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ASSESSMENT FRAMEWORK FOR SUSTAINABLE LIGHTWEIGHT MATERIALS IN AVIATION

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Abstract

Airborne applications are traditionally challenging working environments for structural materials, imposing tough and non-negotiable constraints with respect to stiffness and structural integrity, while the construction must still be as lightweight as possible. This has led to the increased use of fiber composites like carbon- or glass-fiber reinforced plastics (CFRP or GFRP) in aircraft, which offer the required structural properties at the same time as a considerable weight advantage over conventional materials (*e.g.* aluminum) in certain applications. With CFRP or GFRP being predominantly based on petrochemical products, recent efforts to make aviation more sustainable by reducing its dependence on non-renewable resources should be extended to include the identification of alternative production pathways and new materials, yet without compromising their lightweight and high performance properties and characteristics. In this paper, the groundwork for a suitable assessment framework and criteria for the selection of reliable *and* sustainable construction materials is laid. We discuss the example of renewable fibers and propose the notion of the so-called “Loom-In Capability (LIC)”: Analogously to the “Drop-In Capability” used in the assessment of alternative fuels, the LIC should be understood as a parameter to quantify the compatibility of new materials with current processes of aircraft design and construction.

1. INTRODUCTION

Traditionally, aviation has been an exceedingly weight-sensitive industry, and from the outset the construction of aircraft has faced the conflicting requirements of guaranteeing structural integrity in a demanding working environment and minimizing take-off weight. The selection of materials during the process of aircraft design and manufacturing processes therefore follows a very conservative approach: The adoption of new construction materials can take decades, and design margins are often significantly increased to compensate for the lack of in-use experience with a new material.

An impressive development in this respect is the addition of fiber composites to the menu of construction materials, which can amount to 50% of the structural weight in recent aircraft [1]. With their high performance in many crucial construction aspects and their specific weight advantage over conventional materials like aluminum alloys, composites such as carbon-fiber reinforced plastic (CFRP) and glass-fiber reinforced plastic (GFRP) have met the aircraft designers’ need to reduce aircraft structural weight in order to minimize fuel consumption.

While less fuel burn directly translates into an economic advantage for airlines by reducing their operating costs, in recent years the ecological aspect of reducing CO_2 emissions has become an increasingly important issue in civil aviation [2].

By far the most important step in this direction are the ongoing efforts to replace fossil fuels in transport applications by renewable alternatives. Many different approaches are being discussed, ranging from alternative production pathways for kerosene [3, 4] to radical new approaches such as the electrification of flight [4-6].

In a second step, however, the introducing of sustainability into all aspects of commercial aviation including production and processing of the high performance materials used in aircraft construction has to be aimed. In this context, CFRP and GFRP composites, which are predominantly based on petrochemical products like polyacrylonitrile (PAN) and epoxy resin, may be seen as causing a “second order” dependence on fossil resources. Awareness of this problem is not entirely new, and some suggestions exist for other precursors *e.g.* for CFRP, like lignin as a basis for carbon fibers [7]. However, since stiffness and durability of aircraft structures are unequivocally set requirements, the implementation of any sustainable material technology stands under the caveat of the new material being able to support the high mechanical loads.

In this paper we argue that design and development of sustainable *and* structurally reasonable, lightweight materials for use in aviation are important goals to pursue which can be achieved through a variety of pathways, some of which leading to perfect substitutes for conventional materials. The aim of this study is to develop a framework to identify and assess suitable new high performance material candidates, considering a combined catalogue of construction-related and environmentally motivated criteria. We also present this framework’s initial application to selected exemplary materials.

2. ASSESSING ALTERNATIVES IN A MULTI-DIMENSIONAL PARAMETER SPACE

A high-quality evaluation of several alternatives involves multiple criteria and makes a final selection of an alternative traceable, rational and efficient. To this end, a logical assessment framework has to be provided for comparing the performance of sustainable lightweight materials on important attributes.

In an initial evaluation procedure, there is only one crucial criterion on which a decision has to be based. This leads to a technical “search and measurement” process, using a comparative assessment of options according to a defined value function, resulting in a straightforward down-selection to the most attractive alternative, such that the technical problem is solved. This process is relatively trivial, once the value function has been established and the required information of a variety of alternatives has been researched. In this case, no decision needs to be made on the obvious outcome if one option meets all criteria without conflict.

