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Sustainability-Driven Design of Aircraft Composite Components

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Abstract: The current prevailing trend in design across key sectors prioritizes eco-design, emphasizing considerations of environmental aspects in the design process. The present work aims to take a significant leap forward by proposing a design process where sustainability serves as the primary driving force. In this context, sustainability is positioned as a fundamental component to be integrated into the initial stages of design, introducing innovative multidisciplinary criteria that redefine the design paradigm. Within this framework, sustainability is characterized using a comprehensive and quantifiable index encompassing technological, environmental, economic, and circular economy dimensions. To demonstrate the practical application of sustainability as the primary criterion in designing mechanical components, a parametrized finite element model of a composite plate is utilized, integrating both pristine and recycled fibers. Subsequently, a demonstrator derived from the aviation industry—specifically, a hat stiffener—is employed as a validation platform for the proposed methodology, ensuring alignment with the demonstrator's specific requirements. Various representative trade-off scenarios are implemented to guide engineers' decision-making during the conceptual design phase. Additionally, the robustness of the aforementioned methodology is thoroughly assessed concerning changes in the priority assigned to each sustainability criterion and its sensitivity to variations in the initial data. The significance of the proposed design methodology lies in its effectiveness in addressing the complex challenges presented by conflicting sustainability objectives. Furthermore, its adaptability positions it for potential application across various sectors, offering a transformative approach to sustainable engineering practices.

Keywords: sustainability; holistic sustainability index; conceptual design; engineering for sustainability; design-for-sustainability; multi-material design; composites; hat stiffener

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1. Introduction

In the context of mechanical systems design, sustainability is recognized as a crucial factor that addresses the pressing challenges of our society, including climate change and resource scarcity. However, a notable deficiency still exists in emphasizing the integration of sustainability during the initial stages of product development, even though this phase holds the greatest potential for impacting the product's lifecycle [1]. Despite the notable progress made in eco-design, which is evident from commendable initiatives and works (e.g., [2–7]), it is important to recognize that these efforts have predominantly focused on traditional Life Cycle Assessment (LCA) methods. Although eco-design is a praiseworthy initiative that prioritizes environmental aspects during product design, there is an urgent need to embrace more comprehensive approaches to propel sustainability efforts further, especially within critical industries like aviation. In this context, a few initiatives have expanded their scope beyond environmental considerations to also encompass other factors, such as costs, and assess potential trade-offs [8]. Meanwhile, alternative research endeavors have directed their attention toward circular economy principles, specifically emphasizing recyclability criteria during the design phase of aviation components, e.g., [9].

It is evident from the earlier discussion that even the definition of sustainability is challenging due to its lack of precision and clarity. In 1987, the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [10]. Over the past few decades, numerous studies addressing the analysis of sustainability have remarked on the perplexity it creates, e.g., [11]. This perplexity arises from the various interpretations and numerous definitions that emerge in different disciplines or political contexts where the term is employed. With regard to the aviation sector, sustainability is mainly interpreted as environmental sustainability, primarily centered on traditional LCA, focusing on reducing the industry's environmental footprint by addressing mainly greenhouse gas emissions and, in a lesser amount, noise pollution, resource conservation, and waste management, e.g., [3–5].

The authors, in previous works, provided a definition of sustainability that encompassed a broad spectrum of sustainability aspects [12,13] and emphasized the necessity of early integration across the aircraft's lifecycle phases through the adoption of a holistic approach. In this frame, the primary objective of the current research is to surpass traditional design practices and tackle the existing lack of emphasis on sustainability within the conceptual design and the design phase. The current work aims to integrate sustainability not only as an essential component of the design process right from its inception but also to extend its scope beyond the boundaries of environmental considerations, offering a decision-making tool in the design process that encompasses all aspects of sustainability as per the authors' perspective. This broader perspective incorporates various dimensions, including technological advancements, economic viability, and circular economy principles. The research is guided by several fundamental engineering questions. These questions comprise the integration of sustainability aspects as a criterion of the design process, the utilization of recycled materials in sustainable design, and an exploration of how recycled materials influence the overall sustainability of products. Furthermore, there is an emphasis on addressing the practical challenge of communicating and demonstrating this methodology to design engineers, with the ultimate objective of facilitating its rapid acceptance and widespread implementation across the industry. Multi-Criteria Decision Making (MCDM) techniques are employed to formulate a comprehensive sustainability index (SI) as a main design criterion to attain these objectives. While MCDM is frequently utilized to evaluate sustainability and make technology comparisons [14], its integration into the product design phase is introduced for the first time. Sustainability is regarded here as an essential design criterion, offering the users the flexibility to design a product based on their specific priorities, whether they lean toward environmental, economic, or other considerations.

To demonstrate the proposed approach, a composite plate with a specific layup is analyzed, exploring the potential use of both pristine and recycled carbon fiber-reinforced plastics (CFRP) as candidate materials. The study systematically investigates various design alternatives through a finite-element parametric numerical study, following a Design of Experiments (DOE) approach, facilitating the methodical evaluation of different stacking layups and combinations of pristine and recycled CFRP layers. Upon identifying the design configurations that satisfy the functional criteria, the integrated sustainability metric, namely the sustainability index, is calculated to quantify the overall sustainability performance for each design alternative. Utilizing MCDM, various trade-off scenarios are explored, considering different user priorities. Subsequently, the methodology's validation is carried out using a typical aviation component, specifically a hat stiffener. Different configurations are ranked based on their sustainability performance. Finally, the methodology's robustness is evaluated by considering various priority and weighting scenarios, along with sensitivity analyses to address the effect on SI of the potential variations of the raw data. Although the authors have chosen to utilize recycled and remanufactured materials in an effort to potentially enhance the sustainability of composite components, fillers could also be a viable option. Fillers possess the capability to serve as materials that enhance the sustainability of components and should be considered for inclusion in this context, e.g., [15–18]. However, such an investigation falls beyond the scope of the current study.

The novel aspect of the current research lies mainly in involving holistic sustainability as the principal design criterion. The current work proposes a transition from the prevailing state-of-the-art eco-design to an approach centered on sustainability-driven design. As far as the authors are aware, within the aviation sector there is no existing design approach that mirrors this approach.

The paper is structured as follows: Section 2 provides a recap of the definition of sustainability and the metrics used for quantifying its various dimensions. It presents case studies considered in this context and outlines the technological prerequisites for the materials and components under consideration. Section 3 presents the design strategy and outlines the set of requirements for the components under consideration. Section 4 comprehensively presents and discusses the results obtained from the test cases considered. Section 5 involves evaluating the robustness of the methodology by examining different priority and weighting scenarios. Additionally, sensitivity analyses are conducted to assess the potential impact of variations in raw data on the sustainability index. Finally, in Section 6, the paper delivers a conclusive summary highlighting the key findings and contributions of the study. The potential applicability of the proposed engineering approach across various sectors within the field of mechanical engineering is also emphasized.

2. Materials and Methods

2.1. Definition and Involved Metrics of Holistic Sustainability

The current work proposes a sustainability-driven design approach based on a comprehensive definition of sustainability introduced by the authors in previous works [12,13,16]. For the convenience of the reader, the following chapter summarizes the definition of sustainability and the metrics involved in its quantification. According to the above cited works, the sustainability definition takes a holistic approach, considering several pillars encompassing performance, ecological, circularity, economic, and social aspects. In this context, sustainability is defined as the distinctive quality/property of a product, enabling it to outperform or align with the following criteria when compared to similar products existing in the market:

I. Performance criterion: A sustainable product should demonstrate a level of performance that is on par with or superior to comparable products available on the market. This means it should fulfill its intended purpose effectively and efficiently without compromising quality, reliability, or functionality requirements.

II. Financial criterion: Sustainable products should be economically viable and competitive in the marketplace. This implies that the cost of materials, production, maintenance and repair, and disposal should be reasonable and justifiable in order to offer long-term value, such as energy or resource savings, and to ensure economic benefits over their lifecycle.

III. Social pillar: Sustainable products should consider social aspects, considering the well-being of individuals and communities affected by their production, use, and disposal. This involves promoting fair labor practices, ensuring worker safety, respecting human rights, and guaranteeing inclusivity and diversity.

