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A holistic assessment of the circularity potential of CFRP in aviation, under the scope of a hydrogen-fueled aircraft

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Abstract

The heavy lift in reducing the climate impact of aviation lies both on fuel switching as well as on the establishment of a circular lifecycle loop for composite materials. The current study aims to contribute to the assessment of the composites circularity potential in the aviation sector under the scope of a hydrogen-fueled aircraft, either from a conventional or a renewable source. To this end, a holistic material selection tool introduced by the authors in a previous study, is implemented to assess the overall impact of recycled CFRP components and assist material selection. The sensitivity of the tool to different weighting, normalization and aggregation techniques is explored and discussed.

1. Introduction

The aviation industry is responsible for 3% of the total CO_2 emissions in the atmosphere [1]. To mitigate the environmental impact of aviation, during the last years, alternatives to petroleum-based fuels have emerged as potential aviation fuels. Among them, liquid hydrogen has been recognized as a promising fuel for sustainable transportation by providing clean, safe, reliable, and affordable energy [2]. Yet, towards fuel efficiency goals and thus, lowering the environmental burden of aviation, weight reduction remains a principal objective as weight is the main driver for fuel consumption and emissions. The current main approach to reduce weight is the utilization of polymer-based composites to replace metals [3]. Additionally yet, also significant issues represent the great environmental and economic impact related to the production of virgin carbon fibers, as well challenges concerning their recycling and recovery. The high value of said fibers has led to the intensification of the efforts towards identifying efficient ways to recycle and reuse carbon fibers, ideally in closed-loop applications. Currently, only demonstrators or prototypes, such as aircraft seat arm rests have been produced [4].

The current work aims to assess the circularity potential of CFRP for the production of high- performance aircraft components under the scope of a hydrogen-fueled aircraft. To achieve this, a modified material selection support tool, based on multi-criteria decision methodology (MCDA), introduced in [5], is further exploited to assess and compare virgin and recycled CFRP aircraft components with regard to sustainability and circular economy objectives, accounting also for the impact of different fuel types. Environmental and economic impact metrics related to the components under study are integrated into the tool, as well as an appropriate circular economy indicator, related to the material/component level. The latter is expressed through a suitable mechanical property of the component. The type of fuel utilized during the use phase of the components is accounted for, namely kerosene and liquid hydrogen produced through a conventional method as well as through renewable sources, i.e. from wind or geothermal sources. Output of the tool is a quantitative synthetic Index which reflects the trade-off between potentially contradicting aspects associated with circularity, environmental impact and costs, in conjunction with the type of fuel utilized during the aircraft use phase. Finally, the sensitivity of the said tool to different weighting, normalization, and aggregation methods is also evaluated and discussed.

2. Methodology

2.1 Basic Assumptions

The methodology described in the following section can be applied to any aircraft component. The components under investigation include CFRP components comprised of virgin and recycled fibers, either randomly oriented or aligned. For the sake of the present study, the components' geometrical features, with the exception of thickness, are assumed

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to be identical. The component comprised of virgin fibers is assumed to be a woven CFRP with volume fraction of 50%, while for the recycled components, components with randomly oriented (40% vf) and aligned carbon fibers (50% vf) have been considered. To enable comparison among the considered components, the mechanical performance of the recycled components must be identical to the virgin one. Hence, to compensate for the material properties variation among the components, thickness and consequently mass, is adjusted in order for the components to achieve equal stiffness. In the present study, stiffness has been considered an appropriate criterion to compare different materials/components. The mass variation is calculated, based on an approximate formula [4], as follows:

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

where, Rm is the mass ratio between the components under comparison, m is the component thickness, p is the component density, E is the elastic modulus of the components under comparison.

