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Sensitivity Analysis of a Hybrid MCDM Model for Sustainability Assessment—An Example from the Aviation Industry

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Abstract: When it comes to achieving sustainability and circular economy objectives, multi-criteria decision-making (MCDM) tools can be of aid in supporting decision-makers to reach a satisfying solution, especially when conflicting criteria are present. In a previous work of the authors, a hybrid MCDM tool was introduced to support the selection of sustainable materials in aviation. The reliability of an MCDM tool depends decisively on its robustness. Hence, in the present work, the robustness of the aforementioned tool has been assessed by conducting an extensive sensitivity analysis. To this end, the extent to which the results are affected by the normalization method involved in the proposed MCDM tool is examined. In addition, the sensitivity of the final output to the weights' variation as well as to the data values variation has been investigated towards monitoring the stability of the tool in terms of the final ranking obtained. In order to carry out the analysis, a case study from the aviation industry has been considered. In the current study, carbon fiber reinforced plastics (CFRP) components, both virgin and recycled, are assessed and compared with regard to their sustainability by accounting for metrics linked to their whole lifecycle. The latter assessment also accounts for the impact of the fuel type utilized during the use phase of the components. The results show that the proposed tool provides an effective and robust method for the evaluation of the sustainability of aircraft components. Moreover, the present work can provide answers to questions raised concerning the adequacy of the CFRP recycled parts performance and their expected contribution towards sustainability and circular economy goals in aviation.

Keywords: holistic MCDM tool; circular aviation; sustainability; CFRP recycling; aviation; sensitivity analysis; AHP; WSM; data normalization

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1. Introduction

The aviation industry faces great sustainability challenges associated with global warming and climate change [1,2]. It has been estimated that approximately 920 million tons of CO_2 emissions were produced by the aviation industry worldwide in 2019 only [3]; a doubling or even tripling of said emissions is forecasted to occur by 2050 unless radical changes have been implemented [4]. Therefore, the development of sustainable approaches and solutions with regard to future aviation technologies and applications is of utmost importance. To this end, the utilization of low-density polymeric composites for weight reduction represents a major goal for the aviation sector, given that weight considerations are very critical compared to other transportation sectors [5,6]. In this context, carbon fiber reinforced plastics (CFRPs) have been extensively used for lightweight aircraft applications towards achieving better fuel efficiency and, consequently, lowering the associated environmental burden of the aviation sector. Despite the excellent specific properties of CFRPs, issues such as the great environmental and economic impact of their production, as well as difficulties linked to their recyclability, remain open challenges that need to be addressed [5,7]. It is worth noting that currently, approximately 98% of CFRP waste is landfilled [8]. Until today, recycled composites are not being used for mass production in aviation; only demonstrators or prototypes have been developed, targeting secondary aviation applications (e.g., seat armrests, side-wall interior panels) [9,10].

When considering the use of recycled material in aviation, the concern of circular economy (CE) principles is of great importance as it represents an integral part of sustainability. Therefore, apart from the assessment of the environmental impact as well as the economic viability of the recycled components, the dimension of circularity also needs to be examined. In addition, when focusing on high-performance applications, the technological quality features of the recycled component need to be evaluated as the components under consideration must meet specific mechanical performance limits and manufacturing requirements [11]. To this end, new tools are required to support decision-making towards CE practices and sustainability goals; in this frame, multi-criteria decision-making (MCDM) tools can be of aid in supporting decision-makers reach a satisfying solution, especially when conflicting criteria are present. MCDM belongs to a variety of techniques able to determine a preference ordering among alternative solutions whose performance is scored against a series of criteria. MCDM has been used in many fields, including the aviation sector, although the vast majority is focused on the airlines and aircraft level as it occurs from an extensive recent review paper involving MCDM-related studies in the aviation field; among the MCDM methods applied in the aviation sector, AHP, SAW, TOPSIS, ELECTRE, VIKOR, as well as hybrid methods integrating combinations of them, appear to be the most widely used ones, with AHP and TOPSIS being the first choice for decision-making [12]. However, regardless of the choice of the MCDM, it occurs that the sensitivity and robustness of the proposed tools are not systemically examined. Moreover, in cases where a robustness assessment has been conducted, it consists of a sensitivity analysis of the weights' variation, while the sensitivity of the MCDM tool to the data variation appears to be generally neglected. The latter becomes clear from the representative cited works of Table 1, incorporating MCDM methodologies within the aviation sector.

Table 1. Representative works from the aviation sector implementing MCDM methodologies.

Work	MCDM Used	Sensitivity Analysis
Hsu and Liou (2013) [13]	SWM, DEMATEL, ANP	-
Sánchez-Lozano et al. (2015) [14]	AHP and TOPSIS	-
Garg (2016) [15]	AHP, TOPSIS	Weights variation
Bae et al. (2017) [16]	AHP and TOPSIS	-
Görener et al. (2017) [17]	AHP, TOPSIS	-
Barak and Dahooei (2018) [18]	SWM, TOPSIS, VIKOR	-
Sun et al. (2018) [19]	TOPSIS, VIKOR	-
Mahtani, 2018 [20]	AHP	Weights variation

Conducting a sensitivity analysis of MCDM is particularly important in the aviation sector, given the complex and safety-critical nature of decision-making in this industry. Therefore, a data sensitivity analysis is crucial for the reliability of the tool as it helps to identify and manage uncertainty in data inputs (such as measurement error, sampling error, or missing data), leading to more accurate and reliable predictions and better-informed decisions. In this context, the implementation of a reliable and robust MCDM tool can be useful for selecting the most appropriate material, design component, and manufacturing process in the conceptual design and design phase of a product. For a given engineering application, the attention focus lies on the proper selection of criteria and metrics rather than on the selection of the most appropriate MCDM methodology [21].

