation (cost), based on the material used. The objective function for cost, used in the optimization process, is as follows:

$$C = \sum_{i=1}^{n} m_i * cost_i \quad (2)$$

where n is the number of parts for each component, m is the mass of the material(s), and cost is the cost associated with the specific part/material of the component.

2.3.3 Environmental impact assessment

Carbon emissions have a significant impact on the environment. In the present work, the authors define the environmental impact as being quantified by a parameter derived from the sum of the masses (m) of all the component parts, considering the involved materials and the associated carbon dioxide emissions (CO_2) throughout each part's material life cycle. This assumption is made without loss of generalization. Other types of emissions could be included without hindering the methodology. The carbon footprint evaluation encompasses the manufacture, transport, use, and disposal stages of each material. The latter assessment is conducted using ANSYS GRANTA's Eco Audit Tool [31], with calculations based on kilograms of carbon dioxide emissions. This tool enables a rapid assessment of the environmental impact, functioning as a streamlined Life Cycle Inventory (LCI) rather than a comprehensive and time-consuming full Life Cycle Assessment (LCA). This assessment is expressed in an objective function used in the optimization process, as shown below:

$$E = \sum_{i=1}^{n} m_i * CO_{2i} \quad (3)$$

where n is the number of parts for each component, m is the mass of the material(s), and CO_2 are the carbon dioxide emissions.

2.4 Design Post-Optimization Parameters

2.4.1 Circularity performance assessment

Measuring the circular economy (CE) is a controversial topic, as the definition of a circular indicator is debatable and may lead to misleading conclusions. Existing CE indicators primarily focus on material preservation and recyclability [26, 32]. Considering that maintaining the quality of recycled materials is crucial for achieving a closed-loop circular design, where material properties are not downgraded, a CE metric is proposed that links a quality attribute of the examined material, such as specific stiffness, to circularity. This approach is well-justified for aircraft applications, as the permissible design of an aircraft structure must remain within the linear elastic region of the corresponding stress-strain curve. The CE index used in the current design process ranks various material configurations suitable for the component. To rate the materials in terms of circularity, the index is related to the relative reduction in the specific stiffness of each virgin material compared to its recycled counterpart. The circularity index therefore is calculated as such:

$$CIRC = 1 - \sum_{i=1}^{n}\left(\frac{1}{n} * \frac{E' recycled_i - E' virgin_i}{E' virgin_i}\right) \tag{4}$$

where n is the number of parts for each component, E’ is the specific stiffness and calculated as E/ρ, where E is the material’s Young’s modulus and ρ is the density of the material.

2.4.2 Social impact assessment

Social Life Cycle Assessment (S-LCA) is a methodology for evaluating the social impacts of products and services throughout their life cycle. The S-LCA framework employs a stakeholder approach, considering the potential impacts on various stakeholder categories, reflecting that social sustainability involves managing both positive and negative impacts on people (stakeholders). The validity of data regarding social metrics is crucial, and the data can be sourced from licensed and free databases on social and socio-economic risks and impacts (e.g., United Nations, World Bank). The S-LCA subcategories align with the seventeen Sustainable Development Goals (SDGs) [33] set by the United Nations, which includes eliminating poverty and hunger, ensuring quality and accessible education, promoting fair and inclusive labor, and more.

ANSYS Granta, following the UNEP-SETAC [34] guidelines, provides a database with extensive data for about 200 nations, categorized into five stakeholder groups: workers, consumers, the local community, society, and other value chain actors. Each group contains relevant social impact categories corresponding to the S-LCA subcategories. Countries are scored on a normalized scale from zero to one hundred (0-100) for each social impact category, with zero representing the worst performance and one hundred the best. By associating specific life stages with the involved countries and analyzing the social metrics, one can evaluate the Social Life Cycle of a product. This study proposes integrating social impact considerations into the early stages of the design process, based on UNEP/SETAC guidelines and utilizing the ANSYS sLCA tool [30]. The goal is to identify and quantify the social impact of aeronautical components, incorporating it into the design phase. A social index is developed to integrate into the sustainability assessment of aircraft components, facilitating the optimization of components for sustainability, with social impact as a key pillar. This social index enables rapid social assessment from the design phase onward.