IV. Ecological criterion: Sustainable products must address environmental considerations comprehensively. This includes minimizing negative environmental impact throughout their lifecycle, from raw material extraction to disposal. It involves reducing greenhouse gas emissions, conserving resources, minimizing waste generation, and promoting responsible sourcing.

V. Circularity criterion: Sustainable products should embrace the principles of circular economy, aiming to maximize resource utilization and minimize waste. They should be designed for durability, reparability, and reuse or recyclability, enabling materials to be cycled back into the economy rather than ending up as waste.

Additionally, they should encourage the use of renewable resources and prioritize eco-friendly manufacturing processes. Finally, a circularity performance assessment should account for material degradation over multiple recycling loops.

A product can be seen as more sustainable in comparison to similar products when it effectively balances performance, financial viability, social responsibility, ecological impact, and circularity performance and outperforms them from a holistic point of view.

Following the definition of sustainability at the product level, a focused application of sustainability criteria can be defined, which are component specific. In specifying sustainability criteria for aircraft components, the following considerations can be made:

I. Performance Criterion: Aircraft components must adhere to stringent performance standards, meeting functional requirements, structural integrity, and durability within the aircraft while maintaining safety and quality.

II. Financial Criterion: Evaluating the component's economic viability for its entire lifecycle involves assessing costs from extraction, material, manufacturing, and maintenance to end-of-life management, demonstrating long-term economic benefits.

III. Social Criterion: The assessment revolves around ethical considerations during the production of aircraft composites, ensuring fair labor practices, worker safety and health, and promoting inclusivity and diversity within the component's supply chain, e.g., in the composites supply chain. It is important to note that the social criteria can be more readily defined and evaluated at a broader scale, specifically at higher levels such as systems and subsystems, for instance, when considering new technologies of the aircraft or the entire aircraft.

IV. Ecological Criterion: Central to this criterion is the comprehensive consideration of the environmental impact throughout the lifecycle of composite aircraft components. This involves selecting sustainable materials, minimizing waste generation, reducing energy consumption, and mitigating carbon emissions.

V. Circularity Criterion: The primary focus lies in evaluating the potential for recyclability and integration into a closed-loop system within the aerospace industry. Critical factors include efficient disassembly, material separability, and the ability to be recycled.

Hence, in the design of an aircraft component, achieving the most appropriate equilibrium among the aforementioned factors necessitates a comprehensive and tailored approach that considers the harmonization of these elements.

2.2. Integration of Holistic Sustainability as a Main Design Function

In the proposed interpretation of sustainability as a main design function, sustainability emerges as a matter of trade-off between system-internal contradicting aspects linked to mechanical performance, society, costs-resources, environment, and circular economy (Figure 1).

The present study excludes the consideration of the social impact dimension due to its lack of relevance to the specific case study and comparison being conducted. Social impact data proves more accessible and relevant when applied to the system and subsystem levels of an aircraft, such as the propulsion system, an alternative disruptive design, or the aircraft as a whole. However, it becomes notably more challenging to ascertain at the individual component level. Consequently, the evaluation of social implications for the specific use case has been disregarded. Based on the above consideration, a quantified holistic index (Equation (1)), introduced by the authors in their previous works [12,13,19], is implemented in the present study with certain modifications to address potential trade-offs. In this instance, for the first time, the following index serves as the primary design criterion for a typical component.

$$SI = P \times K_P + E \times K_E + C \times K_C + CIRC \times K_{CIRC} \leq 1 \tag{1}$$

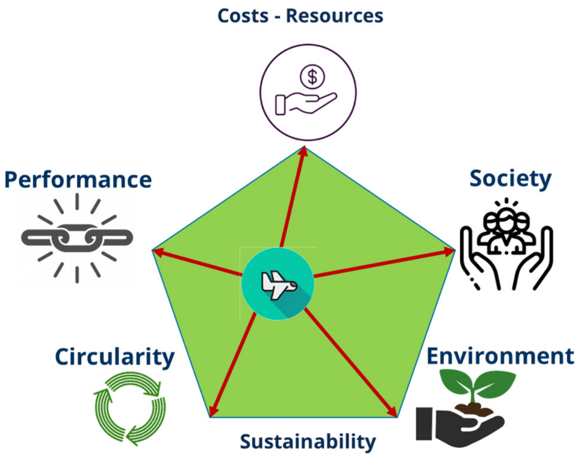
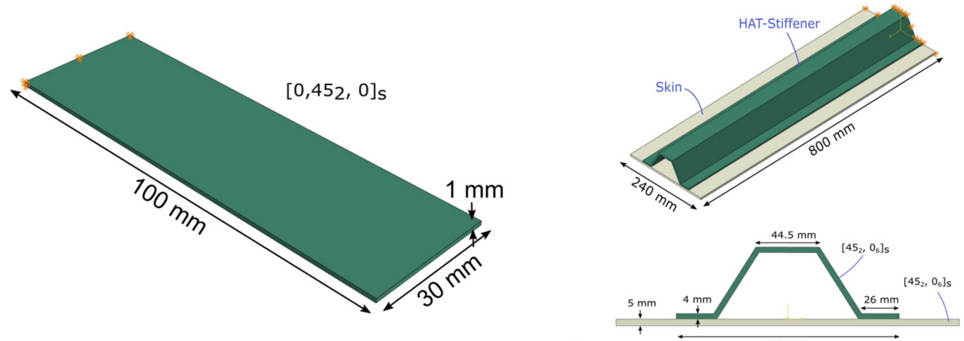


Figure 1. Sustainability as an inherent contradiction of a system, considering five (5) pillars encompassing performance, economic, social, circularity, and ecological aspects (figure created by the authors).

In the current study, *SI* is the holistic sustainability index, with *P*, *C*, *E*, and *CIRC* representing the normalized indices, referring to technological performance, costs, environmental impact, and circularity performance, respectively. Each of these dimensions is expressed using metrics that are pertinent to the investigated use-case applications, which will be further defined in Section 3. The assessment incorporates a multi-criteria decision-making model. Multi-Criteria Decision Making (MCDM) is a decision-making methodology used in complex scenarios where various factors or criteria need consideration. It is employed when there is a need to evaluate multiple options based on different, often conflicting, criteria or objectives. MCDM methods help in systematically assessing and comparing alternatives by considering multiple criteria simultaneously. These criteria could encompass various aspects such as cost, efficiency, environmental impact, social considerations, reliability, and more, depending on the specific context of the decision. The primary goal of MCDM is to provide a structured framework that assists decision-makers in selecting the best possible option or making a well-justified choice among multiple alternatives. In the present study, the model integrates two well-established approaches for addressing evaluation problems, specifically, the Analytic Hierarchy Process (AHP) [20] and the Weighted Sum Model (WSM) [21]. Analytic Hierarchy Process (AHP) is a decision-making methodology used to systematically break down complex problems into smaller, more manageable parts. It allows for the evaluation and comparison of multiple criteria and alternatives in a structured manner, facilitating the selection of the most suitable option by assigning relative weights to criteria and performing pairwise comparisons. The Weighted Sum Model (WSM) is a decision-making technique utilized to evaluate alternatives based on a weighted combination of their respective criteria scores. It involves assigning weights to each criterion, reflecting their relative importance, and assessing alternatives by multiplying their criterion scores by these weights and summing the products. The final value of SI results as a weighted sum of the normalized individual indicators. The min-max normalization method is applied to standardize the values. The weight factors denoted as K_P, K_C, K_E, and K_{CIRC}, are determined through the AHP and represent subjective weightings based on user priorities, signifying the importance of each term in contributing to the overall index value [22].

2.3. Test Cases

Two test cases are introduced to assess the effectiveness of the proposed *SI*. These include an abstracted structural composite plate with a typical layup, as well as a hat stiffener representative for the aviation industry, with both pristine and recycled carbon fiber materials, as shown in Figure 2. The usage of recycled fibers aims to assess both the composite's structural performance as well as its overall impact on its sustainability. Evaluating the holistic sustainability impact involves analyzing, apart from the structural performance, the environmental benefits of using recycled fibers, the economic implications of adopting sustainable practices, and the potential for closed-loop circularity.