In the present study, a hybrid MCDM tool, introduced by the authors in [22], to support the policy decision of selecting a sustainable material for aircraft components has been applied, and its robustness has been examined towards ensuring its reliability as a decision support tool. The research questions that will be addressed in the present work include: (1) What is the level of sustainability of virgin and recycled CFRP components, and how do they compare to each other? (2) How reliable is the assessment of sustainability through MCDM? Based on the above research questions, the work aims to support policy decisions by providing decision-makers with a reliable and robust tool that can aid in the selection of sustainable materials in the aviation industry. The studied tool combines the analytic hierarchy process (AHP) and a weighted sum model (WSM) to obtain the final output. In this context, the influence of the data normalization method, as well as the sensitivity to the weights and data variation, is evaluated. For this purpose, a case study has been considered, aiming to assess the sustainability potential of CFRP recycled composites in aviation with regard to the type of fuel utilized within aircraft operation. In this frame, kerosene, as well as liquid hydrogen from conventional and renewable sources, have been considered. The proposed MCDM tool integrates environmental, economic, and circular economy criteria, as being the most relevant aspects representing sustainability, according to the authors. The output of the model is a weighted sum that can be understood as a metric of sustainability. The results demonstrate that the proposed tool provides an effective and robust method for the evaluation of the sustainability of aircraft components.

2. Methodology

2.1. Basic Considerations

As mentioned above, a case study from the aviation industry involving recycled CFRP components has been considered to assess the robustness of the proposed tool. For the sake of the present study, the geometrical features of the considered components, with the exception of weight, are assumed to be identical. The recycled components comprising of either randomly or aligned fibers are compared against a virgin woven CFRP. To enable comparison and be in compliance with the design requirements, the stiffness of the virgin and recycled components must be identical. To this end, to compensate for the variation of stiffness among the considered components, thickness (and consequently mass) has been treated as a variable that has to be adjusted to achieve equal stiffness. Equal stiffness has been considered an appropriate criterion for the comparison of different materials/components [15]. The expected mass ratio (R_m) between the virgin and the recycled components is calculated based on the following approximate formula [23–25]:

$$R_m = \frac{m_{recycled}}{m_{virgin}} = \frac{p_{recycled}}{p_{virgin}} \left(\frac{E_{virgin}}{E_{recycled}} \right) \tag{1}$$

where m (kg) and p (kg/m^3) represent the mass and the density of the components under comparison, respectively, while E (N/m^2) is the elastic modulus of the components.

2.2. Sustainability-Related Metrics

In the present study, sustainability is understood as a matter of trade-offs among environmental, economic, and circular economy aspects. Therefore, to implement the proposed approach, both the environmental impact and costs of the whole lifecycle of the investigated components need to be assessed and integrated into the MCDM-based tool introduced in Section 2.3. Hence, lifecycle metrics linked to the environment and costs are accounted for; to this end, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) data were gathered from the relevant literature to calculate the said impact of the components. The tool also integrates a circular economy indicator which has been linked to the technological performance of the investigated components. For the sake of the current study, this is expressed through a specific property of the components, namely, specific stiffness.

Environmental impact has been linked to the emitted greenhouse gases (GHG) associated with the whole lifecycle of the components, namely raw material production, manufacturing, use phase, and recycling. GHG emissions represent the most widely reported environmental impact metric across industry and academia [11]. The economic impact of the components has been related to the costs associated with the energy requirements for the production, manufacturing, and recycling of the components or the fuel price when assessing the use phase impact of the components. The relevant environmental and economic impact results associated with production, manufacturing, and recycling are given in $kgCO_2eq$ per specific component mass or in euros per component mass, respectively. LCA starts with the production of the primary material, i.e., carbon fibers (PAN) and epoxy resin [11,26–29]. The autoclave molding process has been chosen as the relevant manufacturing process of the virgin CFRP aviation component. For the manufacturing of recycled components, the compression molding process has been considered [30]. The environmental impact and costs of upgrade technologies of recycled carbon fibers (e.g., sizing, alignment) were not accounted for due to a lack of relevant literature data. The chosen recycling process of the CFRPs has been the fluidized bed process (FBP), as being a promising method for recovering fibers of mechanical properties comparable to these of the virgin ones [6,26]. Compared to other promising recycling methods, which are currently at a low technology readiness level (TRL) (e.g., solvolysis [31]), the FBP method is at a TRL of 6 and is found at the pilot phase. In order to calculate the process-related energy costs, the non-household price of kWh in Germany has been accounted for [32].