However, in the presence of multiple criteria, the non-availability of the ideal alternative usually creates a pre-decision conflict. A decision needs to be made to manage or resolve the conflict of tradeoffs [8]. In this situation, a desirable result of the assessment criteria presented here is to pave the way towards a useful quantitative assessment framework for high-quality decisions in the presence of potential tradeoffs.

Another desirable result of the multiple-criteria decision making process is that the focus is moved away from premature selections of alternatives and toward fundamental objectives. The focus shift helps to identify new alternatives in the process [8-10]. The standard way of thinking about decisions is first to identify alternatives rather than “value-focused thinking”. The former emphasizes fixed procedures and choices instead of on the objectives. The latter can lead to the identification and creation of better alternatives as a consequence of defining fundamental values in the decision making process before attempting any solutions [10].

The task of assessing alternatives in a multi-dimensional parameter space is achieved through criteria selection, scaling, weighting and amalgamation [8, 9]. This leads to the “quantification” of the value and ranking of alternatives and can also be applied to the quantification of innovation potentials of these alternatives, thus quantifying the pre-decision conflict in the absence of a perfect solution.

Value functions and weights for each criterion, as well as the method of amalgamation can be established in several ways [9]. A simple representation of value function translates the original metric of the criterion linearly into a value or score between 0 and 1. In the simplest case, the method of amalgamation is then an additive value function by summation over the weighted score. This approach has been applied to alternative aviation fuels [3,11].

The implementation of such an assessment framework for renewable lightweight material selection is beyond the scope of this paper. Instead, we focus first on the multi-dimensional parameter space, then on “renewable alternatives” and finally identifies possible “renewable alternatives” that need not originate from biological sources, and bio-derived fiber production paths that are “loom-in capable”, *i.e.* being a perfect substitute for high-performance carbon fibers.

3. SELECTION OF CRITERIA

The identification of relevant criteria is at the core of any assessment framework. Thereby, the aim must be to find criteria for each relevant aspect of the problem.

For sustainable structural fiber composites, we suggest three classes of criteria, covering the aspects of mechanical properties (relevant for design and construction), reliability (relevant for certification and operation), and sustainability. In this work, we aim for the integral consideration of all three classes together, where usually these issues were considered separately [12, 13].

With some expense of an additional work, in future studies the selected criteria finally can be combined into a weighted decision matrix.

3.1. Material Characteristics

The first class of criteria are *material characteristics*, *i.e.* intrinsic material properties, which, in a first approximation, do not vary with the specific application (*e.g.* the geometry of a device) or external influences (*e.g.* applied loads).

Sufficiently precise knowledge of such properties for construction materials is a prerequisite for determining load cases in mechanical design.

Due to the large variety of materials and their possible applications in aviation, the material characteristics can further be classified in mechanical, thermal, electrical and optical properties. A first overview of these and some exemplary material properties are shown in Table 1. Note that the intention of this study is to develop a simple and universal assessment framework for lightweight materials, Therefore, we select the basic material characteristics *Young’s Modulus*, *maximum tensile strength*, and *density* as primary metrics to evaluate the structural performance of composite materials.

Table 1: Classification and Short List of Selected Material Characteristics Adapted from Ashby et al [14].

Class	Property	Unit
Mechanical	Young’s Modulus	GPa
	Maximum Tensile Strength	MPa
	Hardness	-
	Fracture Toughness	MPa/m$^{1/2}$
	Density	g/cm³
Thermal	Melting Point	K
	Glass Temperature	K
Electrical	Electric Resistivity	Ω
	Dielectric Constant	-
Optical	Refractive Index	-

For a more product-specific assessment, other parameters like the speed of sound, damping properties, etc. may also be important. Their consideration is, however, not the subject of the present paper, but may be included when specific aircraft components are evaluated.

3.1.1. Young’s Modulus

The Young’s Modulus (E) characterizes the elastic deformability of a material. High values of E imply a high stiffness, whereas flexible composites have low modules. The importance of E for the design of structural elements is explained by the fact that knowledge of a material’s Young’s Modulus is required when load cases on composite plates are simulated by mathematical models [15]. Hence, E must be known at the early stages of aircraft design in order to determine suitable materials *e.g.* for the airframe.

Regarding conventional construction materials in aviation like aluminum and CFRP, the margins of E range from 73 up to 140 GPa [16, 17]. In a first step, we therefore conclude that for straightforwardly replacing one of the commonly used structural materials by a more sustainable one, it would be beneficial if the substitute's E value falls within the same range.