(a) (b)

Figure 2. The two test cases: a structural plate component (**a**) and a Hat Stiffener with skin (**b**) designed with pristine and recycled fibers.

2.3.1. Structural Composite Plate

The first test case is an abstracted composite plate with dimensions of 100 mm × 30 mm and a thickness of 1 mm, which consists of eight layers of CFRP $[0,45_2,0]_s$, using a combination of pristine and recycled fibers, shown in Figure 2a. Alternative CFRP layup designs have been explored that incorporate both pristine and recycled fiber plies to achieve sustainable solutions. In order to achieve this, three different types of recycled composite materials are retrieved from the literature and considered here, with chopped and short fibers obtained through different remanufacturing techniques, namely injection and compression molding.

In terms of structural requirements, the main requirement is to maintain structural integrity while effectively utilizing an increased ratio of recycled-to-pristine fibers. The thickness of the plate within the specific range of 0% to 100% thickness increase is varied to identify the optimal configuration to achieve structural integrity while utilizing materials with reduced stiffness and strength characteristics. Additionally, the structural integrity of the plate is evaluated under typical loading conditions to ensure it remains damage-free, as well as aiming to minimize stiffness loss of the considered component. The loading conditions applied include tension, bending, shear, and torsion.

A Finite Element Model is developed with 10,720 SC8R shell elements, with an element size of appr. 1.5 mm, and one element per ply along the thickness. The Boundary & Loading Conditions are fixed-free, with restricted translational, rotational DOFs and a reference point (RP) for load applications, respectively. The applied loading conditions are under tension, bending, shear, and torsion. A static analysis is performed, followed by a frequency analysis of the first five natural frequencies. The layup, dimensions, and material configuration with the static and dynamic results are saved as a design configuration.

2.3.2. Hat Stiffener with Skin

The second test case comes from aviation and is a "hat stiffener" with skin, as it is a key structural component used to reinforce and provide support to aircraft parts like wings and fuselage. It improves structural integrity, which enhances safety and performance and is optimized for a balance between strength and weight efficiency [23]. The skin of the stiffener consists of 20 plies of symmetrically placed pristine carbon fibers [24,25]. The "hat stiffener" contains 16 plies of either pristine or recycled fibers, using the same materials as for the composite plate. In Figure 2b, the parameterized space of the examined components is depicted in green color, while the attached skin is shown in ochre. A Finite Element Model (FEM) is developed (similar to test case 1), where the skin and the hat are discretized with 38,400 and 28,160 SC8R shell elements, respectively. The boundary and loading conditions are similar to those of the composite plate, and a safety factor of 2.0 is considered.

2.4. Materials

Both pristine woven and recycled composite plies have been considered (Table 1). Properties for the pristine woven composite are determined by applying the rule of mixtures for T300 and F-220/193/50 fibers and epoxy, respectively. Young's Moduli of the recycled plies resulting from different remanufacturing methods are referenced in [26], and the shear moduli are estimated to have the same contribution to the overall stiffness for reasons of modeling simplicity and to better focusing on the effect of the fibers' properties to the design process. This decision to assume uniformity across some properties aimed to better facilitate the demonstration of our design approach under these assumptions, acknowledging, however, the complexities that arise due to limited information and, subsequently, the necessity of fully characterizing the mechanical properties of recycled fibers.

Table 1. Four selected materials with their mechanical properties.

Materials—Fiber Volume Fraction		**Type**	**E_{11}**	**E_{33}**	**G_{12}**	**Density (ρ)**	**Layer Thickness**
			GPa	**GPa**	**GPa**	**kg/m^3**	**mm**
M_0	vCF-60%	Pristine	55.0	7.5	4.0	1480	0.125
M_1	RCF-18%	Recycled	16.3	7.5	4.0	1170	0.125
M_2	RCF-30%	Recycled	37.1	7.5	4.0	1380	0.125
M_3	RCF-50%	Recycled	39.8	7.5	4.0	1440	0.125

3. Implementation

3.1. Design Strategy

The design focus is on exploring different layup configurations for a given symmetric layup, encompassing all possible design combinations. The spiral development approach (Figures 3 and 4 [23]) is applied to address the specific requirements of design for sustainability. In Steps 1 and 2, the problem is thoroughly described by representing the structure through abstract functions and establishing the core objectives and requirements. In Step 3, the simulation strategy is selected, here being a finite element analysis, and the model is developed. In Step 4, the parametric space is populated through a design of experiment analysis, which generates various combinations and configurations for static and dynamic analyses. These scenarios are then executed, post-process analyses are conducted to assess their performance and behavior under the same loading conditions, and a dataset of all design configurations is formed. In Step 5, a synthesis of the most suitable solution to solving the main contradiction is performed by ranking the scenarios based on their effectiveness in meeting the structural integrity objective and considering a high recycling rate In Step 6, the sustainability index is assessed by taking environmental impact, cost-effectiveness, and circularity into consideration to ensure the chosen scenario aligns with a sustainable solution. Verification of the most sustainable solution is performed to assess the sensitivity and robustness of the design approach, and it emphasizes flexibility, adaptability, and continuous improvement to achieve optimal results that align with the original requirements.

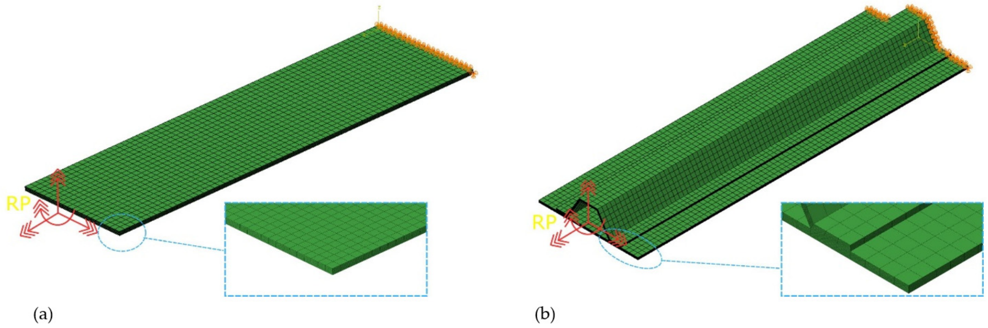
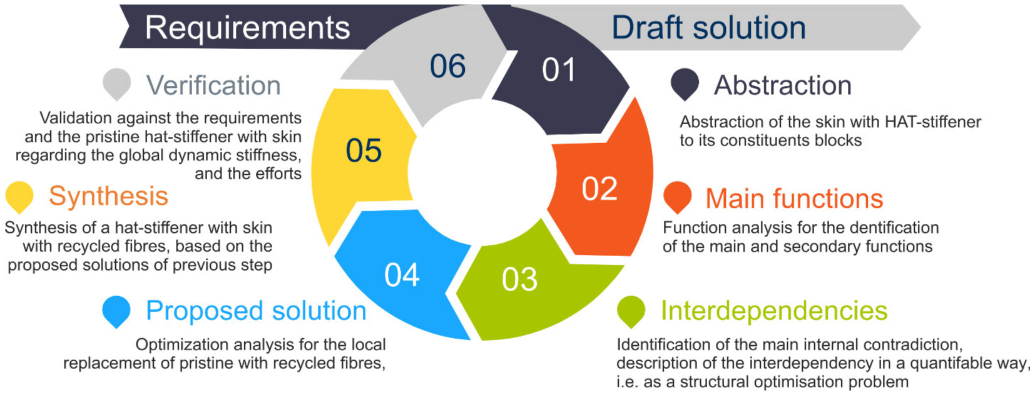


Figure 3. The FE models highlighting the mesh, loads, and boundary conditions of the (**a**) structural plate component and (**b**) of the hat stiffener with skin.