For the assessment of the impact of the components' mass variation on emissions and costs linked to the use phase, the type of fuel is accounted for, where fuel consumption is assumed to be proportional to the component mass [11,33]. Hence, the components have been considered a load that must be carried by aircraft during flight. In this context, the environmental and economic impact results are given in a service function unit, namely, per component mass per km, which represents a wider approach for all aircraft types and classes and types regardless of the split between passengers and cargo payloads [34]. Four types of fuels were considered, i.e., kerosene, conventionally produced liquid hydrogen, liquid hydrogen from a wind source, and liquid hydrogen from a geothermal source, where the respective environmental and cost metrics relating to these fuels have been taken from [34]. The assessment of the overall impact of the use phase was conducted considering that the average lifetime distance of Airbus A320 was approximated based on the number of flying hours for which it was designed, i.e., 60,000 flying hours over a lifespan of 25 years, and the average cruising speed, i.e., 840 km/h [35,36].

For achieving the transition towards a CE, indicators and metrics for measuring CE progress are required. Up to now, various interpretations have been proposed, e.g., [37,38]. However, said interpretations lead to a variety of metrics and indicators in both content and form [39], while many of them focus on materials preservation [40,41]. In the aviation sector, the prevailing interpretation of circularity refers to the percentage of the aircraft mass which can be recycled or reused at the End-of-Life (EoL) of the aircraft [42]. However, in the above interpretation, the performance features of the recycled products are undermined, which in our view, represent an essential parameter when using a recycled product for an aviation application. Hence, considering that the quality of the recycled material represents a decisive factor towards CE goals as quality is linked to the durability of a material, a CE metric is introduced in the present study, which is linked to a quality feature of the component under study, i.e., a mechanical property. In the context of this study, the latter is expressed through the specific stiffness of the investigated components. For the focus on an aviation application, the choice of the specific stiffness is well justified as, in most applications, the allowable design of an aircraft structure does not exceed the linear elastic region of the stress-strain curve; in the case of CFRPs, this region remains almost linear up to failure. Considering the absence of standardized circular economy indicators in the aviation sector, future studies could focus on developing more specific circular economy indicators. However, this task is beyond the scope of the present work.

2.3. Structure of the Hybrid MCDM Tool and Sensitivity Analysis

The MCDM-based tool implemented herein has been introduced by the authors in [22] as a material selection tool for the aviation sector. The said tool combines the AHP and a WSM, whose output is a weighted sum of the normalized individual indicators. The advantage of integrating the WSM into the proposed hybrid tool is that it offers a proportional linear transformation of the raw data; namely, it maintains the relative order of magnitude of the standardized scores. The latter allows for a more effective and comprehensible interpretation of the final ranking obtained, as well as for distinguishing the impact of each term on the final output. The tool integrates environmental and economic metrics related to the component under study, as well as a suitable CE indicator, as introduced in Section 2.2. Based on the definitions of Section 2.2, the WSM equation, as it has been introduced in the previous work of the authors [22], is given as:

$$S_i = K_{CEI} \cdot CEI_{Q_i} + K_C \cdot C_i + K_E \cdot E_i \quad (2)$$

where S_i is the final output value of the i component and can be considered a metric of overall sustainability and emerges as a matter of trade-off between environmental impact, costs, and circularity performance. E_i and C_i are the inversed normalized environmental and cost indicators of the i component, respectively. The inversed values have been considered due to the fact that environmental impact and costs have a negative impact on the overall sustainability index and, hence, the smaller these factors are, the higher the sustainability index becomes. CEI_{Q_i} is the normalized quality-related CEI of the i component, expressed through the specific stiffness of the considered components. K_{CEI}, K_C, and K_E stand for dimensionless weight factors and reflect the importance attributed to each term of the overall index value.

2.3.1. Factors' Weights Determination

Determination of the criteria weights is a frequent issue in many MCDM techniques. Hence, the selection of a proper weighting method is crucial in solving a multi-criteria decision problem as the weighting procedure followed may significantly influence the result; in this context, a variety of different weighting methods exist, with AHP receiving high popularity [43]. So as to define the weight factors of the above criteria, the AHP [44] was applied in [22], which is considered one of the most widely employed established decision-making methodologies [45]. AHP is based on pairwise comparisons; namely, it evaluates relationships between pairs when making group comparisons to judge which of each alternative is preferred. The main strength of AHP lies in its capability to combine it with other MCDM methodologies to obtain a flexible and tailored solution approach. The determination of the weight factors (K_{CEI}, K_C, K_E) is subjective, reflecting the priority criteria of the user for a specific application. The final ranking among the alternative components occurs through the application of the WSM. However, one of the main concerns regards the inconsistency of decision makers in pairwise comparisons owing to the large number of comparisons needed to obtain the weights [46]. In 2015, another pairwise comparison-based method, namely the best-worst method (BWM), was introduced as an appropriate alternative to AHP in MCDM problems, demonstrating some advantages over AHP, such as fewer pairwise comparisons required and hence, better consistency. The BWM determines the pairwise relative comparisons, i.e., the preference between only the best and the worst criterion over all other criteria [47,48]. For both AHP and BWM, a similar linguistic terminology is being used, i.e., the importance of the criteria is defined on the same scale, i.e., 1–9, where 1 means that two criteria are of equal importance, while 9 means that the selected criterion is extremely more important compared to another criterion, as presented in Table 2. Therefore, a direct comparison can be made under the same level of reference so as the effect of the utilized weighting method can be clearly determined.

Table 2. The AHP Scale [44].