3. Implementation and demonstration of the approach

3.1 Reference case study of hat-stiffened panel

In this study, a common aviation component, specifically a hat stiffened panel, is considered. This component is fundamental for reinforcing aircraft structures, enhancing structural integrity, and offering a balance between weight efficiency and strength due to its unique design. Various material combinations are evaluated, and a parametric analysis is executed, with a view to comparing and optimize the different configurations with regards to sustainability. Assessing the comprehensive sustainability effect includes analyzing the structural performance along with the environmental, financial, circularity, and social impact of the selection of a design configuration. The geometry of the hat-stiffened panel is comprised of two parts, namely the skin and the stringer. The reference case is a hat-stiffened panel made of Aluminium 2024 T3, on both the skin and the stringer and its dimensions are displayed in Figure 4. The dimensions are based on the reference case study of earlier works by the authors [10].

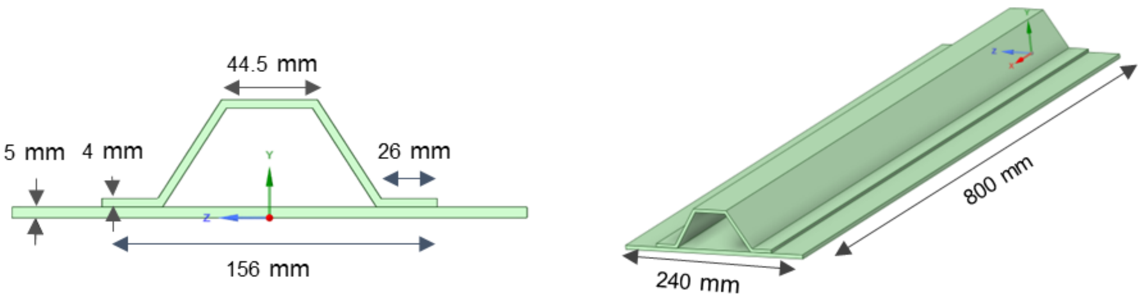

Figure 3 - Dimensions of the reference case study hat-stiffener.

The process of defining structural and sustainability requirements occurs within the component's design phase. Specific aims are set for the structural and sustainability requirements of the design. Table 1 showcases the essential requirements. Structural requirements include warranting the structural integrity of the component, allowing geometrical dimension modifications, and focusing on retaining the safety factor above 1.5, minimizing total deformation and maximum principal stress, and maximizing mode 1 eigenfrequency. Furthermore, sustainability requirements are associated with minimizing the environmental footprint, the cost, the social impact, and maximizing the circularity performance of the component.

Table 1 – Functional requirements of the hat-stiffened panel

Requirements	Current State	Target State
Structural	• Reference geometry. • Reference mass. • Safety factor (SF) of 1.5	• The safety factor should be above 1.5 • No damage should occur • Minimization of total deformation • Maximization of mode 1 eigenfrequency • Minimization of maximum tensile stress
Sustainability	• No sustainability requirements at current state of the reference.	• Minimization of the environmental footprint • Minimization of cost • Minimization of social impact • Maximization of circularity

3.1.1 *Development of a numerical model for the MOO*

The Boundary & Loading Conditions involve setting fixed supports on the surfaces of one profile of the skin and stringer, while applying a distributed tensile load on the surfaces of the other profile of the stringer and skin. The applied loading has a magnitude of 650,000 N, chosen to ensure that the reference material and geometrical configuration achieve a minimum Safety Factor Value of 1.5. The Boundary & Loading Conditions are illustrated in Figure 4.

For the development of a parametric simulation model, the finite element (FE) software ANSYS is used for the investigation of the static and dynamic behavior of different design variants. This enables the generation of an FE model with parameters that define the material type and thickness of each component of the stiffener. The skin and the stringer are discretized with 12282 solid Hexa/Prism finite elements. The contact between the stringer and the skin is considered bonded. Analysis was performed, using the commercial software ANSYS [35], involving a detailed investigation of the static as well as the dynamic behavior of the test cases is conducted.