Validation against the requirements and the pristine hat-stiffener with skin regarding the global dynamic stiffness, and the efforts

Abstraction of the skin with HAT-stiffener to its constituents blocks

Synthesis of a hat-stiffener with skin with recycled fibres, based on the proposed solutions of previous step

Function analysis for the dentification of the main and secondary functions

Optimization analysis for the local replacement of pristine with recycled fibres,

Identification of the main internal contradiction, description of the interdependency in a quantifiable way, i.e. as a structural optimisation problem

Figure 4. The adapted spiral development approach in the case of a "hat stiffener" [23].

3.2. Setting the Requirements List

The process of defining structural and sustainability requirements occurs within the component's design phase and the subsequent demonstration phase. Table 2 serves as a comprehensive display of these essential requisites. Structural requirements involve ensuring the absence of damage, allowing specific geometric dimension adjustments within a defined thickness range of up to 12.5%, and minimizing stiffness loss. Meanwhile, sustainability requirements pertain to incorporating three (3) distinct recycled materials, examining the correlation between stiffness loss and recycling efforts, and assessing the relationship between increased mass, material selection, and the sustainability index.

It is clear that the use of virgin fibers outperforms recycled fibers in terms of their properties, yet this contradicts the ecological benefits of using recycled fibers, which have a better environmental performance under the precondition of efficient recycling technologies. In this context, it becomes essential to reconcile these opposing aims: (a) the need to minimize weight, crucial for aerospace applications where the superior quality of virgin fibers is vital, and (b) the desire to maximize the utilization of recycled fibers for the sake of ecological sustainability. However, achieving equilibrium between these two objectives is intricate and demands further exploration and optimization. The materials chosen, as outlined in Table 1, were selected based on existing data available in literature sources. It is important to note that this data acts as a starting point, recognizing that achieving the desired balance will require additional research and optimization endeavors.

Table 2. Structural and sustainability requirements.

<table>
<tr><th></th><th>Current State</th><th>Target State</th></tr>
<tr><td rowspan="2">Structural requirements</td><td>• Reference geometry.
• Reference mass.</td><td>• No damage should occur.
• Geometrical dimensions can be increased in specific thickness ranges up to 12.5%.
• Stiffness loss shall be minimized.</td></tr>
<tr><td colspan="2">• No damage to the component should occur.
• Effort is significantly below damage initiation for typical loading conditions.
• Typical loading conditions (bending, tensile, torsion, and shear).
• Boundary conditions are fixed-free, with restricted translational, rotational DOFs.
• Safety Factor (SF) of 2.0.
• Recycled materials from aeronautical structures.
• The main structural stiffness should remain the same.</td></tr>
<tr><td>Sustainability requirements</td><td>• No sustainability requirements at current state.</td><td>• Three (3) different recycled materials.
• Identify the relationship between stiffness loss and efforts to recycle proportion.
• Identify the relationship between mass increase, material selection, and sustainability index.</td></tr>
</table>

3.3. Create Design Variants Using FEM

For the development of a parametric simulation model, the finite element (FE) software ABAQUS is used, and a parametric Python script is implemented 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 layer. Subsequently, a finite element analysis (FEA) is performed, and a detailed investigation of the static as well as the dynamic behavior of the test cases is conducted.

For this, an in-house algorithmic framework has been developed to thoroughly investigate the parametric space available. In order to achieve this, MATLAB scripts have been utilized, in combination with the commercial FEM software ABAQUS R2023 to parameterize the selected case studies, namely the structural plate and hat stiffener, with a focus on their geometric and material properties. In the current work, a range of thickness variations for each layer have been considered, allowing for an increase of 12.5% up to 100% compared to the original thickness. In terms of materials, a spectrum that spans from pristine carbon fibers (M_0) to three different recycled options has been explored (see Table 1). For both case studies, the modifications are applied to pairs of plies to maintain the symmetric plies arrangement. When implementing thickness increases for the hat stiffener, this adjustment involves translating the plies upwards and vertically in relation to the hat-skin interface. For the composite plate, the plies are translated relative to the middle section of the component.

A Finite Element Model is developed for both test cases using SC8R shell elements, with an element size of appr. 1.5 mm, and one element per ply along the thickness. The boundary and loading conditions are fixed-free, with restricted translational, rotational DOFs and a reference point (RP) for load applications. Initially, a static analysis is conducted, followed by a dynamic analysis of the first five natural frequencies. The layup, dimensions, and material arrangement are stored in a database together with the static and dynamic results to form a design configuration. The design configuration dataset is assessed in terms of structural and sustainability criteria to assess the most suitable design configuration each time.

Test Case 1 (composite plate), with a symmetric ply configuration of eight layers, five materials, and five thickness variations, results in a total of 65,536 unique design variants. However, it is important to note that when the ply's thickness is symmetrically increased by more than 25%, the predefined boundaries for total volume increase are violated. As a result, the available parametric space is constrained, leading to 1630 design variants when a 12.5% volume increase is aimed. In Test Case 2 (hat stiffener), the larger volume and greater number of plies provide greater flexibility, enabling us to explore various available thickness options.

4. Results and Discussion

4.1. Identification of Best Structural-Performing Scenarios

Starting with the structural plate, FEM analysis is performed to assess the structural performance of all possible scenarios listed in the previous subsection. Both stiffness and damage initiation are accounted for to ensure the ability of the component to perform under normal operational conditions. Stiffness loss is expressed as the relative variation of each of the first five eigenfrequencies due to the introduction of the recycled fibers, according to Equation (2):

$$f_i = \frac{\left| ef_{i,\,ref} - ef_{i,\,rec} \right|}{ef_{i,\,ref}} \cdot 100 \tag{2}$$

where f_i is the relative variation in the eigenfrequency of the i_{th} mode, $e_{fi,rec}$ the eigenfrequency of i_{th} mode for structures with pristine and recycled fibers, and $ef_{i,ref}$ the eigenfrequency of i_{th} mode for the reference structure containing only pristine fibers.

Finally, for damage initiation detection, a simplified equivalent effort to each failure mode is applied. According to Equation (3), damage initiation of a ply due to tensile stress σ_{11} occurs when Eff_{11} exceeds unity, where R_{11} denotes the strength in one of the two main in-plane directions of the woven ply [27].

$$Eff_{ij} = \frac{\sigma_{ij}}{R_{ij}} \;\; i, j = \{1,\, 2\} \tag{3}$$

The structural performance error is defined as the Euclidean norm of all constituents to quantify the performance of the analyzed scenarios. Any violation of the allowable stress limits results in a structural performance error exceeding 100, leading to the rejection of the scenario. Figure 5 presents a summary of the performance in increasing order within the examined valid parametric space for plates featuring a combination of pristine and recycled carbon fibers and a total volume increase of 12.5% (Figure 5, left). This analysis encompassed 767 qualified scenarios. All possible designs are on the left of Figure 5, while the right part depicts the five best structural-performing design scenarios, with a structural performance error ranging only between 0.26% to 0.96%.

For a 12.5% increase in total volume, the structurally optimal scenario is characterized by a combination of pristine material (pristine, gray color) and recycled fibers (RCF-50, blue color) at a volume ratio of 22% and 78%, respectively. Conversely, other effective scenarios in Figure 5 (right) include the use of pristine material, along with materials RCF-18, RCF-30 and RCF-50, in a ratio of 25%, 20%, and 55%, respectively. In this case, the ply-thickness increase varies from 25% to 75%.

Figure 5 (right) provides information regarding the five most suitable scenarios given the design requirement. In the upper part of the figure, the first column corresponds to the reference scenario (scenario 0) with gray color (pristine materials). The next five columns correspond to the material distribution in (%) of each scenario corresponding to four selected materials. At the lower part of the figure, the first column corresponds equally to the reference scenario (scenario 0), with each rectangle representing a layer of the layup. In this case, since there exists a symmetric layup with eight layers, only the four are illustrated. The next five columns correspond to the thickness distribution in (mm) of the corresponding layers, and the color corresponds to the selected materials.