2.2. Life-cycle metrics and processes

The material selection tool implemented in the current study exploits life-cycle metrics in order to calculate a quantitative Index and eventually provide a ranking among the considered components. To this end, LCA and LCC data from the most recent literature are used to calculate the environmental and economic impact of the components with regards to their calculated mass. Environmental impact has been related to the Greenhouse Gases (GHG) emitted from each of the life-cycle phases considered, i.e. production, manufacturing, use phase, and recycling. GHG emissions represent the most widely reported environmental impact metric in the industry and academia [6]. The obtained results are expressed in kgCO_2eq per component mass or per component mass per km (when assessing the use phase). The economic impact of the considered components has been linked to the costs referring to either the energy costs associated with the production, manufacturing, and recycling processes (expressed as € per component mass) or to the utilized fuel cost (€ per component mass per km) when assessing the impact of the use phase. The overall assessment also accounts for the impact of the fuel implemented during the use phase of the components, i.e. kerosene, conventionally produced liquid hydrogen, liquid hydrogen from a wind source, and liquid hydrogen from a geothermal source. The life-cycle assessment starts with the primary material production referring to the virgin CFRP component [6-9]. For the manufacturing process, the autoclave process has been considered for the virgin components while for the recycled ones compression molding is considered as the relevant manufacturing process [10]. The impact of the alignment process of the recycled components comprised of aligned fibers was not taken into account due to lack of consistent literature data. The impact associated with the use phase is fuel-dependent and the said impact is directly related to the calculated mass of the considered component. Hence, the components are considered as loads to be carried by the aircraft. Relevant LCA and LCC data regarding the different fuels considered, has been adapted from [11]. For the use phase, the average lifetime distance of a commercial aircraft is taken into account [12, 13]. Regarding the recycling of CFRPs, the fluidized bed process (FBP) has been considered in this study as being a promising recycling technique for CFRPs, capable of recovering carbon fibers with mechanical properties comparable to those of virgin ones [14].

2.3 Structure of the holistic assessment tool

The mentioned MCDA tool, previously implemented in another study [5] towards material selection support in aviation, has been adapted to the scope and requirements of the present study. The current tool combines the Analytic Hierarchy Process (AHP) and a linear aggregation method, i.e. summation of normalized and weighted individual indicators. The tool integrates environmental and economic metrics referring to the component under study, as well as a suitable quality-related circular economy indicator (CEI), expressed through a specific property of the material. Based on the above definitions, the mathematical formula takes the form:

$$P = K_{CEI} \times CEI_Q + K_C \times C + K_E \times E \tag{2}$$

where, E and C are the normalized environmental and economic impact indicators, respectively. CEI_Q is the normalized quality-based CEI, while K_Q, K_C, and K_E stand for dimensionless weight factors, reflecting the importance of each term to the overall Index value. To obtain the normalized indicators, the min-max method was implemented to rescale the range of the individual indicators between 0 and 1. Min-max normalization is considered one of the most widely used methods for data normalization [15]. For every data set, the minimum value of the dataset is transformed into a 0, the maximum value is transformed into a 1, and every other value is transformed into a decimal between 0 and 1. The general formula for the min-max method is given as:

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

where x' is the normalized value, x is the initial value, min(x) and max(x) are the minimum and maximum values of the dataset, respectively. For values which are not beneficial to the final output of the Index, namely environmental impact, and costs, the reverted min-max scaling has been applied.

To determine the weights of equation (2), the analytic hierarchy process (AHP) has been implemented, which is considered one of the most widely established multicriteria decision-making methodology [16]. The AHP method is employed to rank a set of alternative solutions and select the 'best' option among this set of alternatives. The selection is made with respect to an overall goal, broken down into a set of chosen criteria. The paired comparisons are used to compare the alternatives with regard to the criteria defined and estimate the criteria weights, on a scale of 1 to 9, where 1 means that the criteria are equally important, while 9 means that the selected criterion is extremely more important than another criterion. The main strength of AHP lies in the capability to combine it with a variety of other methodologies, for obtaining tailored solution approaches. The definition of the weight factors (K_{CEI}, K_C, K_E) is subjective and reflects the priority criteria of each stakeholder and the targeted application. The AHP analysis was implemented using the freeware 'SuperDecisions' [17]. The final output of the said tool is the summation of the weighted and normalized KPIs, i.e. a quantitative Index (P) which represents the trade-off between aspects associated with circularity, environment and costs, accounting simultaneously for the type of fuel implemented. The latter calculations are performed via a spreadsheet (excel-based) model.