However, this does not necessarily prohibit the use of a lower E material, but deviant modules change the required thickness of *e.g.* composites plates when structural elements are developed. This may require a significant redesign of the component (or the entire structure) to achieve a different load distribution and plate thicknesses that can be supported at differing Young's Modules [18].

3.1.2. Maximum Tensile Strength

The maximum tensile strength (σ) is defined by the maximum force per area that can be applied before breaking a solid. Like E, σ is crucial to the initial stages of aircraft design because only with high values of σ can the structural integrity of an aircraft component be guaranteed under high load cases in operation.

As for the Young's Modulus, we conclude from established design practices using conventional materials that the maximum tensile strength of a renewable substitute has to be in the same range as for the high performance materials in use today. This is between 440 MPa for aluminum [16], and 2000 MPa in case of CFRP [17].

3.1.3. Density

The mass-density ρ is a frequently used metric in lightweight design. If the density of a construction material can be reduced at constant E and σ this directly translates into weight reductions [14].

A good benchmark for sustainable construction materials are the densities of the two presently used structural materials aluminum and CFRP, from which we find a range of 1.4 - 2.78 g/cm³ [16,19]. Note that in contrast to Young's Modulus and maximum tensile strength, no absolutely limiting constraints for the density follow from structural requirements. For example, if a material has a high density, yet also a high value of E, one can keep the thickness of construction panels small, and the absolute weight of the panel may not be higher than that of a thicker panel made from a lower density material. However, in combination with the margins of E and σ introduced above, it follows that the desirable density is also somewhat constrained, if structural redesign is to be avoided.

3.2. Criteria of Reliability and Quality Aspects

High endurance, good reliability and consistent quality of construction materials are prerequisite for their use in airborne vehicles. For fiber composites, reliability and production quality are strongly coupled with aspects of certification like fatigue, impact and non-destructive testing methods [20].

In general, however, certification of aircraft components and devices is a complex procedure and depends on the targeted applications. It is therefore challenging to establish a direct link between the reliability of materials and their certification for aviation use. In particular, this renders it difficult to estimate the probability with which a new material may pass the certification process.

Nevertheless it can be argued that a material with high inherent variation of its mechanical properties has a lower chance to eventually be certified than one for which these properties are more homogeneous. Our goal in the present assessment category is therefore to provide some indications whether it is, in principle, likely to get a new, sustainable material certified in the future, or whether major (physics-based) uncertainties will remain. As an example for the variation of mechanical properties, below we discuss E and σ, which were previously introduced as key structural design parameters.

3.2.1. Variations in Maximum Tensile Strength

First, let us consider variations in the maximum tensile strength σ. Due to statistically distributed defects, there are inherent fluctuations in the observed fracture toughness in any solid. Regarding brittle materials, these are typically assessed using Weibull statistics, where the Weibull Modulus *m* is a dimensionless factor quantifying the measured scattering width of the maximum tensile strengths σ around the average value σ_0 [21]:

$$(1) \qquad P_f = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

Note that P_f is the probability of a failure of the specimen. Metals usually offer high m (roughly 100 for steels), which corresponds to a very low scattering of σ between different samples. In contrast, some ceramics like Si_3N_4 have high variations in their tensile behavior, which is reflected by their low m (of 8 - 9) [22]. Statistics over unidirectional CFRP plates show a moderate variation in tensile strength values, with a value of $m = 25$ [23].

When designing structural components in aviation, different factors of safety must be considered in order to guarantee the reliability of aircraft structures. This safety factor *s* can be defined as [24]:

$$(2) \qquad s = \frac{\text{material strength}}{\text{applied load to the structure}}$$

Considering the Weibull distribution introduced above, the probability P_t that the safety factor is violated by strong variations in the material's inherent tensile strength can be expressed by:

$$(3) \qquad P_t = 1 - \exp\left[-\left(\frac{1}{s}\right)^m\right]$$

The safety factor given by the Federal Aviation Regulation (FAR) in 1964 for aircraft structures is $s = 1.5$ [25]. Note that this factor was originally introduced to prevent failure of a designed structural component due to unforeseeable overloads, such as gusts or impact damage. Referring to traditional construction materials, the quality (here, more specifically, the tensile strength) of the material itself was implicitly assumed to be sufficiently homogeneous between specimens (*i.e.*, high values of *m*).