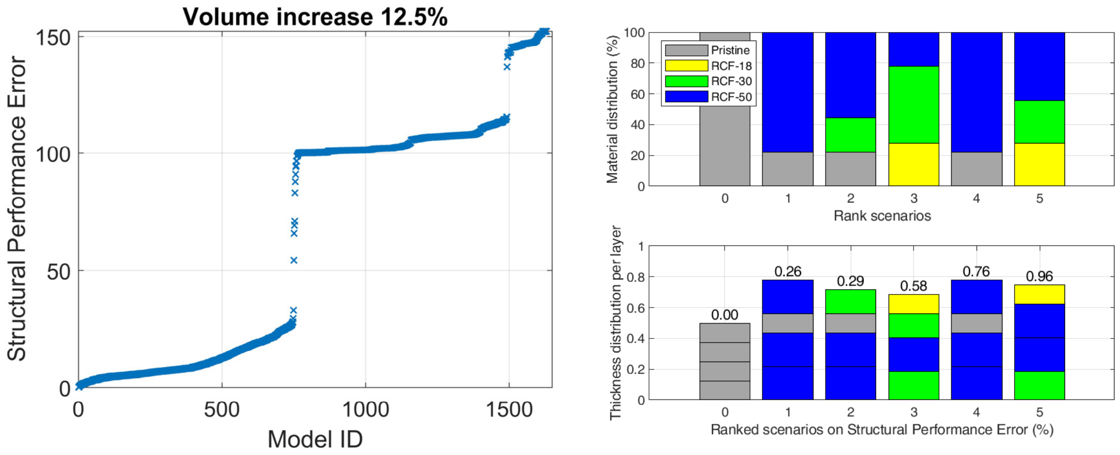


Figure 5. Results for the structural performance of the composite plate for two target goals; the lower the error, the better structural performance of the design scenario; structural five best-performing scenarios for the component plate.

From the analysis focusing solely on structural performance, it is evident that opting for recycled composites is impractical. This reasoning stems from the resultant lower weight and the necessity to augment weight when utilizing recycled composites to attain equivalent properties to virgin composites. This reality persists due to the inherent downgrading of recycled fibers during the recycling process and the absence of effective methods for reprocessing recycled fibers.

4.2. Identification of Most Sustainable Design Configurations

Subsequent to identifying the scenarios with optimal structural performance, the comprehensive sustainability assessment follows. It is emphasized that configurations failing to meet the essential structural requirements are deliberately omitted from subsequent sustainability assessments [9]. This exclusionary measure is rooted in the rationale that evaluating the sustainability of configurations unable to fulfill their intended purpose is unnecessary. Consequently, the focus remains steadfast on configurations that meet the requisite structural criteria for further sustainability assessment.

Hence, for the design configurations that meet the eligibility criteria and have passed the structural requirements established during the design phase, the SI has been calculated based on Equation (1) and is shown in Figure 6 as the Sustainability Performance Error:

$$\text{Sustainability Performance Error} = 1 - \text{SI} \leq 1 \tag{4}$$

Structural performance is expressed through the weighted sum of the five eigenfrequencies related to each design configuration, while the environmental impact of material production and manufacturing, material costs, and production costs are also considered, with relevant data and citations provided in Appendix A. Circularity performance is expressed as the proportion of recycled materials in each design configuration. The influence of the utilization phase is omitted when computing the sustainability index since it can fluctuate depending on the final application. Regarding variations in weightings, five different scenarios were assessed, where the priorities have been set using the Saaty scale, while the aggregation of the SI has been performed using the WSM method, as described in Section 2.2. Five different policy scenarios, as shown in Table 3, have been considered, and the results are shown in Figure 6:

1. In the first scenario, the importance of all sustainability pillars is equal (25%).
2. In the second scenario, environmental impact and technological performance factors (32%) are considered more important than circularity performance (24%) and much more important than costs (12%).

3. In the third scenario, costs are deemed much more important (70%) than any other pillar, while all other criteria are equal (10%).
4. In the fourth scenario, circularity performance (67%) is considered much more important than any other criterion, with all other criteria held equal (11%).
5. In the fifth scenario, technological performance is considered more important (37%) than circularity performance and environmental impact (23%), with the latter two being considered more important than costs (17%).

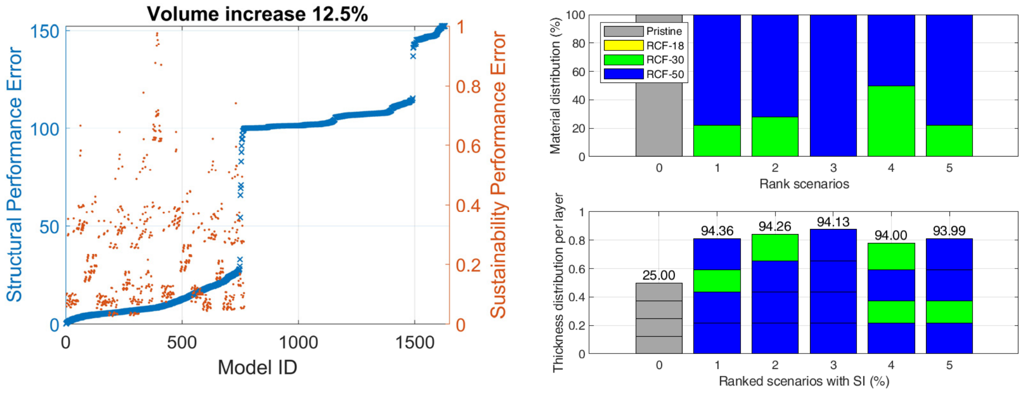


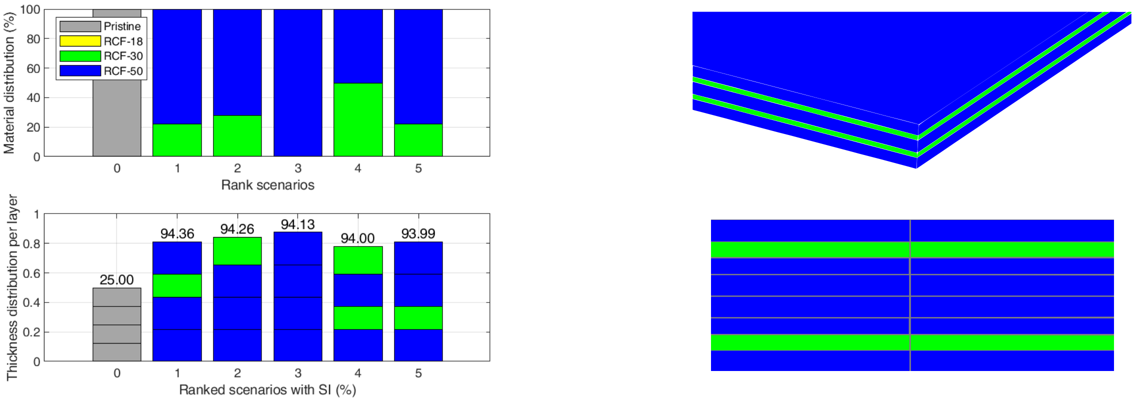
Figure 6. Results for the sustainability of the composite plate (**left**); the five best-performing scenarios for the composite plate- equal approach scenarios (**right**).

Table 3. Five different scenarios are influenced by different weighting of technological performance P, costs C, environmental impact E, and circularity performance CIRC.