2.3.1 Assessment of the tool sensitivity to the weighting method

Although the Analytic Hierarchy Process (AHP) has a long tradition in multi-criteria decision-making, one of the main concerns regards the inconsistency of decision makers in pairwise comparisons. Recently, the Best-Worst Method (BWM) was introduced to reduce the inconsistency by a concept that needs considerably less pairwise comparisons. The BWM involves the solution of a non-linear model (NLM) to derive the weights from the comparisons while a linear model (LM) was introduced in a follow-up to approximate the original NLM. [18]. Therefore, to assess the sensitivity of the holistic tool to the weighting method implemented, the BWM has been also considered as an alternative to the AHP technique towards determining the weights (importance) values of the Index terms, i.e. circularity, environmental impact, and costs. Both weighting methods are based on the paired comparisons approach and the importance of the criteria is defined on the same scale, i.e. 1-9, using the same terminology. Therefore, comparison is made under the same judgements base and the effect of the utilized weighting method can be clearly determined.

2.3.2 Assessment of the tool sensitivity to the normalization technique

To assess the effect of the normalization technique, an alternative to the min-max normalization technique has been also applied, i.e., proportionate normalization [15]. In this method, the single value of the dataset is divided by the total sum of the dataset and the normalized values maintain proportionality, reflecting the percentage of the sum of the total value of the indicators. Dividing by the sum ensures that even the smallest value greater than zero comes out with a positive normalized value while the differences between the normalized values become narrow.

2.3.3 Assessment of the tool sensitivity to the aggregation technique

Aggregation combines the values of a set of indicators into a single summary 'composite' or 'aggregate' measure. To assess the sensitivity of the holistic tool to the aggregation technique, the geometric aggregation has also been applied. Although additive aggregation is a widely used aggregation method [19], an undesirable feature regards the implied full compensability, meaning that poor performance in some indicators is compensated for by high values in other indicators. If multi-criteria analysis entails full non-compensability, the use of a geometric aggregation seems to be an attractive aggregation method. The general formula of the geometric aggregation is given by:

$$CI = \prod_{i=1}^{n} {x_i}^{w_i} \tag{4}$$

where x_i are the normalized values and w_i are the respective weights of the normalized values.

3. Results and Discussion

3.1 Circularity Potential Calculation

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Considering that quality of the recycled material is a decisive factor for achieving circularity, a CE metric is introduced linking circularity to a quality feature of the investigated material, i.e. its specific stiffness. For aircraft applications, that choice is well justified as the allowable design of an aircraft structure does not exceed the linear elastic region of the corresponding stress-strain curve. Table 1 shows the elastic modulus and the density of the investigated components, as taken from [10]. Based on these values, the specific stiffness and the resulting equivalent weigt were calculated from eq(1). The virgin component demonstrates the higher specific stiffness compared to the recycled components, followed closely by the recycled component comprised of 60% aligned fibers. This is also depicted on their similar resulting weights. 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 tehcnologies (mainly alignment) of the recycled fibers in order to be able to compete with the virgin CFRP components, in terms of quality.

Table 1: Summary of the investigated components properties

Component type	**Elastic modulus (GPa)**	**Density (g/cm^3)**	**Specific Stiffness ($GPa/(g/cm^3)$)**	**Resulting Weight (kg)**
Woven virgin 50%	70	1.6	43.75	1000
Recycled aligned 50%	60.8	1.5	40.53	1080
Recycled random 40%	39.8	1.44	27.64	1580

3.2 Environmental and Economic Impact Indicators Calculation

Based on the calculated weights of the three investigated components, the respective environmental (GHG emissions) and economic impact (costs) were calculated and are demonstrated in Tables 2,3. The said impact accounts for the impact of four different fuels as described in a previous section. The higher values in terms of GHG emissions and costs, are shown in bold. Based on these results, the virgin CFPP component shows by far the higher GHG emissions and costs associated with the primary material production and the manufacturing of the component, owing to significant energy intensity of the virgin carbon fibers (PAN fibers) as well as to the energy intensity of the autoclave manufacturing process. However, the latter impact contributes only to a small percentage to the overall impact of the components, as the use phase clearly dominates the life-cycle impact of the components in terms of GHG emissions and costs. It is noteworthy that nearly 99% of the environmental impact and costs are owed to the use phase when kerosene is used and over 97% when liquid hydrogen is used, for both virgin and recycled components. Yet, when liquid hydrogen from a hydrothermal source is considered, the above percentage considerably decreases as the use phase in that case contributes to nearly 83%, when considering a virgin component;

When comparing the investigated components, the lower GHG emissions belong to the recycled component comprised of aligned fibers for which hydrogen from a geothermal source has been used. Although this component is heavier than 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. This is owed to the fact that the GHG emissions associated with the use phase of the components are over 98% lower when hydrogen from a a geothermal source is used. The latter highlights that the environmental impact associated with the production and manufacturing of virgin CFRP components cannot be neglected in such a case and that urges the need to turn to CFRP recycling in order to avoid the energy-intensive process of PAN fibers production. Yet, this implies the use of a sustainable fuel such as hydrogen from a renewable source such as geothermy. The worst by far environmental and economic impact regards the recycled component comprised of randomly oriented fibers. It is more than evident that such a component cannot compete with a virgin component, especially when addressed to a high-performance application, and hence, upgrade technologies are required.