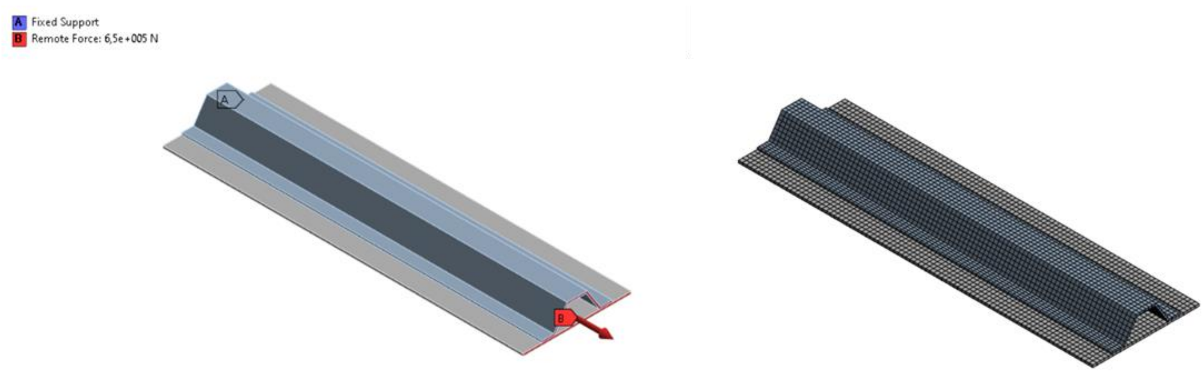

Figure 4 - Boundary Conditions and mesh on the reference case.

3.1.2 Material Combinations

The materials used, are suitable for aerospace applications and their characteristic values are mentioned in Table 2. For Unidirectional CFRP, it is assumed that the characteristic values pertain to the direction of the tensile load, which is also the loading condition of the component.

Table 2 - Properties of the involved materials [31]

	Properties	*Aluminium 2024 T3*	*17-4PH Stainless Steel*	*Epoxy/HS carbon fiber, UD prepreg, UD lay-up (CFRP)*
Mechanical	*E (GPa)*	73.5	196	141
	v	0.3367	0.275455	0.329848
	G (GPa)	28	77	53.04
	ρ (kg/m^3)	2767.96	7861	1564.93
	σyield (GPa)	0.328	0.833	1.943
Environmental Impact	*Manufacturing process*	Roll Forming	Metal Powder Forming	Autoclave
	Disposal	Recycle	Recycle	Downcycle
	CO2 Footprint	12.99	9.109	49.464
Costs	*Part cost (€/kg)*	4.44	17.75	205.5

Five material configurations are examined, which are displayed in Table 3. The engineering data for each material were provided by ANSYS Granta [30].

Table 3 - Component configurations/combinations

Component Configurations		
No	**Skin**	**Stringer**
1	Aluminium 2024 T3	Aluminium 2024 T3
2	CFRP	Aluminium 2024 T3
3	Aluminium 2024 T3	CFRP
4	CFRP	CFRP
5	17-4PH Stainless Steel	CFRP

3.2 Design Optimization setup- Multi Objective Optimization

The parametric design is executed to obtain the optimal design points when taking into account the factors shown in Table 4.

Table 4 - Constraints, variables, and target parameters of the optimization process

Constraints	Variables	Parameters
Minimum safety factor: >1.5	• Thickness of skin: 3-6mm • Thickness of stringer: 3-6mm • Crown width: 35-65 mm	• Maximum total deformation • Maximum principal stress • Mode 1 eigenfrequency • Cost • Environmental impact

In the optimization stage, three of the five pillars that are investigated are mechanical performance, costs and environmental impact, which are defined by the design variation and the material selection. The geometrical modifications of the thickness of the skin and the stringer, and the crown width, which is the width of the top part of the stringer and is correlated with the distance between the skin and the stringer, regulate the total of the parameters.

3.2.1 Mechanical Performance Assessment

The parameters of Maximum Total Deformation Maximum Principal Stress, and Mode 1 Eigenfrequency describe the mechanical performance pillar and are evaluated during the design's static and dynamic analysis stages.

3.2.2 Costs

The Cost parameter refers to the Costs and the procedure for calculating it follows Equation 2. To obtain representative estimations of the part's cost, certain assumptions were required. The mass of the part is considered to be one kilogram and the length is 0.8 meters, the batch size is 1000 samples, and the final cost of each part represents an average value. Table 2 indicates the part price referring to each material involved.

3.2.3 Environmental impact assessment

The Environmental impact parameter is attributed to the Environmental Impact Assessment and can be evaluated following Equation 3. CO_2 emissions are calculated for each material by assuming that only virgin materials are used, each material undergoes only a primary process and the transport and use phases are excluded, due to their complexity in tracking. Table 2 displays the manufacture and disposal stage for each material, as well as the calculated carbon footprint.