Sustainability Scenarios	Normalized Indices of the Holistic Sustainability Index SI			
	Technological Performance P	Costs C	Environmental Impact E	Circularity Performance CIRC
1st Equal Weighting	25%	25%	25%	25%
2nd Environment & Circularity	32%	12%	32%	24%
3rd Costs Approach	10%	70%	10%	10%
4th Circularity Performance	11%	11%	11%	67%
5th Environmental Impact	37%	17%	23%	23%

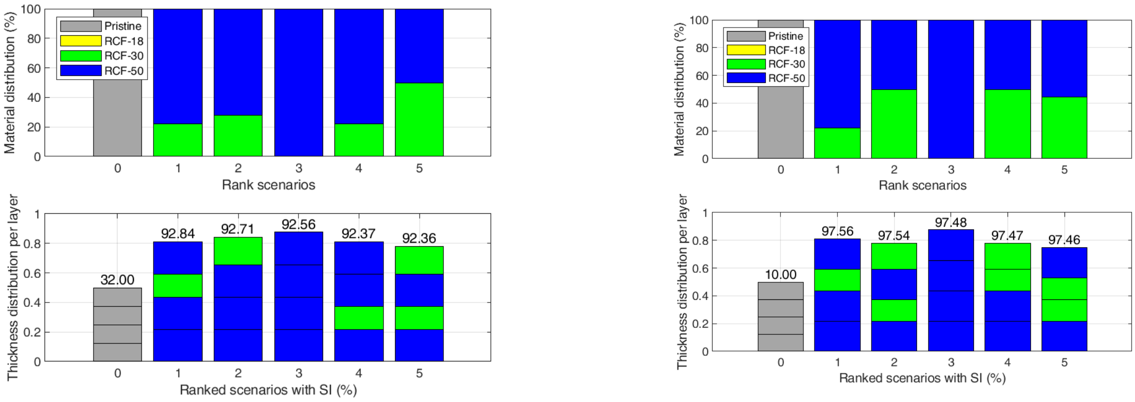
The determination of which dimension holds more importance than the others is based on the authors' personal considerations; however, this can also be retrieved from a stakeholders' analysis in typical product development and design applications. The quantified percentage weights (Table 3) for each sustainability dimension are derived using AHP, as described in Section 2.2.

In Figure 7, the five best-performing design configurations in terms of the obtained SI are depicted for each of the five scenarios described in Table 3. The design configuration featuring the composite made of pristine materials is also illustrated as a reference. For example, regarding the equal weighting scenario, Figure 7(a1) (upper chart) illustrates the material percentage of the design configurations related to the highest SI attained. For the best-performing scenario, this signifies that 20% of the material volume comprises recycled carbon fiber with a volume fraction of 30%, while the remaining 80% of the total volume consists of recycled carbon fiber composite with a 50% volume fraction. Additionally, in the bottom chart of Figure 7(a1), the material attributed to each layer is displayed in terms of the thickness of each layer. It should be noted that, due to the composite's symmetry, only the first four layers are plotted.



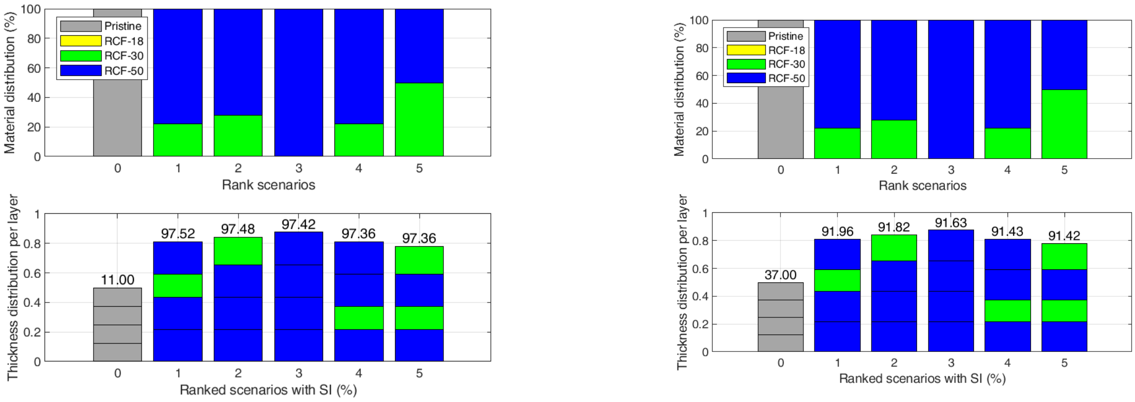
(**a1**) Equal importance

(**a2**) Layup of the best-ranked scenario of "Equal importance"



(**b**) Environment and Circularity

(**c**) Costs approach



(**d**) Circularity Performance

(**e**) Environmental Impact

Figure 7. (**top-left**) SI of the five best-performing scenarios for the composite plate-equal weighting scenarios; (**top-right**) illustration of the first scenario's best-performing design configuration; (**middle-left**) SIs for Environmental and Circularity approach; (**middle-right**) SI for Costs approach; (**bottom-left**) SI for Circularity Performance approach; (**bottom-right**) SI for Environmental impact approach.

Furthermore, at each subplot of Figure 7, the SI is provided at the top of each scenario for both the reference scenario (gray color) as well as the five best-ranked scenarios according to each policy. As an example, in Figure 7(a1), for the equal importance policy scenario, the SI of the reference design scenario is calculated at 25.00%. Compared to this value, the SI of the five best-ranked scenarios ranges between 93.99% and 94.36%, an increase of

276%, which is a significant increase worthy of further study on this approach in terms of quantifying sustainability.

According to Figure 7(a1), for the best-performing scenario, all layers are increased in thickness, particularly those containing the recycled composite of fibers with a volume fraction of 50%. In Figure 7(a2), the design of the composite is depicted, showcasing the composition of each layer. Figure 7b–e corresponds to the second, third, fourth, and fifth scenarios, respectively. It is worth noting that the most effective designs across all scenarios predominantly consist of recycled fibers with a volume fraction of 50%. However, the absence of RCF-18 material, despite their high energy and cost-efficient manufacturing, can be attributed to the inferior properties of this material.

It is important to note that across all five scenarios, the most effective configurations regarding their SI solely consist of recycled composites. This emphasizes the impact on environmental factors, costs, and the potential for circularity in determining the overall sustainability of the components. Moreover, although the best-performing scenarios exhibit layers with significantly increased thickness (almost double) compared to the design composed solely of pristine fibers, this augmentation is not adequate to offset the gains in environmental impact, costs, and circularity performance.

In conducting a comprehensive sustainability assessment, the viability of recycled composites becomes apparent when all parameters are considered. The findings underscore that considering a holistic view of sustainability, utilizing recycled composites—particularly those with a high-volume ratio—can substantially enhance the sustainability profile of the component. As illustrated in the results, this strategic use of recycled composites not only improves sustainability but also renders them a viable choice for practical applications.

4.3. Validation of the Design Method on the "Hat Stiffener" Case

The validation of the design method on the "hat stiffener" case is performed on equal weighting scenarios and are presented at Figure 8.

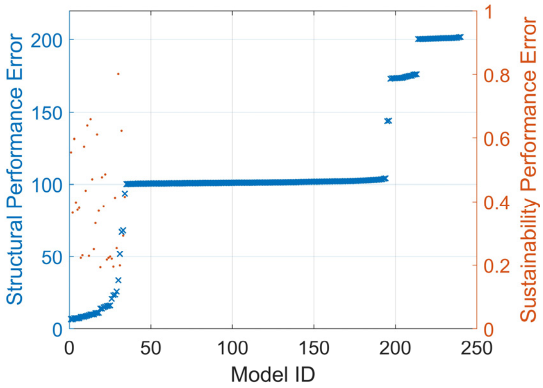
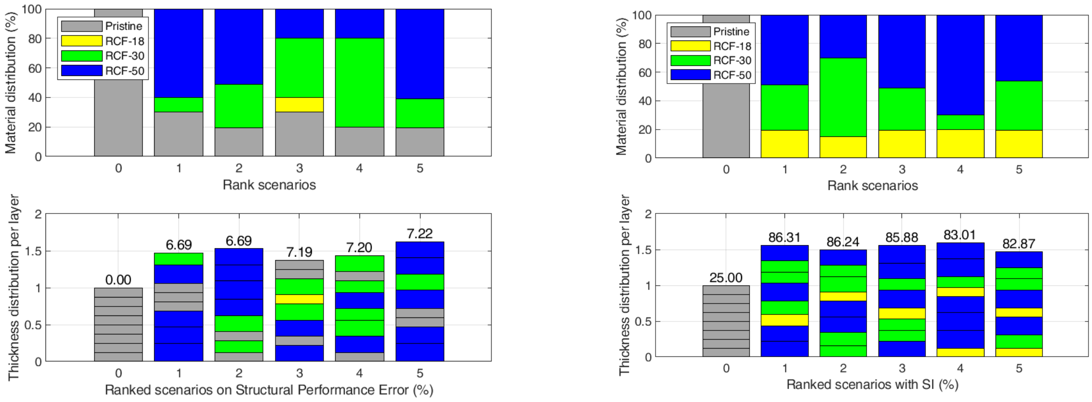
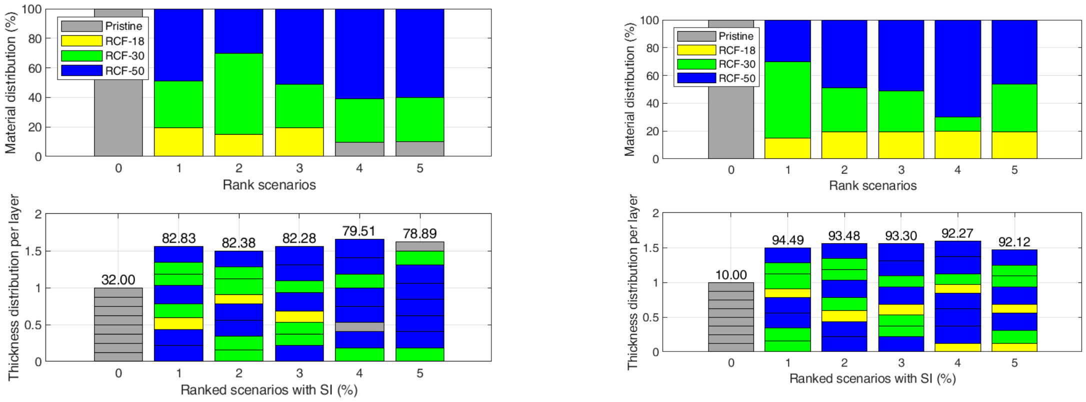