Concerning the economic impact of the investigated components, 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, owing to the currently high cost of liquid hydrogen and especially the ones produced through renewable sources. This could currently act as a prohibiting factor for the extended use of liquid hydrogen, at least for the near future.

Yet, it should be noted that other factors such as the feasibility of the upgrade technologies of the fibers, the efficiency of the recycling processes and the capabilities of a remanufacturing methods to produce recycled components of high quality, as well as the availability of the recycled fibers, must be considered.

Table 2: Environmental impact of the investigated components

Component Type	Primary Material Production (kgCO2eq-mass)	Component Manuf. (kgCO2eq-mass)	Use phase (kgCO2eq-mass-lifetime km)				Recycling (kgCO2eq-mass)
			Kerosene	Liquid Hydrogen	Liquid Hydrogen wind	Liquid Hydrogen geothermal	
Woven virgin 50%	**20 440**	**103 000**	52 920 000	5 544 000	3 024 000	756 000	1 540
Recycled aligned 50%	1 921	1,717	57 153 600	5 987 520	3 265 920	816 480	1 663
Recycled random 40%	3 549	2,512	**83 613 600**	**8 759 520**	**4 777 920**	**1 194 480**	**2 433**

Table 3: Economic impact of the investigated components

Component Type	Primary Material Production (€-mass)	Component Manuf. (€-mass)	Use phase (kgCO2eq-mass-lifetime km)				Recycling (€-mass)
			Kerosene	Liquid Hydrogen	Liquid Hydrogen wind	Liquid Hydrogen geothermal	
Woven virgin 50%	**17 905**	**3 340**	4 032 000	7 056 000	21 168 000	21 168 000	499
Recylced aligned 50%	1 560	1 858	4 354 560	7 620 480	22 861 440	22 861 440	539
Recycled random 40%	2 882	2 718	**6 370 560**	**11 148 480**	**33 445 440**	**33 445 440**	**788**

3.3 Weighting procedure sensitivity results

To derive the weights (importance factors) of the holistic Index terms, i.e. circularity, environmental impact, costs, the AHP process and the BWM method were used. The definition of the terms importance was made under the same scale, i.e. 1-9, using the same terminology, 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. Based on the user judgments and the pairwise comparisons for each process, a weight factor occurs. Therefore, comparison is made under the same judgements base and the effect of the utilized weighting method can be determined. Table 4 shows the weight factors occurred for the three different scenarios after the initial judgments have taken place, using both weighting methods. Scenario 1 strongly prioritizes environmental impact over costs, while circularity is considered moderately to strongly more important than costs, and environmental impact is considered moderately more important than circularity. The second scenario assumes that circularity is equally important to environmental impact while both latter are considered strongly to very strongly more important than costs. Finally, the third scenario assumes that circularity is equally important to costs, while environmental impact is considered very strongly more important than both circularity and costs.

Table 4: Resulting weights occurred for the considered scenarios

	Scenario 1		Scenario 2		Scenario 3	
	AHP	BWM	AHP	BWM	AHP	BWM
Circularity	0.28	0.27	0.46	0.46	0.13	0.125
Environment	0.63	0.64	0.46	0.46	0.75	0.75
Costs	0.09	0.09	0.08	0.08	0.12	0.125

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The results indicate that the two weighting processes followed, lead to the same weighting factors and hence, the holistic tool output is not expected to be affected by the weighting process followed. However, the sensitivity of the weighting procedure when more than three criteria (terms) are considered, remains something to be investigated.