Semantics	Grade	Reciprocal
Extremely preferred	9	1/9
Very strongly to extremely	8	1/8
Very strongly preferred	7	1/7
Strongly to very strongly	6	1/6
Strongly preferred	5	1/5
Moderately to strongly	4	1/4
Moderately preferred	3	1/3
Equally to moderately	2	1/2
Equally preferred	1	1

Although in the current work, the AHP was considered for the determination of the weight factors, BWM can be considered an effective alternative to the AHP method. However, the number of criteria (3) considered in the current study does not lead to different results as the number of pairwise comparisons as well as the system to be solved are identical for the two techniques. Yet, the sensitivity of the weighting procedure when more than three criteria (terms) are considered, and hence, a larger number of comparisons are made remains something to be investigated.

2.3.2. Assessment of the Tool Sensitivity to the Applied Normalization Technique

Normalization is a critical step in any decision-making process as it transforms heterogeneous data into data that share a common scale. In the literature, a variety of normalization techniques have been proposed, including the min-max method, the z-score, the ranking normalization, the distance to target normalization, and the proportionate normalization, which are considered the five most widely employed ones [49]. In order to obtain the normalized indicators in [22], the min-max method was implemented to rescale the range of the individual indicators between 0 and 1. The general equation of the min-max technique [49] is given as:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{3}$$

where x' is the normalized value, x is the original value, $\min(x)$ and $\max(x)$ are the minimum and maximum values of each individual indicator, respectively. In this study, to assess the sensitivity of the results to the normalization technique utilized, two alternative normalization methods were implemented, namely z-score and proportionate normalization. Z-score normalization is a typical methodology widely used in statistics. A z-score describes the position of a raw score in terms of its distance from the mean when measured in standard deviation units. On the other hand, proportionate normalization has the advantage that each value of a dataset is divided by the total sum; in this way, the normalized values maintain proportionality, reflecting the percentage of the sum of the total indicator's values. Dividing by the sum ensures that even the smallest value, which is greater than zero, is attributed a positive normalized value, while the differences among the normalized values become narrow. Alternative normalization techniques, such as ranking normalization and distance to target normalization, were considered inappropriate for this case study. More specifically, ranking normalization is a qualitative method; therefore, a quantitative assessment of the differences among the considered alternatives is not feasible. Finally, distance to target normalization requires the definition of a desired target (deriving mainly from policy targets), which in our case, is not a straightforward one.

2.3.3. Assessment of the Tool to Criteria Weights and Data Variation

Following the assessment of the influence of the different methodologies integrated into the tool, an assessment of rank stability was conducted by accounting for weight factors and data value variations. To this end, a series of indicative weighting scenarios were considered for which smaller and larger adjustments have been made with respect to the applied weights as derived from the AHP analysis. In addition, a thorough sensitivity analysis with respect to the data value variation has been conducted. In order to test the sensitivity of the method to small changes in the values of the original data, 1000 samples were simulated by perturbing the original data by a random error. It is assumed that the errors follow a normal distribution with zero mean and standard deviation proportional to the standard deviation of the corresponding indicator of the initial data. Each of these samples was ordered according to the values of the overall sustainability index, and the mean ranking for each material, as well as the standard deviation, was calculated. All the simulations are implemented in R version 4.1.1 [50].

3. Results and Discussion

3.1. Circular Economy Indicator Calculation

In Table 3, the elastic modulus and the density of the investigated components, as taken from [30], are presented. Based on these values, the specific stiffness for each component was calculated, as well as the resulting weight, in order for the components to present equal stiffness. As mentioned in Section 2.2, the normalized specific stiffness, i.e., the stiffness ratio of the component under study to the virgin one, has been used in Equation (2) as the relevant CEI. Based on the Table 3 values, the virgin component demonstrates a higher specific stiffness compared to the recycled components, as expected, followed closely by the recycled component comprised of 50% aligned fibers. On the other hand, the recycled component comprised of randomly oriented fibers shows by far the lower quality, resulting in a considerable weight increase compared to the other two components. The poor quality of the randomly oriented recycled components highlights the need for upgrade technologies (mainly alignment) of the recycled fibers in order to be able to compete with the virgin CFRP components in terms of quality.

Table 3. Properties of The Investigated Components—Circular economy metric [data adapted from [30].

Component Type	Elastic Modulus (GPa)	Density (g/cm^3)	Specific Stiffness ($GPa/(g/cm^3)$)	Resulting Weight (kg)
Woven virgin	70	1.6	43.75	1000
Recycled aligned	60.8	1.5	40.53	1080
Recycled random	39.8	1.44	27.64	1580

3.2. Environmental and Economic Impact Indicators Calculation

Based on the obtained weight of each component, the environmental impact and costs were calculated, accounting for the whole lifecycle of the components. The results are presented in Tables 4 and 5, where data have been adapted from relevant works, as described in Section 2.2. The impact relating to the use phase of the components accounts for the different types of fuel that have been considered. The higher values, in terms of environmental impact and costs, are noted in bold.