Figure 8. Results for the sustainability of the hat stiffener.

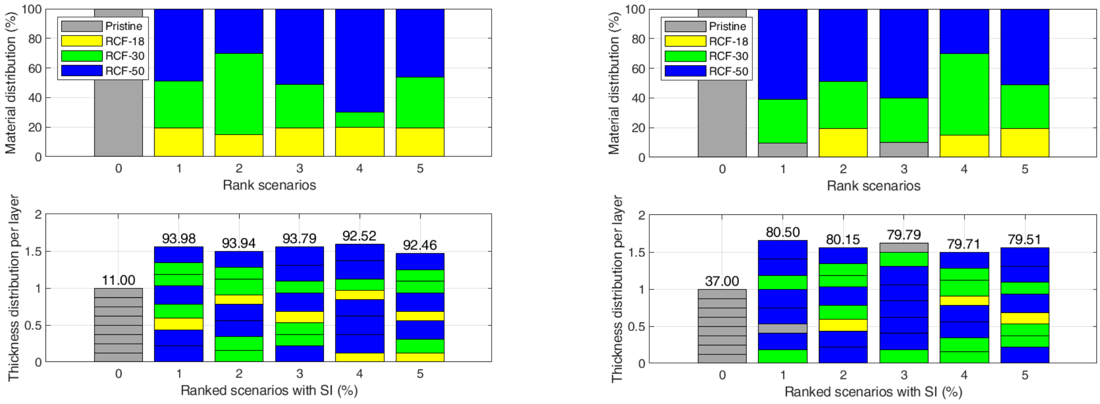
In Figure 9, it is evident that the five most sustainable designs for the hat stiffener exclude the pristine materials and use a combination of the three recycled materials to recompensate the stiffness loss with an increase in the thickness, which is, however, similar to the thickness increase of the five best designs with high structural performance. It is notable that the best design for equal importance (a2), with 86.31%, is also scoring 1st at (b, Environment and Circularity and d, Circularity Performance) with 82.83% and 93.98%, while being just 2nd at (c, Costs approach and e, Environmental Impact) with 93.48% and 80.15%, meaning that this design configuration is suitable for different design policies. The best design for (c, Costs approach) is ranked 2nd at (a, b and d) and 4th at (e). The best design for (e) Environmental Impact is only ranked 4th at (b, Environment and Circularity) and is not among the five best at the other policies. In general, it is worth mentioning that the SI differences between the five best at each policy are quite small, meaning that based on other criteria, e.g., manufacturing capabilities, any of the five designs could be accepted from an engineering point of view. A sensitivity analysis is performed to assess possible variations to the results and the robustness of our method.



(**a1**) 5 best structural-performing scenarios (**a2**) Equal importance



(**b**) Environment and Circularity (**c**) Costs approach



(**d**) Circularity Performance (**e**) Environmental Impact

Figure 9. Results of five best-performing scenarios for the **hat stiffener**, regarding (**top-left**) the **structural performance**, (**top-right**) SI of the five best-performing scenarios for the composite plate with **equal weighting** scenarios, (**middle-left**) SIs for Environmental and Circularity approach, (**middle-right**) SI for Costs approach, (**bottom-left**) SI for Circularity Performance approach, (**bottom-right)** SI for Environmental impact approach.

In all investigated policy and design scenarios shown in Figures 7 and 9, where the quantified SI is provided at the top of each scenario, a significant increase between the reference scenario (gray color) and the five best-ranked scenarios according to each policy is observed. In fact, the relative increase of the sustainability index ranges approximately from 115% (for the policy scenario of the environmental impact of the hat stiffener) up to 870% (for the policy costs approach of the plate), a significant increase, worthwhile of further studying this approach in terms of quantifying sustainability and the actual meaning of this increase in terms of decision making during the design phase.

5. Sensitivity Analysis and Robustness of the Methodology

It is noticeable that the solutions demonstrating the highest performance might not always align with the most sustainable ones. Nonetheless, sustainable solutions can still emerge from the initial 10 solutions. However, an important consideration emerges regarding the robustness of these findings, especially when examining slight alterations to the original data, given that numerous design variants showcase minimal variation.

In order to assess the sensitivity of the proposed tool to small changes in the values of the initial data, the scenario of equal weights among all the criteria in the holistic sustainability index is adopted, and 1000 pretreated samples of the initial data were simulated in each of the following cases. It is assumed that the errors that perturb the initial data follow a normal distribution with zero mean and standard deviation equal to 0.05%, 1.0%, 5.0%, and 10.0% of the standard deviation of the corresponding variables of the original data:

- 0.1% (lower extreme typical from measurement noise in experimental conditions)
- 1.0% (typical from measurement noise)
- 5.0% (typical of deviations from material properties)
- 10.0% (typical from manufacturing deviations of the parts, extreme case)

The simulated samples were normalized using the min-max method, ranked with respect to the overall sustainability index, and the mean, standard deviation, min, and max rank of each plate were calculated for each selected value of the standard deviation.

The mean, the standard deviation, the min, and the max rank of the ten most sustainable composite plates are depicted in Table 4 for each selected value of the standard deviation of the error validation of the design method. The proposed method is fairly stable in terms of the mean rank for a relatively large value of the standard deviation of the errors (Figure 10).

The intervals mean ± one standard deviation of the rankings are depicted in Figure 9 for the different levels of noise variation. For the cases of 0.05% and 1.0%, the mean ranks are almost identical to the initial ranking, but this is not the case for the error's standard deviation equal to 5.0% and 10.0% of the standard deviation of the corresponding variables of the original data. As expected, the larger the standard deviation of the errors, the larger the variability of each plate ranking. Despite the increase of the variation of the rankings the mean rankings seem not to change significantly from the initial ranking.

Table 4. Main descriptive statistics for the simulated samples.