3.4 Normalization and aggregation procedures sensitivity results

Following the weights definition of the Index terms, normalization and aggregation were applied in order to derive the holistic Index. As described in Section 2.3.2 and 2.3.3, two different normalization and two different aggregation methods were implemented, resulting in a number of four different combinations, i.e. a) min-max normalization followed by linear aggregation, b) min-max normalization followed by geometric aggregation, c) proportionate normalization followed by linear aggregation, and d) proportionate normalization followed by geometric aggregation. Implementing each of the above combinations, a holistic Index was calculated and a ranking among the investigated components occurred. Regarding the weighting procedure of the Index Terms, the two first scenarios (Scenario 1 and Scenario 2) as described previously, were accounted for, as two representative scenarios. Figure 1 and Figure 2 show the ranking of the considered components for the two different scenarios, accounting for all possible normalization-aggregation methods combinations.

As a general comment, regarding the obtained ranking among the investigated components, it is clear that the holistic tool prioritizes the virgin components for which liquid hydrogen either from a conventional or a renewable source has been considered. The recycled component comprised of randomly oriented fibers presents by far the lowest score compared to their alternatives; this highlights the need for upgrade technologies towards improving the quality and therefore, promote their circularity. Moreover, the recycled aligned components, for all hydrogen fuel types, present a quite high score, owing to the comparable to virgin quality and the environmental friendliness of liquid hydrogen, especially when derived from a renewable source. Further remarks on the sensitivity of the obtained ranking to different combinations of normalization and aggregation techniques follow.

3.4.1 Min-max normalization and linear aggregation

The ranking obtained from the above combination clearly prioritizes the virgin components for which liquid hydrogen has been considered in the use phase, either from a conventional or a renewable source. The output values of the mentioned components are by far higher compared to the recycled random components, and especially those ‘running’ on kerosene. The latter applies for both scenarios considered, although for the second scenario, some slight ranking order exchanges are observed. The combination of min-max normalization and linear aggregation leads to reasonable results, respecting the importance weights set by a potential user. The differences among the investigated components are distinguishable while the results and the ranking order appear to be satisfactory from the technological point of view.

3.4.2 Min-max normalization and geometric aggregation

While this combination also clearly prioritizes the high-quality components ‘running’ on liquid hydrogen for both Scenario 1 and 2, the randomly oriented recycled components have been attributed a value of zero. This constitutes the prime drawback of geometric aggregation which regards the presence of zeros in the calculations. If one indicator has a zero value after the normalization procedure, then the geometric aggregation will result in zero for the overall index. Hence, geometric aggregation would be useful when strictly positive indicators are expressed in different ratio-scales than 0-1. Although the zero values for the ‘random’ components reflect the low quality and the high environmental impact due to their higher weight, a comparison among the ‘random’ components when different fuels are considered, cannot be made as all these components are assigned a zero value. Moreover, if in the place of a ‘random’ component another component of near to virgin quality was considered, the zero value attributed to such a component would seem totally illogical.

3.4.3 Proportional normalization and linear aggregation

This combination appears also to prioritize the components of high-quality, ‘running’ on hydrogen; however, the difference gaps with the randomly oriented recycled components are not much distinguishable compared to the first normalization-aggregation combination considered, while the distinction between the high-quality components ‘running’ on different types of liquid hydrogen, are almost negligible. The latter applies for both scenarios. Moreover, the fact that three out of four ‘random’ components are assigned a score very close to the ‘virgin’ ones indicates that this combination appears to subestimate the impact of quality while it seems to overestimate the impact of environmental friendliness, especially for scenario 2 where the criteria of environment and circularity are considered of equal importance.

3.4.4 Proportional normalization and geometric aggregation

This combination seems to resolve the problem observed in the second normalization-aggregation combination considered, i.e. the presence of zero output values, owed to the geometric aggregation approach. This is owed to proportionate normalization in which the division by the sum ensures that even the smallest value greater than zero comes out with a positive normalized value. Moreover, while the high-quality components are also prioritized in this combination, the differences among them are not very clear while the gap between them and the randomly oriented recycled components are smaller compared to the first normalization-aggregation combination considered herein. That is something not expected as the recycled random components are characterized by very low quality.