3.2.4 Multi-Objective Optimization

Initially, a Design of Experiments, for each one of the five material configurations, is conducted using the Central Composite Design method, estimating several design points with different geometrical configurations. Subsequently, the Response Surface Method (RSM) is applied, utilizing genetic aggregation to evaluate numerous geometric designs based on the pillars of performance, costs and environmental impact, within the designated experimental domain. Each material configuration provides a unique RSM model, including all the equations that relate the geometrical inputs with the performance outputs. These models are introduced into the software for simulation and model-based design, Simulink, to obtain specific sampled geometrical designs and conduct a full factorial design to combine them and create multiple design variants. The constraint for the safety factor, which guarantees the mechanical performance rigidity requirements, limits the possible output design variants. During optimization, the objective values and constraints are set, guiding the process to meet these targets.

3.3 Post-Optimization Social Impact and Circularity Performance assessment

Circularity Performance and Social Impact assessments are expressed through the Circularity index and the Social index accordingly, which are independent of the geometrical features of the design but dependent on the material configurations, therefore they need to be assessed in the post-processing stage. These metrics are included in the Sustainability Index as normalized values.

3.3.1 Circularity Performance Assessment

Considering the methodology that was previously described, the circularity index is evaluated. Referring to [29], properties concerning virgin CFRP of Vf=50% and recycled random CFRP fibers of Vf=40% are introduced. Both Aluminium 2024 T3 and 17-4PH Stainless Steel maintain their specific stiffness theoretically intact during the recycling phase. Table 5 demonstrates the quality reduction on the specific stiffness of each material after recycling.

Table 5 – Quality Reduction of the specific stiffness after recycling

Material type	Quality Reduction
CFRP	36.82 %
Aluminium 2024 T3	<1 %
17-4PH Stainless Steel	<1 %

3.3.2 Social Impact Assessment

The social index, as described above, is directly linked to the life phases of an aviation component and the countries where each stage might occur. Since data on alliances between companies, transportation of products, and their use are unclear, assumptions are necessary to showcase the method. Specifically, the data used for these analyses are sampled, considering all potential trades between countries involved in the life cycle. Research has been conducted to identify the countries where each material is extracted (for metals) or produced (for CFRP, including carbon fibers and epoxy resin), undergoes primary manufacturing (for metals), is manufactured as a component of the hat stiffened panel for aviation purposes, and is recycled, assuming none will end up in a landfill. The Social Hotspot Summary provides important qualitative information about different scenarios in the life cycle of a product. The authors aimed to quantify the data and include them in a ranking of possible life cycle scenarios for a Hat Stiffened Panel, to incorporate them into the social parameter in the sustainability index. A threshold of 50% is set, referring to categories where each country is 50% below the world average, creating a Social Hotspot in this category. Each "X" indicating a Social Hotspot is scored as one point, and the total score for each scenario is the sum of the Social Hotspots across the five categories. Best and worst-case scenarios for all material combinations were identified. Every other scenario scores between the best and worst cases for the material configuration it refers to. Subsequently, a full factorial design of experiments was conducted for each material combination with around 8000 generated cases, and min-max normalization was performed for all possible scenarios to incorporate them into the Sustainability Index. Table 6 indicates the best- and worst-case scenarios for the AL-AL configuration, as an example. As can be observed, the best-case scenario occurs when the life cycle of the component is related to the following countries: Canada, Switzerland, France and Australia, while the worst-case scenario occurs in countries such as India, Mexico, Argentina and Nigeria, where the sociopolitical situation in these countries is more unstable.

Table 6 – Best and Worst case scenarios for the AL-AL case

Best case scenario for Aluminium 2024 T3- Aluminium 2024 T3							
Life Phase	**NATION**	**S1 Workers**	**S2 Consumers**	**S3 Local community**	**S4 Society**	**S5 Value chain (others)**	
Material 1-Bauxite	CAN		X	XX	XX		5
Manufacture 1-Aluminium formation	SUI			XX	X		3
Manufacture 2- HSP	FRA			XX	XX		4
End of life	AUS			XX	X		3
Score		0	1	8	6	0	**15**