Based on these results, it becomes clear that the virgin CFRP component presents by far the highest environmental impact and costs with regard to its production and manufacturing. This is owed to the significant energy required to produce PAN fibers as well as the considerable energy requirements of the autoclave manufacturing process. Nevertheless, the impact associated with the production and manufacturing phases contributes only to a small percentage of the overall impact, owing to the use phase impact, which clearly dominates the total lifecycle impact of the component. It is worth noting that nearly 99% of the total impact is owed to the use phase when kerosene fuel is used. A similar situation applies when liquid hydrogen from a conventional or wind source is considered; in this case, over 95% of the total impact is still owed to the use phase. However, when liquid hydrogen from a geothermal source is considered, the use phase environmental impact hardly accounts for 84% of the total impact. This remark highlights that the decarbonization of the aviation sector is expected to shift a considerable amount of the environmental burden to the production and manufacturing phases. On the other hand, the latter remark does not concern the lifecycle costs impact as the costs associated with the use of hydrogen are almost double compared to these of kerosene and over four times larger when hydrogen from renewable sources is used. This is owed to the current high cost of liquid hydrogen and especially the ones produced from renewable sources. Therefore, the use phase cost impact dominates the total lifecycle costs, regardless of the type of fuel utilized. The currently high cost of liquid hydrogen, and especially that deriving from renewable sources, may act as a prohibiting factor for the extensive use of liquid hydrogen, at least for the near future.

Table 4. Environmental Impact (LCA) metrics of The Investigated Components.

Component Type	Primary Material Production ($kgCO_2eq$-Mass)	Component Manuf. ($kgCO_2eq$-Mass)	Use Phase ($kgCO_2eq$-Mass-Lifetime Km)				Recycling ($kgCO_2eq$-Mass)
			Kerosene	Liquid Hydrogen	Liquid Hydrogen Wind	Liquid Hydrogen Geothermal	
Woven virgin	**20,440**	**103,000**	52,920,000	5,544,000	3,024,000	756,000	1540
Recycled aligned	1921	1717	57,153,600	5,987,520	3,265,920	816,480	1663
Recycled random	3549	2512	**83,613,600**	**8,759,520**	**4,777,920**	**1,194,480**	**2433**

Table 5. Economic Impact (LCC) metrics of The Investigated Components.

Component Type	Primary Material Production (€-Mass)	Component Manuf. (€-Mass)	Use Phase ($kgCO_2eq$-Mass-Lifetime Km)				Recycling (€-Mass)
			Kerosene	Liquid Hydrogen	Liquid Hydrogen Wind	Liquid Hydrogen Geothermal	
Woven virgin	**17,905**	**3340**	4,032,000	7,056,000	21,168,000	21,168,000	499
Recycled aligned	1560	1858	4,354,560	7,620,480	22,861,440	22,861,440	539
Recycled random	2882	2718	**6,370,560**	**11,148,480**	**33,445,440**	**33,445,440**	**788**

When comparing the components under consideration, the lower environmental impact belongs to the recycled component comprised of aligned fibers for which hydrogen from a geothermal source has been used. Although this component is heavier compared to the virgin one, the environmental gains derived from the production phase of the recycled material are sufficient to compensate for the increased GHG emissions of the use phase compared to the virgin one; the latter remark does not apply though to the lifecycle costs. From the above remark, it becomes clear that the environmental impact associated with the production and manufacturing of virgin CFRP components cannot be neglected, and this urges the need to turn to CFRP recycling to avoid the energy-intensive process of PAN fiber production. Moreover, the environmental gains from the implementation of liquid hydrogen from renewable sources are highlighted, although issues concerning liquid hydrogen storage, transportation and infrastructure must also be considered. Yet, for the recycled components to be competitive with the virgin ones, a comparable to virgin quality appears as a mandatory requirement. Moreover, it should be noted that other factors, such as the feasibility of upgrade technologies of the fibers, the efficiency of the recycling processes and the capabilities of remanufacturing methods to produce recycled components of high quality, as well as the availability of the recycled fibers, must be considered. The worst by far environmental and economic impact concerns the recycled component comprised of randomly oriented fibers. This makes evident that such a component cannot compete with a virgin component, especially when addressed at a high-performance application, and hence, upgrade technologies would be required.

3.3. Sensitivity Analysis Results

The individual LCA, LCC and circular economy parameters of Tables 3–5 were exploited for the calculation of the overall sustainability Index of Equation (2). Based on this calculation, a ranking occurred among the considered components, for which four different types of fuel have been accounted for.

3.3.1. Normalization Method Sensitivity Results

As described in Section 2.3.2, three different normalization methods were implemented for the values integrated into the weighted sum, which resulted in three different combinations: (a) min-max normalization, (b) z-score normalization and (c) proportionate normalization. For each of the above combinations, the sustainability index was calculated, and a ranking among the considered components was derived. In order to test the sensitivity of the final ranking to the applied normalization method, an equal weighting was considered. The rankings obtained from the three different combinations are listed in Table 6.

Table 6. Comparison of The Ranking Obtained from The Different Normalization Methods.