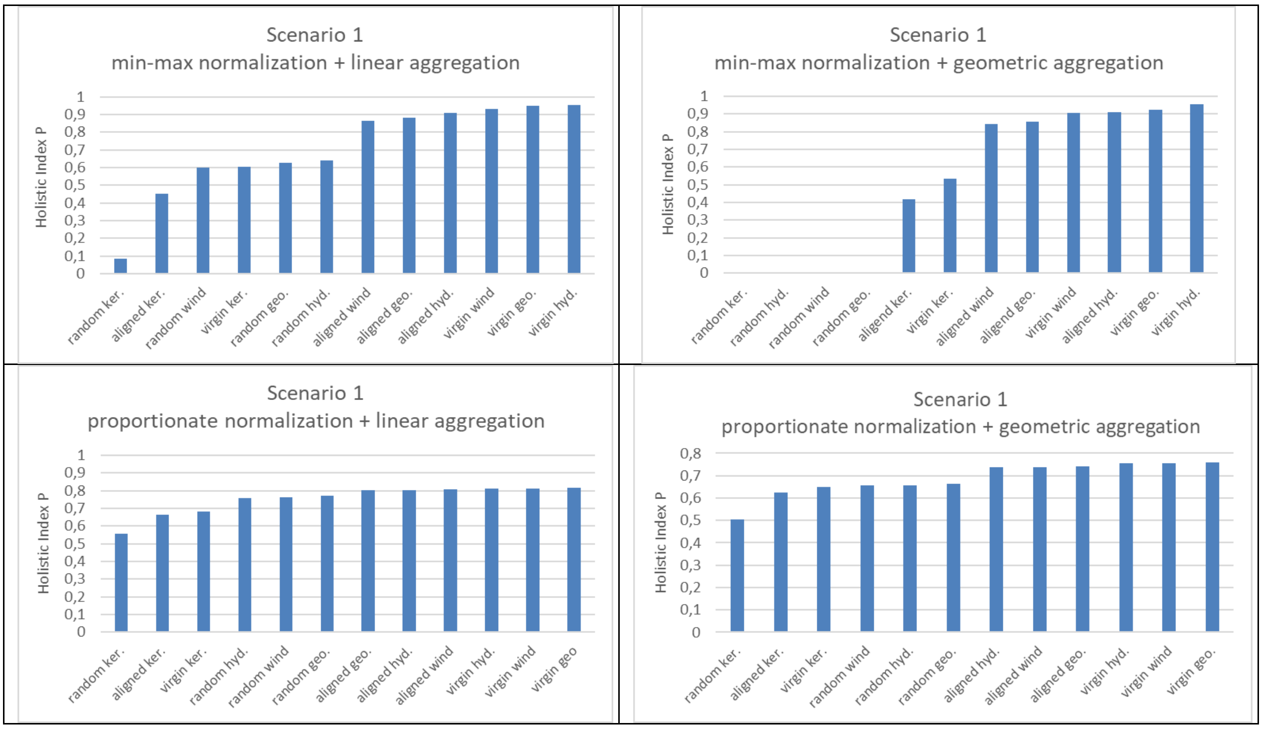

Figure 1: Ranking of the investigated components – Scenario 1

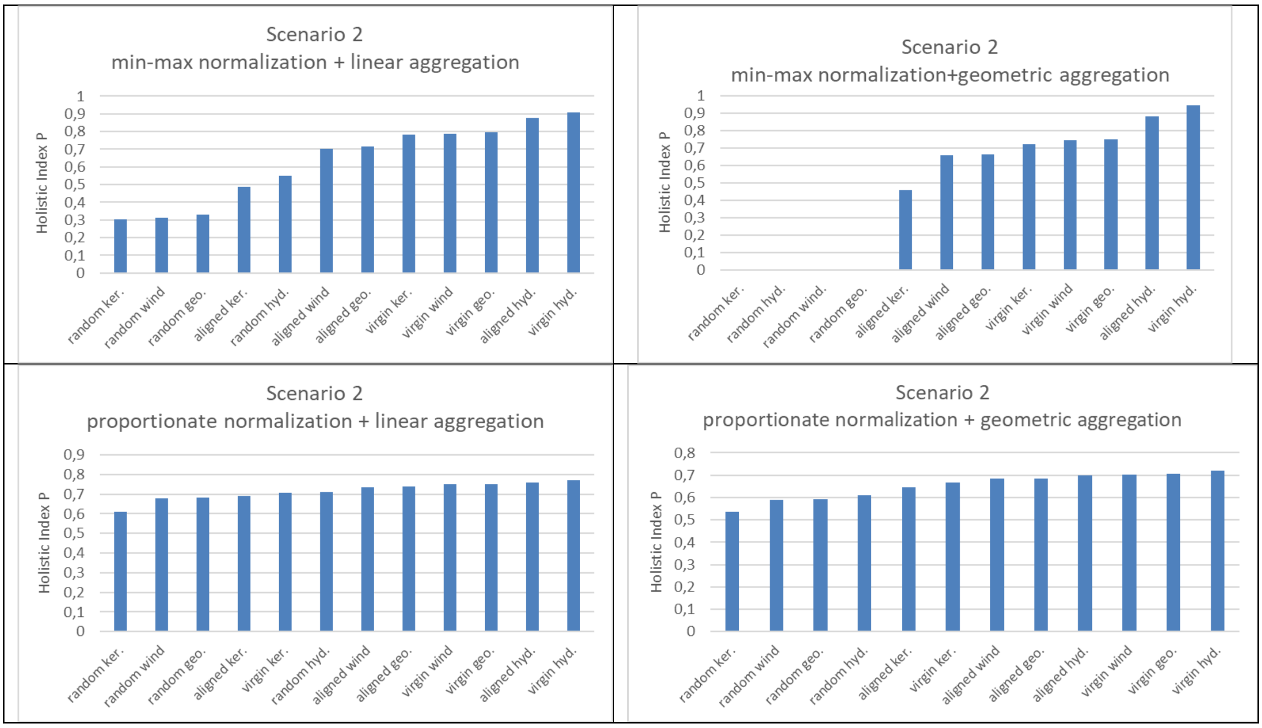

Figure 2: Ranking of the investigated components – Scenario 2

4. Conclusions

In the current work, an already established tool by the authors to support material selection in aviation, is adapted to aid selection of a recycled CFRP component in aviation and hence, contribute to assess their suitability of recycled components in the aviation industry. The mentioned tool combines life-cycle metrics, including environmental, economic, and circularity aspects, in which the circularity potential of CFRP is linked a quality feature of the considered components. The tool also accounts for the type of fuel utilized during the use phase, i.e. kerosene and liquid hydrogen, either from a conventional or a renewable source.

The individual assessment of the environmental and economic impact has shown that a recycled component of high quality seems to compete well with a virgin component in terms of environmental emissions and costs through its life cycle. Moreover, it has been highlighted that the use phase dominates the impact, and therefore the emissions and costs of production and manufacturing appear negligible when these related to the use phase, except when liquid hydrogen from a renewable source has been considered, especially from a geothermal source. It has also been shown that, the use of hydrogen fuel, especially that derived from renewable sources, during an average lifetime of a commercial aircraft is extremely beneficial in terms of environmental emissions, compared to the use of kerosene. Nevertheless, other aspects associated with the production, transportation and storage of liquid hydrogen have not been accounted for as they were not into the scope of the current study. On the other hand, the high costs of hydrogen may currently appear as a prohibiting factor for more extensive use in aviation.