In the present context, however, we employ the safety design margin quantified by *s* to determine P_t: Uncontrollable variations in the material's tensile strength are treated as the reason for unforeseeable overloads, leading to structural failure in individual specimens, even if a safety factor of 1.5 has been used in component design. Assuming that the probability of transgressing the safety factor has to be in dimensions of $P_t = 10^{-3} - 10^{-9}$, it then follows that m should at least be in a range of m = 17 - 51.

3.2.2. Variations in Young's Modulus

In the experimental determination of a material's Young's Modulus, the value of E measured will be slightly different for each sampling process due to small differences in the experimental setup and calibration. These little variances can be captured by the calculation of statistical errors. If the statistical variations are appropriately accounted for in the design, they will not result in unreliability issues of the resulting components.

Another difficulty, however, are variations in E due to the different quality of production batches. This is an important point in particular for new fiber-reinforced construction materials like CFRP and is likely to be significant for new sustainable materials as well.

In order to capture this issue, a similar statistical approach as was used for the maximum tensile strength above can be applied to variations in E. In strict analogy to the discussion of Section 3.2.1, a critical material-specific Weibull Modulus with respect to the Young's Modulus (m_E) can be shown to be in the range of m_E = 17 - 51.

3.3. Criteria of Sustainability

Sustainability is a frequently used term nowadays. Unfortunately, it is not sharply defined and the interpretation of its meaning depends on the context in which it is used. A commonly accepted but rather unspecific understanding of the meaning of sustainability has been stated by the Brundtland Commission of the United Nations in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [26]. In the 2005 World Summit Outcome the metaphor of the three pillars of sustainability has been formulated, *i.e.*, emphasizing "the economic, social and environmental aspects" of sustainable development [27].

Due to the lack of an accurate definition and the commonly rather vague understanding of its meaning, the sustainability of a product or a process is difficult to measure. Currently, various sustainability indicators, sustainability standards and certification schemes have been developed, each distinguished by its own focus, criteria and/or metrics.

It is out of the scope of this paper to develop a framework for the general and holistic assessment of a material's sustainability. The idea is rather to implement only selected criteria that can be quantified through clearly defined metrics and that are most relevant for the assessment of the potential of alternative materials with respect to aircraft design.

In order to select sustainability metrics, relevant for this purpose, it is helpful to reconsider the drivers for the search for alternative (particularly renewable) construction materials. As mentioned in the Introduction, this search is mainly motivated by the requirement to reduce the aviation sector's environmental impact, which can comprehensively be captured by the *carbon footprint* and *energy efficiency*, as well as the production *costs*.

Since these three criteria are the main drivers for a sustainable development of aviation to date, we decide to select them for a short assessment in this work.

Note that we select only criteria related to economic or ecological aspects of sustainability. Importantly, this selection by no means implies that social aspects of sustainability are less important. However, the scope of this work is the assessment of materials and general production procedures. While certain economic and ecological aspects of sustainability can be attributed at this level of assessment, in our understanding social aspects rather come into play when specific production chains (*i.e.*, with specific locations, involved companies and factories etc.) are to be assessed.

A similar argument is valid for other factors like water demand, acidification and human-toxicity.

3.3.1. Carbon Footprint

The carbon footprint can be defined as "the total amount of CO_2 and other greenhouse gases over the full life cycle of a process or product" [28]. This includes the balancing of all life cycle stages of a material including the manufacturing, use and end of life. Apart from CO_2, other gases like methane are also taken into account since they also have a significantly impact on global warming.

Our final goal is the comparison, and short assessment of suitable materials at an initial stage. Therefore we limit the consideration of the carbon foot printing to the production of raw materials.

With this restriction it follows that producing 1 kg CFRP releases 33 - 36 kg CO_2 to the atmosphere [29]. In contrast, the carbon footprint of raw-aluminum is obviously lower (1.19 kgCO_2/kg) [30]. This shows that the margin of CO_2 emission to date is commensurately high.

3.3.2. Energy Efficiency

The energy efficiency in the context of our study is defined by the energy, which is required for producing 1 kg raw material. This energy demand can also be called "embodied energy" [29].

The energy efficiency is the second sustainability metric used to quantify the ecological impacts. As a high energy demand for producing raw materials is also reflected in production costs, the energy efficiency can in a second step be interpreted as an economic assessment parameter as well.