Component Id			**Ranking Order**		
No	**Component Type**	**Fuel**	**Min–Max**	**z-Score**	**Proportionate**
1	Woven virgin	Kerosene	5	5	10
2	Woven virgin	LH2 (conventional source)	1	1	1
3	Woven virgin	LH2 (wind source)	4	4	4
4	Woven virgin	LH2 (geothermal source)	3	3	3
5	Recycled aligned	Kerosene	8	8	11
6	Recycled aligned	LH2 (conventional source)	2	2	2
7	Recycled aligned	LH2 (wind source)	7	7	7
8	Recycled aligned	LH2 (geothermal source)	6	6	5
9	Recycled random	Kerosene	12	12	12
10	Recycled random	LH2 (conventional source)	9	9	6
11	Recycled random	LH2 (wind source)	11	11	9
12	Recycled random	LH2 (geothermal source)	10	10	8

Based on the obtained rankings for the three different normalization methods, min-max normalization and z-score suggested the same ranking among the components. On the other hand, proportionate normalization led to a different ranking. Nevertheless, the first four places and the last one are identical to those obtained by the first two normalization methods. All normalization methods identified the virgin component, for which liquid hydrogen from a conventional source has been considered, as the most sustainable solution. On the other hand, the recycled component comprising randomly oriented fibers showed by far the lowest index, owing to its low quality; this highlights the need for upgrade technologies to improve quality and hence promote circularity and sustainability. Moreover, it is noteworthy that the recycled aligned component, for which liquid hydrogen from a conventional source has been accounted, ranks second; the latter applies to all three normalization techniques. This can be attributed to its comparable to virgin quality, as well as to its environmental friendliness.

3.3.2. Sensitivity to Weights and Data Variation

In order to assess the sensitivity of the tool to the weights' variation, two steps have been followed. Initially, the weights have been considerably varied to assess whether the final ranking is affected by such variations and consequently assess the efficiency of the tool. To this end, the scenarios described in Section 3.3.1 have been considered. The AHP pairwise comparisons were completed by the authors based on their knowledge and expertise in the field. In each of the said scenarios, one criterion is strongly prioritized over the other two criteria. A scenario assuming an equal weighting among the criteria has also been included. The pairwise comparisons of the aforementioned scenarios and the resulting weights are demonstrated in Table 7. All scenarios were checked for consistency, indicating a consistency ratio value below the threshold value of 0.1. The consistency ratio is a metric that indicates the consistency between pairwise comparisons. The rankings obtained from the aforementioned scenarios are presented in Table 8. The min-max normalization was considered for the normalization of the initial data. The results suggested different rankings for the different scenarios considered, and thus, the proposed method was found to be sensitive to the variations of the weight derived from considerable changes in the decision maker's judgments.

Table 7. Pairwise Comparisons and Resulting Weights for Different Scenarios.

	Scenario 1—Equal Weighting			
	Environmental Impact	**Costs**	**Circularity**	**Weight Factor/Priority**
Environmental Impact	1	1	1	≈33.3%
Costs	1	1	1	≈33.3%
Circularity	1	1	1	≈33.3%
	Scenario 2—environmental impact prioritization			
Environmental Impact	1	5	3	≈66%
Costs	1/5	1	1	≈16%
Circularity	1/3	1	1	≈18%
	Scenario 3—circularity prioritization			
Environmental Impact	1	3	1/5	≈21%
Costs	1/3	1	1/5	≈10%
Circularity	5	5	1	≈69%
	Scenario 4—costs prioritization			
Environmental Impact	1	1/5	2	≈18%
Costs	5	1	5	≈70%
Circularity	1/2	1/5	1	≈12%

In the second step of the sensitivity analysis, the rank stability of the MCDM tool was evaluated by adding noise to the criteria weights. To this end, the scenario for which environmental impact was prioritized (Scenario 2) was taken as the reference scenario, and minor adjustments to the user judgments were made. Therefore, based on the AHP scale of Table 1, three alternatives to the reference scenario were considered, for which one scale above or below the reference judgments was accounted for. The pairwise comparisons of the aforementioned scenarios are presented in Table 9. The results showed that the considered minor weight adjustments did not alter the ranking order (except for an exchange between two places of the alternative scenario 3), and hence, the proposed method does not appear to be affected by such minor weight adjustments.

Table 8. Ranking Obtained from The Different Weighting Scenarios of Table 6.

Component Identifier	Ranking Order			
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
virgin ker.	5	10	2	4
virgin hyd.	1	1	1	1
virgin wind	4	4	8	3
virgin geo.	3	2	7	2
aligned ker.	8	11	4	8
aligned hyd.	2	3	3	5
aligned wind	7	6	10	7
aligned geo.	6	5	9	6
random ker.	12	12	6	12
random hyd.	9	7	5	9
random wind	11	9	12	11
random geo.	10	8	11	10

Table 9. Pairwise Comparisons for The Assessment of Small Weights Variations.

	Reference Scenario			
	Environmental Impact	**Costs**	**Circularity**	**Weight Factor/Priority**
Environmental Impact	1	5	3	≈66%
Costs	1/5	1	1	≈16%
Circularity	1/3	1	1	≈18%
	Alternative Scenario 1			
Environmental Impact	1	4	3	≈63%
Costs	1/4	1	1	≈18%
Circularity	1/3	1	1	≈19%
	Alternative Scenario 2			
Environmental Impact	1	5	3	≈64%
Costs	1/5	1	2	≈21%
Circularity	1/3	1/2	1	≈15%
	Alternative Scenario 3			
Environmental Impact	1	6	3	≈67%
Costs	1/6	1	1/2	≈11%
Circularity	1/3	2	1	≈22%

In order to test the stability of the method to small changes in the values of the initial data, 1000 perturbated samples of the original 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 0.01, 0.05, 0.1, 0.25, and 0.5 of the standard deviation of the corresponding indices of the original data. The simulated samples were normalized with the three normalization methods (min-max, z-score and proportionate), ranked with respect to the overall sustainability index, and the mean rank of each material was calculated for each normalization method and for each selected value of the standard error. In Table 10, the mean ranking of each material based on the 1000 simulated samples for the Min–Max and z-score normalization methods are presented for all the selected values of errors' standard deviation. In Table 11, the corresponding mean ranks for the proportional normalization method are presented. The proposed method is fairly stable in terms of the mean rank for each normalization method and for a relatively large value of the standard deviation of the errors.