Worst case scenario for Aluminium 2024 T3- Aluminium 2024 T3							
Life Phase	**NATION**	**S1 Workers**	**S2 Consumers**	**S3 Local community**	**S4 Society**	**S5 Value chain (others)**	
Material 1-Bauxite	IND	XXXXXX	X	XXXXX	XX	X	16
Manufacture 1-Aluminium formation	MEX	XXXX	XXX	XXXX	XX	X	14
Manufacture 2- HSP	ARG	XXXX	XX	XX	XX	XX	12
End of life	NGR	XXXX	XX	XXXXXX	XX	XXX	17
Score		18	8	18	8	7	**59**

4. Results and Discussion

Following the MOO and post-optimization stages, all data concerning the investigated pillars of the multiple design variants and material configurations are collected into a dataset and a min-max normalization is conducted for each pillar. Afterwards, the Sustainability Assessment takes place, by utilizing an MCDM approach.

4.1 Design Optimization Results- MOO

The Response Surface method predicts the observed response in points within the designated experimental domain and the full factorial design that follows provides specific design variants per material configuration. Subsequently, the design variants are restricted by the safety factor constraint and only those surpassing the required value are considered for the optimization stage. Table 7 showcases the number of design variants per material configuration.

Table 7 - Number of design variants for each configuration

Material Configuration (skin + stringer)	Number of Design Variants
Aluminium 2024 T3 + Aluminium 2024 T3	363
CFRP + Aluminium 2024 T3	657
Aluminium 2024 T3 + CFRP	854
CFRP + CFRP	1727
17-4PH Stainless Steel + CFRP	882

4.2 Design Post-optimization results

Regarding the Social Impact Assessment, the final results are based on the methodology presented in Section 3.3.2. The best and worst-case scenarios for AL-AL are presented, in Table 6, as a reference.

Concerning the Circular Economy Pillar, the calculations concerning the Circularity index is calculated using Equation 3, and the values for the various configurations are displayed in Table 8:

Table 8 - Circularity performance Index for the different configurations.

Configuration		CIRC
Skin Material	Stringer Material	
Aluminium 2024 T3	Aluminium 2024 T3	1
CFRP	Aluminium 2024 T3	0.815
Aluminium 2024 T3	CFRP	0.815
CFRP	CFRP	0.63
17-4PH Stainless Steel	CFRP	0.815

The integration of the Social Impact metric and the Circularity metric into the Sustainability Index requires normalization of the values. For the Social Index, it is important to note that the best-case (optimal) scenarios are used for each configuration separately in this study.

4.3 Sustainability assessment of the design alternatives

A Matlab [36] script was applied based on the principles of Multi-Criteria Decision Making to evaluate and compare various material configurations and their geometrical modifications. The objective was to identify the optimal configuration in terms of sustainability, by utilizing Equation 1 of the Sustainability Index (SI). The results can vary significantly based on different weighting factors. In this case, the equal weights scenario is considered. In Table 9, the ranking of the design configurations, the mean value and the standard deviation of the geometrical variations and the sustainability indexes are displayed. The optimal design configuration is Aluminium 2024 T3 on both the skin and the stringer of the hat stiffened panel. The sustainability index is significantly higher than the following configuration of Aluminium 2024 T3-CFRP, as it has achieved a better balance between the five pillars. Both thicknesses of the skin and the stringer are thicker than the reference case (5 mm for the skin and 4 mm for the stringer) and the crown width does not vary greatly from the reference (44.5 mm). The design configurations ranked in the second and third positions have relatively similar sustainability indexes, and certain design variants might provide comparable results overall. The least optimal design configuration is deemed the material CFRP on both the skin and the stringer, while it provides poor results in specific pillars such as the circularity assessment pillar and the costs.

Table 9- Ranking, geometrical features and sustainability index for each design configuration

Design Configurations Ranking		
Thickness skin (mm)	**Thickness stringer (mm)**	**Crown width (mm)**
No.1 - Aluminium 2024 T3 + Aluminium 2024 T3- SI = 0.912 ± 0.011		
5.40 ±0.46	5.31 ± 0.59	47.94 ± 8.93
No.2 - Aluminium 2024 T3 + CFRP - SI = 0.667 ± 0.033		
5.30 ± 0.51	4.58 ± 0.95	51.13 ± 9.07
No.3 - CFRP +Aluminium 2024 T3 - SI = 0.625 ± 0.029		
4.85 ± 0.81	5.36 ± 0.55	47.74 ± 9.10
No.4 - St.Steel + CFRP - SI = 0.553 ± 0.027		
5.25 ± 0.55	4.72 ± 0.91	49.77 ± 9.41
No. 5 - CFRP + CFRP - SI = 0.486 ± 0.047		
4.50 ± 0.94	4.50 ± 0.94	50.00 ± 9.42