The sensitivity of the holistic tool to two different weighting methods as well as to a number of combinations of normalization-aggregation methods, was also evaluated. It was demonstrated that the two weighting processes followed, i.e. AHP and BWM, lead to identical importance weights based on a number of possible scenarios, and hence, the holistic tool outputs are not expected to be affected by the weighting process followed. For all possible normalization-aggregation combinations, the ranking obtained from the implementation of the holistic tool showed that the virgin component presents the best overall performance, followed closely by the component comprising of aligned recycled fibers with a vf of 50%. The holistic Index output prioritizes especially the high-quality virgin components for which a renewable source for hydrogen production is assumed. On the other hand, the worst performance belongs to the random one indicating that retaining the quality of the virgin material is a major demand, in order to comply with sustainability and circularity targets in the aviation sector, especially when a closed-loop approach is demanded. Although the different combinations did not suggest the same ranking among the components, the first combination, which is the currently used approach for the established holistic tool, appears to lead to more reasonable results, and the differences among the components are more distinguishable compared to the other combinations considered. Moreover, the obtained ranking for the first combination seems to respect more the proposed stakeholder needs defined from the weighting process followed and appears to be more satisfactory from the technological point of view.

Implementation of circular economy principles in aviation is more and more demanding in order to achieve the goals and objectives of sustainable aviation. To this end, implementation of tools based on MCDA methodologies are needed to assess sustainability and circularity in a concise and holistic manner and consequently support decision makers to take difficult choices, especially when contradicting aspects are included in their selection criteria.

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