In the fabrication of 1 kg raw aluminum, the amount of the required energy is 109.4 MJ [30]. In addition, the energy efficiency of CFRP is, in a primary production, up to 500 MJ/kg [29]. In comparison to the carbon footprint the gap between aluminum and CFRP is manageable.

3.3.3. Production Costs

According to our understanding, a business case is economically sustainable if the margins are profitable for investors and, at the same time, wages for workers, technical and administrative staff etc. are sufficient for an adequate living. The profitability must be ensured along the entire value chain and for all stakeholders (worker as well as investors).

An indicator for the economic sustainability of a product according to this notion the production cost. If they are calculated covering the entire production chain, including appropriate payment of employees and considering internationally recognized environmental and social obligations as well as profitable margins for intermediate products, the production costs (in relation to the market price of the evaluated product) represent a suitable metric for the assessment of its economic sustainability.

Apart from sustainability-related issues, aircraft are commercial commodities in a highly competitive market. Therefore, production costs represent an extremely important criterion that is always in the focus of discussion, whenever new or novel technologies are considered for implementation in civil aviation.

Regarding the two structural materials CFRP and aluminum alloys, a huge gap between the market price of raw aluminum (*i.e.* 2.4 \$/kg) and CFRP (40 - 44 \$/kg) exists [29], which can be taken as a first indication to the different material production costs.

4. FRAMEWORK BOUNDARIES

Within the metrics selected in Section 3, we now recapitulate the respective ranges identified for the different assessment criteria (Table 2).

Table 2: Decision Matrix Parameter Ranges

Criterion	Min	Max
E (GPa)	70	140
σ (MPa)	440	2000
ρ (g/cm³)	1.4	2.9
m	17	51
m_E	17	51
CO_2/kg	1.19	36
MJ/kg	109.74	500
\$/kg	2.4	44

In Table 2, the upper and lower boundaries of the particular criteria are defined. In further works, a scoring system and weighting factors have to be introduced in order to evaluate possible material candidates with the assessment matrix method. Nevertheless, a first sighting will now show, if the selected fiber candidates, namely natural fibers and lignin-based carbon fibers, can meet these constraints and hence give a first hint of their suitability in sustainable airborne applications.

5. THE EXAMPLE OF RENEWABLE FIBERS

With the acceptable parameter boundaries of the assessment framework established (see Section 4), we now put the framework to use by applying it to potentially renewable high performance fiber alternatives discussed to date.

To this purpose, we concentrate on the fibers only because they carry the main loads when fiber-composite sample is under stress. The resin matrix of the composite, into which the fibers are embedded, does not accept as much stress, and is therefore of secondary interest for now.

5.1. Natural Fiber Composites

In any discussion of sustainable lightweight materials, among the first options which have to be highlighted are natural-fiber composites (NFCs). These composites are made from natural fibers embedded into a matrix of conventional or, possibly, biogenic polymers. The latter composites are so-called “bio- or green-composites” [31, 32].

The embedded natural fibers can be derived from plants, animals or minerals. Among these, plant fibers seem to exhibit some benefits compared to the other classes due to their mechanical properties, the possibility of mass-producing them (*i.e.*, the scalability of the process) and their potential for CO_2 reductions [33].

In the automotive sector, NFCs are today used for structures such as hat-racks or other interior components. The dominant natural fiber types used here are made of flax, hemp or jute [34]. In these applications, however, load-bearing components are still made from conventional materials. The future potential of integrating NFCs into automobile construction is predominantly as a replacement of GFRP by a more sustainable material [35].

5.2. Lignin-Based Carbon-Fibers

Another option of producing sustainable composites is to use lignin as basis for carbon fibers. Lignin is, besides cellulose and hemicelluloses, a natural constituent of wood, in which the content of lignin is about 20-30 % [36]. In paper milling, cellulose and lignin are separated by chemical processes (*i.e.* Kraft, Organosolv, Alcell, etc). Thereby, waste lignin is accumulated in great quantities [37]. Because of the high world-wide demand for cellulose products, the undesired side products lignin could become an attractive feed-stock available at low cost [7].

The approach to produce carbon fibers from different biogenic precursors has been explored since the end of the 19th century [38], but progress in this domain has sometimes been difficult. For the particular case of lignin-based carbon fibers (LBCF), first research activities started in the early 1990ies [39], and in the last ten years, further investigations have been conducted to optimize the processes and the fibers’ mechanical properties [7, 37, 40, 41]. To date, however, there is still no commercial use of LBCF, but first lightweight applications like rotor blades for wind mills were sighted [42].