Table 10. Mean Ranking for The Min–Max and Z-score Normalization Methods.

		Mean Rank									
		0.01		**0.05**		**0.1**		**0.25**		**0.5**	
Id No	**Initial Rank**	**Min–Max**	**z-Score**	**Min–Max**	**z-Score**	**Min–Max**	**z-Score**	**Min–Max**	**z-Score**	**Min–Max**	**z-Score**
1	5	4.98	5.00	4.51	4.91	4.30	4.73	4.48	4.78	4.71	4.81
2	1	1.00	1.00	1.00	1.00	1.02	1.03	1.29	1.30	2.11	2.12
3	4	4.02	4.00	4.05	3.80	4.02	3.86	4.25	4.23	4.46	4.46
4	3	3.00	3.00	3.45	3.29	3.70	3.53	4.04	3.98	4.35	4.33
5	8	7.97	8.00	7.51	7.93	7.30	7.67	6.82	7.09	6.40	6.55
6	2	2.00	2.00	2.00	2.00	2.00	1.98	2.30	2.17	2,93	2.88
7	7	7.03	7.00	7.08	6.82	7.05	6.83	6.67	6.54	6.22	6.17
8	6	6.00	6.00	6.42	6.25	6.60	6.37	6.30	6.16	5.90	5.85
9	12	12.00	12.00	11.71	11.99	11.44	11.86	11.23	11.46	11.08	11.19
10	9	9.00	9.00	9.00	9.00	9.00	9.00	8.85	8.75	8.21	8.11
11	11	11.00	11.00	11.08	10.86	11.06	10.81	11.02	10.91	10.91	10.85
12	10	10.00	10.00	10.21	10.15	10.50	10.33	10.75	10.63	10.73	10.67

Table 11. Mean Ranking for The Proportionate Normalization Method.

		0.01	**0.05**	**0.25**	**0.5**
		Mean Rank	**Mean Rank**	**Mean Rank**	**Mean Rank**
Id No	**Initial Rank**	**Prop**	**Prop**	**Prop**	**Prop**
1	10	10.00	9.99	9.67	8.98
2	1	1.00	1.14	1.94	3.02
3	4	4.00	4.32	4.61	4.77
4	3	3.00	3.25	4.09	4.48
5	11	11.00	11.00	10.45	9.73
6	2	2.00	1.86	2.21	3.15
7	7	7.00	6.59	5.56	5.50
8	5	5.03	5.16	4.85	5.06
9	12	12.00	12.00	12.00	11.88
10	6	5.97	5.68	5.16	5.26
11	9	9.00	8.96	9.04	8.43
12	8	8.00	8.05	8.44	7.75

In Figure 1, the mean ranks and an interval of ±one standard deviation of the rankings are presented for the different levels of noise variation and the three studied normalization methods. As it is observed in Figure 1, the larger the standard deviation of the errors, the larger the variability of each material ranking. Despite the increase in the variation of the rankings, the mean rankings seem to converge to the initial ranking.