In Figure 5, a graphic representation of the optimal configurations for each material combination is showcased. It is apparent that the design configuration with Aluminium 2024 T3 on both the skin and the stringer, excels almost in each category, and the configuration with CFRP on both the skin and the stringer offers inferior sustainability.

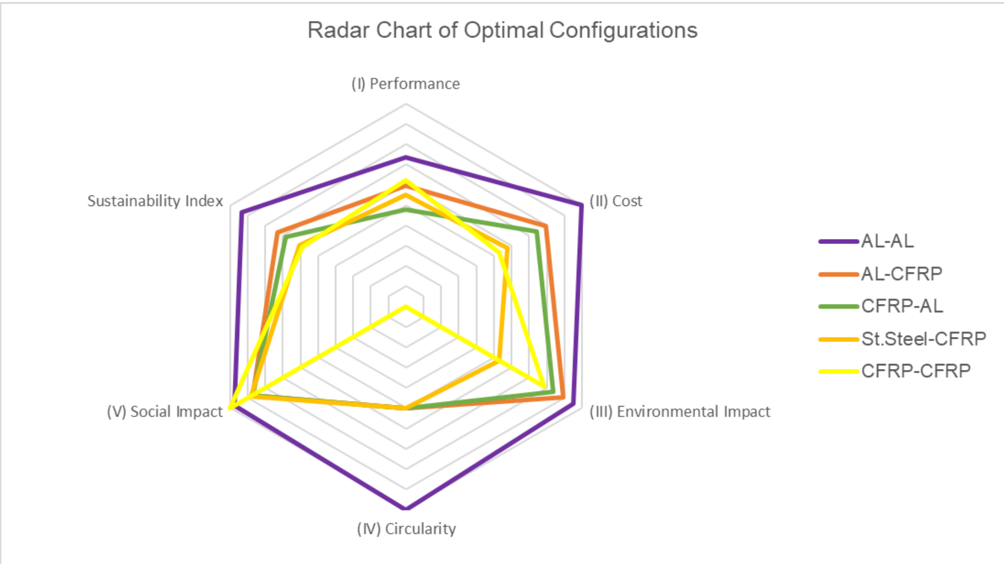

Figure 5 – Radar Chart of optimal designs for each material configuration

5. Conclusions

In the present study, sustainability is integrated as a design driver of the conceptual design and the design phase, broadening the interpretation of sustainability beyond environmental concerns. This novel approach emphasizes the simultaneous evaluation of various sustainability-related factors, including performance, environmental impact, costs, social implications, and circular economy principles. By utilizing Multi-Objective Optimization (MOO) and Multi-Criteria Decision-Making (MCDM) techniques, the methodology explores different material combinations and geometric variations of typical aviation components, namely a hat stiffened panels, to identify the most sustainable design alternatives. The proposed methodology proposes a quantitative sustainability index, which serves as a crucial tool for directly comparing and ranking different design options. This index enables designers to make informed decisions during the initial design phases, especially when faced with conflicting design criteria. To illustrate the approach, an in-depth case study focused on analyzing a hat-stiffened panel with different material configurations. The study found that the Aluminium 2024 T3 configuration for both skin and stringer was the most sustainable as it showcased balanced performance in all metrics, while the CFRP skin with CFRP stringer was the least sustainable, because it provided poor results on specific metrics.

Looking ahead, the methodology shows significant potential for broader application in the aviation industry and beyond. Future research could focus on refining the quantification and integration of sustainability metrics, expanding the range of materials and geometric configurations considered, and enhancing the Multi-Criteria Decision-Making (MCDM) process for more accurate sustainability assessments. Additionally, adapting the methodology for use in other sectors such as automotive, civil engineer, machine design, and energy would increase its versatility. Finally, further collaborating with stakeholders and aligning the methodology with regulatory frameworks could facilitate its adoption, leading to more comprehensive and widely applicable sustainability evaluations.

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7. Copyright Statement

8. References

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