5.3. Qualitative Assessment and Discussion

Evidently, the quality and usefulness of any evaluation using the assessment matrix method strongly depends on the amount of data available on each alternative: If one has access to a more extensive data inventory, the conclusions found from the assessment matrix will be more decisive. For this paper, we have collected data on the Young’s Modulus E, the maximum tensile strength $\sigma_{m,}$ the mass density ρ, m, the energy efficiency, the carbon footprint and the market price for the two discussed sustainable material candidates. In Table 3 miscellaneous data for hemp, flax, jute and lignin-based carbon fibers are listed.

Table 3: Selected Values for a Short Evaluation

Criteria	Natural Fibers	LBCF	References
E (GPa)	26 - 70	40 - 61	[31, 39-41]
σ (MPa)	345 - 1035	660	[31, 39]
ρ (g/cm³)	1.3 - 1.5	n.a.[1]	[31]
m	1.19 - 2.24	3 - 10	[43-45]
CO_2/kg	0.29 - 1.4	24	[29, 46]
MJ/kg	9.5 - 33	670	[29, 46]
$/kg	0.35 - 4.2	0.3	[29, 36]

With the help of this database, we are now able to discuss the two alternative materials, natural fibers (NF) and LBCF, and perform a short evaluation of the alternative fibers using a soft (+, o, -) scoring system.

A first observation from Table 3 is that the mechanical properties E, σ_m and ρ, of natural fibers seem sufficient for structural applications when benchmarked against the assessment matrix constraints introduced in Section 4. However, it has to be noted that these properties deteriorate when the fibers are immerged into the polymer resin composite matrix. For this reason, natural fibers are given a score of “o” with respect to mechanical evaluation criteria.
Regarding criteria of reliability, renewable fiber composites with NF face a tough challenge: The scattering of their tensile strengths, expressed in terms of the *m* leads to a problematical variation in mechanical properties between different samples. The extremely low *m* implies that, considering the probability P_f defined in Eq. (3), more than every 10th sample must be expected to fail, even if a safety factor of 1.5 is implemented in the design. Consequently, to make the use of these fiber composites for future structural applications feasible, two avenues may be pursued: Either the design margins have to be significantly increased for these materials, or the variation of their mechanical properties must be restricted (*i.e.* the value of *m* augmented) by further research and development. With respect to our soft evaluation scheme, reliability criteria are therefore scored negatively with a “-“.
Finally, with respect to sustainability, we can assert a significant advantage of NF over conventional carbon fibers and lignin-based carbon fibers because of their comparatively low CO_2 emissions, the small energy demand and the low market price compared to CFRP. Hence, natural fibers are scored with “+” in this category.

Lignin-based carbon fibers also can be shown to have adequate mechanical properties, although E is somewhat below the benchmark set in Table 2. Analog to NF, a decrease in E and σ must be expected when embedding LBCF into resin matrix materials. As for NF, a neutral score “o” is chosen for LBCF.

Regarding the scattering of mechanical properties for different samples, LBCF exhibit moderate variance. Still, their *m* is significantly below the margins set in section 3.2. A negative (“-”) score is therefore attributed to LBCF.
With respect to the category of sustainability, the commensurately high carbon footprint and energy demand associated with the production of LBCF is a disadvantage, which, however, has to be balanced with the relative low production costs. This leads in summary to another “0“ score.

For completeness, let us also conduct a short assessment of CFRP. Because of their good mechanical properties which are taken as upper boundaries of the mechanical properties in Section 3.1, we decide on a “+” in this category. Since the values of *m* are in the middle range of the required values, a “o” is an adequate score with respect to reliability. The production of CFRP uses a lot of energy and causes high CO_2 emissions. Combined with the high production costs and the fact, that conventional carbon fibers were made of non renewable precursors, this gives the CFRP a “-” in the sustainability category.

Summarizing the different fibers and criteria, the result of the qualitative assessment can be seen in Table 4:

Table 4: Qualitative Assessment of Carbon-Fiber Reinforced Plastics (CFRP), Natural Fibers (NF) and Lignin-Based Carbon Fibers (LBCF).