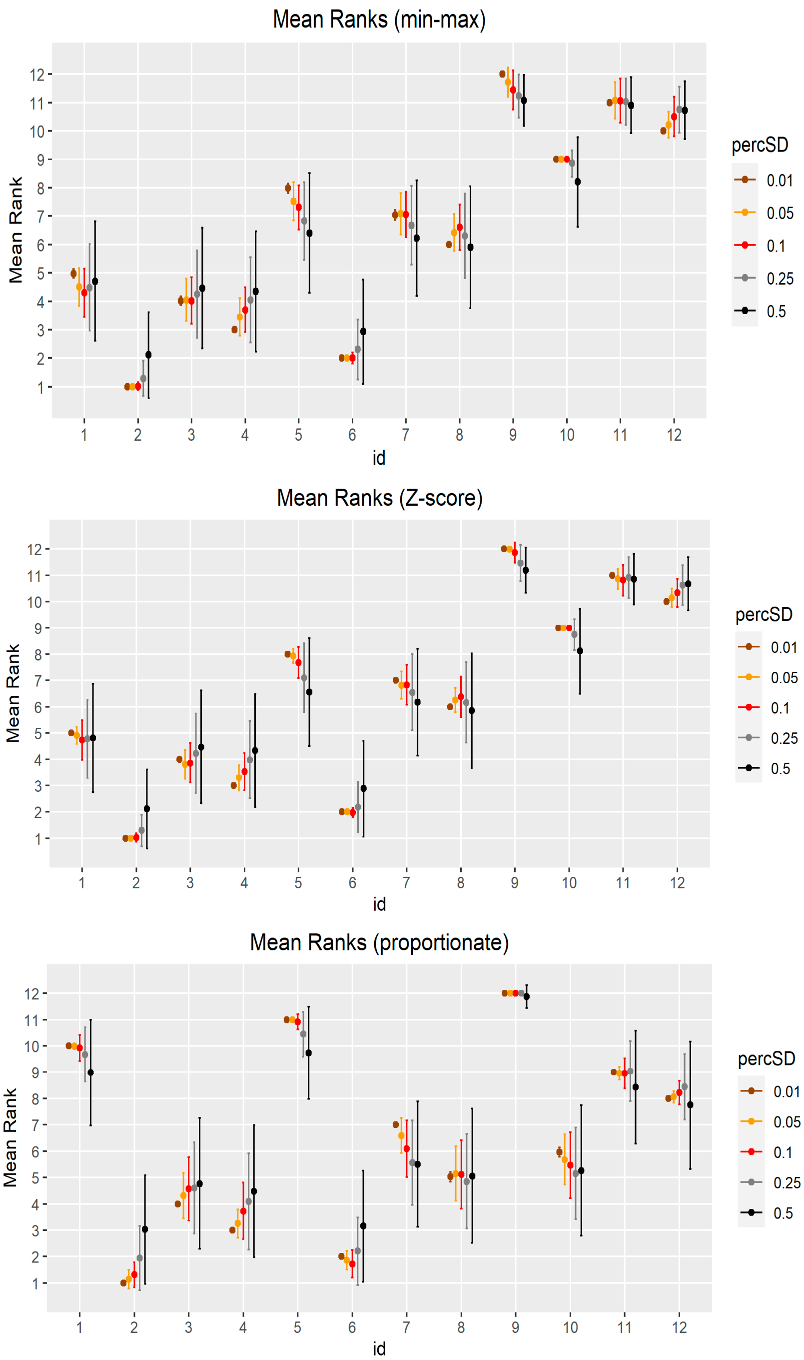

Figure 1. Mean Ranks ± One Standard Deviation of The Rankings for The Different Levels of Noise Variation (percSD).

4. Conclusions

In the present study, the robustness of a hybrid MCDM-based tool proposed by the authors for the aviation sector has been investigated. The latter is performed by accounting for a use case in which the sustainability of composite aircraft components is compared. The proposed tool combines lifecycle metrics linked to environmental, economic and circular economy aspects. Circular economy performance has been associated with a quality feature of the considered components. The tool is able to account for the type of fuel utilized during the use phase of the components. Although liquid hydrogen is not currently certified as an aviation fuel (SAF) by ASTM, its application is being actively researched and developed by various stakeholders in the aviation industry and is considered the most promising fuel option for future aircraft [1]. In this context, it is mandatory to consider and evaluate the sustainability of hydrogen as a potential fuel option for future aircraft.

The environmental impact and cost assessment of the examined components highlighted that a recycled component of near-to-virgin quality can potentially compete with a virgin component, accounting for its whole lifecycle. To this end, the utilization of liquid hydrogen from a renewable source appears necessary. Yet, to achieve a near-to-virgin quality, upgrade techniques and effective remanufacturing methods are required. Furthermore, it has been remarked that the use phase in the aviation sector dominates the overall impact; the latter signifies that the environmental emissions and costs linked to the production and manufacturing phases appear almost negligible compared to these of the use phase. However, when liquid hydrogen from a renewable source, especially from geothermy, has been accounted for, the impact of production and manufacturing comprises a considerable amount of the overall impact. The latter indicates that the decarbonization of the aviation sector may shift the environmental, at least, burden to the production and manufacturing phases. Moreover, although the environmental benefits of using liquid hydrogen are undeniable, the currently high costs of hydrogen compared to kerosene may act as a prohibiting factor for its extensive use in aviation. In addition, the impact of other aspects relating to the production, transportation and storage of liquid hydrogen must also be accounted for, although the latter assessments were outside the scope of this study.

The sensitivity of the MCDM tool to the normalization method applied, as well as to the weights and data variation, has been examined. The sensitivity analysis on the applied normalization method suggested the same ranking for the min-max and z-score methods, while the proportionate normalization method suggested a different ranking. Nonetheless, the first and the last ordered components are identical for all normalization methods. Moreover, the tool was found not to be sensitive to small variations of the weights; on the other hand, larger weights variations suggested a different ranking for the scenarios considered. Finally, the sensitivity analysis on the initial data values did not show a significant change in the final components' rankings compared to the initially obtained ones with respect to the different levels of noise variation for the three studied normalization methods. The latter remarks are quite encouraging and demonstrate the efficiency of the proposed tool as a reliable and robust decision-support tool for the aviation sector.

The goal of this work has been to enhance the reliability of the tool and bolster its credibility for making critical decisions in the aviation sector. Such decisions entail choosing suitable technologies, production and manufacturing procedures for components and materials, as well as determining the appropriate fuel for new aircraft. Future studies could focus on further validating the tool, including its sensitivity to different weights and criteria towards its practical use in the aviation industry, with input from a broader range of experts and stakeholders, ultimately contributing to more sustainable and informed decision-making.

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Nomenclature

AHP	Analytic Hierarchy Process
BWM	Best-Worst Method
CE	Circular Economy
CEI	Circular Economy Indicator
CFRP	Carbon Fiber Reinforced Plastics
ELECTRE	Elimination and Choice Translating Reality
EoL	End of Life
FBP	Fluidized Bed Process
GHG	Greenhouse Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDM	Multi-Criteria Decision-Making
PAN fibers	Polyacrylonitrile fibers
SAW	Simple Additive Weighting
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
WSM	Weighted Sum Model

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