		Mean Rank							
		0.1%		**1.0%**		**5.0%**		**10%**	
Id	**Initial Rank**	**Mean (Sd)**	**(min–max)**	**Mean (Sd)**	**(min–max)**	**Mean (Sd)**	**(min–max)**	**Mean (Sd)**	**(min–max)**
1	1	1.00 (0.0)	(1–1)	1.03 (0.17)	(1–2)	2.01 (1.58)	(1–15)	4.86 (4.44)	(1–27)
2	2	2.00 (0.0)	(2–2)	1.98 (0.18)	(1–3)	3.09 (2.25)	(1–19)	5.94 (5.15)	(1–30)
3	3	3.00 (0.0)	(3–3)	3.00 (0.12)	(2–4)	4.14 (2.98)	(1–19)	5.91 (5.27)	(1–29)
4	4	4.80 (1.00)	(4–8)	5.28 (1.13)	(3–10)	8.09 (4.24)	(1–24)	11.57 (6.92)	(1–37)
5	5	5.00 (1.05)	(4–8)	5.39 (1.38)	(3–10)	7.35 (4.23)	(1–22)	9.74 (6.64)	(1–31)
6	6	6.46 (1.18)	(4–9)	6.24 (1.48)	(4–10)	6.95 (4.17)	(1–27)	8.68 (6.42)	(1–39)
7	7	6.78 (1.10)	(4–9)	6.73 (1.41)	(4–11)	9.48 (4.59)	(1–26)	12.25 (7.12)	(1–39)
8	8	6.97 (1.09)	(4–9)	6.77 (1.41)	(4–10)	9.26 (4.52)	(1–26)	11.56 (7.06)	(1–45)
9	9	9.03 (0.22)	(8–10)	8.91 (0.99)	(4–13)	10.29 (4.71)	(1–25)	12.25 (7.12)	(1–39)
10	10	10.04 (0.35)	(9–11)	10.03 (0.89)	(6–15)	9.89 (5.01)	(1–28)	9.74 (6.64)	(1–31)

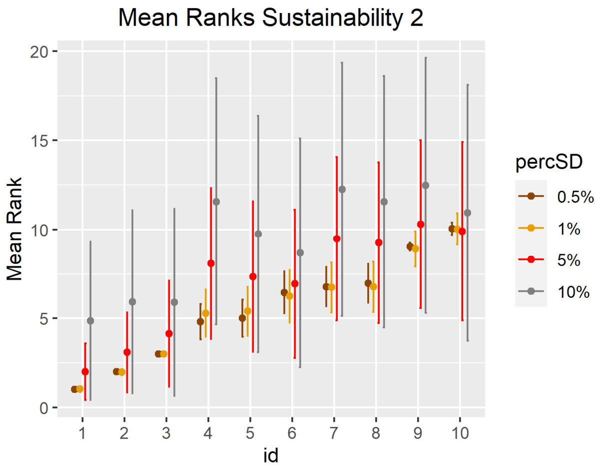


Figure 10. Mean Ranks ± one standard deviation of the rankings for the different levels of noise variation (percSD) out of the ten most sustainable plates.

6. Conclusions and Outlook

The aim of this work is to propose a novel approach driven by sustainability considerations, where sustainability is defined as a balance among performance, environmental, social, and economic goals. By assigning numerical values to different dimensions and assessing their connections, it provides an objective evaluation of design options. This approach enables designers and stakeholders to make informed decisions based on a comprehensive understanding of sustainability factors. It serves as a valuable tool for assessing the environmental, social, and economic impacts of design choices, aiding in the selection of options that align with sustainability goals.

The present findings highlight the feasibility of assessing diverse design variations through a holistic sustainability approach on two typical geometries for aircraft composite components. This indicates the potential for a design that does not singularly excel in structural robustness, cost-efficiency, social acceptance, or environmental sustainability. Instead, it aims to interconnect these aspects to fulfill the criteria of each sustainability pillar and achieve an optimal equilibrium among these dimensions. While structural performance is a crucial consideration, the sustainability index encourages a broader perspective that encompasses a range of factors. This recognition highlights the complexity of sustainability, as it requires balancing multiple objectives and considering long-term impacts, where political decisions play a crucial role.

This can be better understood when the current understanding of sustainability in aviation is considered. The aviation approach with regards to sustainability and the ongoing understanding of sustainability in aviation, as they are briefly mentioned as a triple helix of environmental, social, and economic aspects, currently deviate from each other. This is also due to historic developments in the aviation sector, as depicted, for example, in Europe by the Clean Sky I & II research funding programs, where one of the main focuses was on the environmental impact. Accordingly, and as a continuation of this momentum, the aviation concept of sustainability is limited to a part of environmental sustainability, leaving out other equally impactful aspects of aviation, such as the impact on society and on the planet.

The main results from the current work investigations can be summarized in the following theses as take-home messages:

- More effort is required to develop a clear “engineering” definition and ways to measure what we call sustainability. As measuring sustainability is not as straightforward as measuring fuel consumption or structural loads, many methods and tools are being developed, but all have significant assumptions and limitations, pinpointing the need to develop a standardized approach.
- Many experts utilize life cycle assessment (LCA) as a method to measure sustainability. But LCA covers material and energy flows, some economic aspects (LCC), which are

far from providing a complete picture of sustainability. Our method tries to include aspects of LCA as a part of a more comprehensive tool, considering also the other aforementioned aspects of sustainability.

- Under given loading conditions and for component-specific cases, it is possible to attain a higher ratio of recycled-to-pristine fibers while minimizing stiffness loss by implementing localized adaptations to the fiber reinforcement and thickness.
- The different importance of the five sustainability pillars results in various suitable design configurations, indicating that the sustainability index is rather a technopolitical index, rather than a pure technological index for engineering.
- The integration of sustainability into the design phase encourages a shift toward a circular economy model, providing an alternative design paradigm. The circular economy aspect of the sustainability index emphasizes the importance of designing products and systems that enable resource efficiency, waste reduction, and the promotion of a closed-loop system.

A limitation regarding the credibility of the assessment lies in the insufficiency of data pertaining to environmental impact, costs, and mechanical efficiency, particularly concerning recycled materials and their methods of remanufacturing. Lastly, a limitation involves the difficulty of making comparisons with similar design methodologies. Currently, there are no design methodologies specifically tailored for aviation with a focus on sustainability, to the best of the authors' knowledge. Eco-design serves as a state-of-the-art model, and a transition from eco-design to a more comprehensive sustainability-driven design approach is suggested by the authors. Valuable insights could be gained by performing a comparative analysis between the authors' proposed methodology and the established eco-design for specific components. However, obtaining the necessary information for such a comparison proves challenging due to the absence of openly available literature.

Future research in the context of the present study should prioritize the refinement and expansion of the quantified sustainability index to improve its accuracy and robustness. Continual enhancements to the sustainability index will enable a more precise and comprehensive evaluation of sustainability features. Furthermore, the development of design algorithms that incorporate this index will provide designers with valuable digital tools to optimize their designs for sustainability. By considering the sustainability index during the design process, designers can make informed decisions that lead to optimal sustainable outcomes. Moreover, it is crucial to incorporate social factors into the design process to ensure equity and inclusiveness. By considering the diverse perspectives and needs of stakeholders, the design process can account for social needs and, as such, design to benefit a wider range of individuals and communities, thus counter-balancing modern decision-making under the cost-benefit approach. In addition, future endeavors could encompass the expansion to incorporate a wider array of case studies, thereby highlighting how the proposed approach can be applied in diverse contexts across the aerospace industry.

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Appendix A

Table A1. Properties for the estimation of the non-mechanical pillars of the Sustainability Index, with values retrieved from the literature [26,28–34].

	Raw Material GWP (Fiber & Resin) (kg CO_2eq/kg)	CFRP Manufacturing GWP (kg CO_2eq/kg)	Raw Material Costs—Energy Wise (Fiber & Resin) (MJ per kg) (EUR/kg)	Manufacturing Costs—Energy Wise (MJ/kg)
Pristine CFRP (autoclave)	Fiber: 30.1 Epoxy: 6.7	109	Fiber: 461 (31) Epoxy: 139 (9)	21.9 (1.5)
Recycled CFRP 1 (injection molding)	Fiber recycling: 1.54 PP resin: 1.85	1.33	Fiber recycling: 9.98 (0.67) PP resin: 77.19 (5)	19 (1.3)
Recycled CFRP 2 (compression molding)	Fiber recycling: 1.54 Epoxy: 6.7	1.59	Fiber recycling: 9.98 (0.67) Epoxy: 6.7 (0.45)	14.4 (1)
Recycled CFRP 3 (compression molding)	Fiber recycling: 1.54 Epoxy: 6.7	1.59	Fiber recycling: 9.98 (0.67) Epoxy: 6.7 (0.45)	14.4 (1)

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