	CFRP	NF	LBCF
Mechanics	+	0	0
Reliability	0	-	-
Sustainability	-	+	0

This brief outlook shows that all discussed fibers have their advantages and disadvantages. Referred to at least one of the three classes, mechanics, reliability, and sustainability, all discussed fibers need for exceedingly progresses before applying them with no curtailment in one of these issues.

6. DEFINING AND IDENTIFYING A NOVEL CLASS OF RENEWABLE FIBERS

To date, the implementation of sustainable and simultaneously load-bearing fiber composites seems to be a challenging issue. Without the need for a quantitative assessment, the qualitative assessment of Table 4 shows that either the materials in use are derived from non-renewable precursors, or renewable fiber-composites offer still a poor performance than the conventional ones. Therefore, none of the options discussed in this study resolves the pre-decision conflict for renewable fiber in high-performance applications.
Regarding the sustainable lightweight materials, two examples of the standard assumptions are, firstly, that “renewable alternatives” are often taken synonymously with bio-derived materials, and secondly, that bio-derived fibers for fiber-reinforced plastics are often expected to be inferior in performance. Both these examples show a tacit acceptance of presumptions that may turn out to be a

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[1] No data available. Due to the similarly atomic composition and microstructure of LBCF, it can be assumed that the density is in the margin of conventional carbon fibers.

limitation to identifying radically new innovation potentials.

However, the value-focused approach to multiple-criteria assessment framework does not exclude the possibility that further alternatives do exist. In order to tackle this problem we first postulate that there must be a third option that satisfies the criterion we call “loom-in” capability, and then identify essential properties of this solution.

The idea of “loom-in” capability is coupled to the technology of alternative fuels, where the term “drop-in” capability guarantees that high-performance standards are met even for renewable alternatives. A “drop-in fuel blend” can be defined as “a substitute for conventional jet fuel, that is completely interchangeable and compatible with conventional jet fuel when blended with conventional jet fuel […]” [47]. In analogy, it follows that a renewable fiber is “loom-in capable” if it can be blended with conventional carbon fibers in any ratio, even 100%, with no impact on the further manufacturing and use of a CFRP product.

An example for “drop-in” capable alternative fuels is the “biomass-to-liquid” (BTL) production path for kerosene. Bio-derived synthesis gas is fed into a Fischer-Tropsch process to produce synthetic kerosene that has reached a 50%-blend certification for substitution of fossil kerosene [48]. Using this analogy, we may think of a production path of processing biomass to “loom-in” fibers. One radical example for a “loom-in” fiber (LIF) would be the replacement of petrol-based polyacrylonitrile by an alternatively produced one. The alternative resource of these chemicals may be of biological origin.

Furthermore, carbon, and hydrogen may be derived from aerial carbon-dioxide and water, just as renewable “drop-in” fuels are now being developed from tapping into these sources without bio-photosynthesis [49-51]. According to this development, there is a strong indication that, firstly, “high-performance” carbon fiber may as well be derived from biological sources and secondly, that “renewable alternatives” for carbon fibers may also originate from aerial carbon-dioxide without the need of biological photosynthesis.

However, there might be other suitable fiber-feedstock, precursors and manufacturing processes still to be investigated. In any case, there is, due to the complex multidimensional parameter space, a need for a suitable assessment framework. To this purpose, this study has given a selection of metrics and a first short assessment of sustainable fiber candidates.

7. CONCLUSIONS AND OUTLOOK

Efforts to prepare the aviation sector for future economic and ecological challenges will only be successful if the issues of economic growth and sustainability are addressed together. A comprehensive approach to this twofold problem must include the search for renewable alternatives to fossil resources. Evidently, the huge demand for carbon-based fuel (kerosene) is to a large extent responsible for the contribution of aviation to the pillage of non-renewable resources, and substantial research efforts a dedicated to identifying suitable replacements. In this paper, our goal was to raise awareness for the additional fossil resource dependence of aviation due to some of its popular lightweight construction materials such as CFRP, which also rely on petrochemicals as feedstock. We first presented some guidelines how potential alternative construction materials might be evaluated, introducing the multiple-criteria assessment matrix as a tool. In a second step, we conducted a first evaluating overview on two examples of renewable fibers, namely natural fibers and lignin-based carbon fibers, both of which are discussed as sustainable replacements for conventional carbon fibers in CFRP composites.

In establishing the assessment framework for future renewable materials, our approach has addressed three categories of criteria: First, if they are to be used in the design of load-bearing structures, sufficient *mechanical properties* must be stipulated for these materials. Second, one must ensure their *reliability* in the sense that deviations from the required mechanical properties are exceedingly rare. Third, the question of their *sustainability* must be posed. Note that, while a complete sustainability assessment rests on the three pillars of economic, ecological and sociological sustainability, in this first step we have not considered the latter aspect.

For all of these categories, suitable metrics for a future quantitative assessment were then identified, such as e.g. the Young’s Modulus and maximum tensile strength as examples of important structural material properties. The acceptable parameter ranges for each metric were inferred from the properties of the state-of-the-art materials used in aircraft structural components today. The application of the thus established assessment framework to natural fibers and to lignin-based carbon fibers lead to the interesting result that each fiber achieved a favorable score in one of the three categories. However, at their present level of development, no overall best alternative – in the sense of combining all criteria into an assessment matrix – could be identified.

Finally, drawing inspiration from the much further developed research field of alternative (potentially renewable) fuels, we have suggested to introduce the notion of “Loom-In Capability” for alternative fibers: Much like “drop-in capable” fuels, which are defined to be infinitely blendable and fully compatible with conventional kerosene, a “loom-in capable” fiber should be completely and in any ratio exchangeable with conventional carbon fibers at any step in the composite manufacturing process. This value-focused approach led to the identification of new production pathways for high-performance carbon fibers from renewable resources that are expected to meet all main criteria and that will be the subject of future research.

References

[1] Airbus A350xwb web page, "*www.a350xwb.com*," 20.8.2013.

[2] European Union, “*Flightpath 2050 Europe ’ s Vision for Aviation*,” 2011.

[3] C. Endres, C. Falter, A. Roth, F. Riegel, and A. Sizmann, “Renewable Aviation Fuels – Assessment of Three Selected Fuel Production Pathways," in *Proceedings of the 61. Deutscher Luft- und Raumfahrt Kongress,* 2012.

[4] H. Kuhn, C. Falter, and A. Sizmann, “Renewable Energy Perspectives for Aviation,” in *Proceedings of the 3rd CEAS Air & Space Conference and AIAA Congress Venice*, 2011, pp. 1249-1259.

[5] H. Kuhn and A. Sizmann, “Fundamental Prerequisites for Electric Flying,” in *Proceedings of the 61. Deutscher Luft- und Raumfahrtkongress, 2012*

[6] A. T. Isikveren, A. Seitz, P. C. Vratny, and C. Pornet, “Conceptual Studies of Universally-Electric Systems Architectures Suitable for Transport Aircraft,” *Proceedings of the 61. Deutscher Luft- und Raumfahrt Kongress,* 2012.

[7] G. Gellerstedt, E. Sjöholm, and I. Brodin, “The Wood -Based Biorefinery: A Source of Carbon Fiber?,” *The Open Agriculture Journal*, vol. 3, pp. 119-124, 2010.

[8] M. Zeleny, "*Multiple Criteria Decision Making*," McGraw-Hill, New-York, 1982.

[9] B. F. Hobbs and P. Meier, "*Energy Decisions and the Environment*," Kluwer Academic Publishers, Norwell, 2000.

[10] R. L. Keeney, “*Value-Focused Thinking*,” Harvard University Press, Boston, 1992.

[11] S. Naundorf, A. Roth, C. Endres, and A. Sizmann, “Alternative Fuels for Aviation : Progress , Prioritization and Perspectives,” in *Proceedings of the 60. Deutscher Luft- und Raumfahrt Kongress,* 2011.

[12] L. Y. Ljungberg, “Materials Selection and Design for Development of Sustainable Products,” *Materials & Design*, vol. 28, pp. 466-479, 2005.

[13] M. F. Ashby, Y. J. M. Brechet, D. Cebon, and L. Salvo, “Selection Strategies for Materials and Processes," *Materials and Design*, vol. 25, pp. 51-67, 2004.

[14] M. F. Ashby, *Materials Selection in Mechanical Design*, Butterworth-Heinemann, Oxford, 2011.

[15] J. C. Halpin and J. L. Kardos, “The Halpin-Tsai Equations: A review,” *Polymer Engineering and Science*, vol. 16, no. 5, pp. 344-352, 1976.

[16] www.matweb.com, “Datasheet Aluinum AA 2024 T3,” *3.7.2013.*

[17] R. Kleinholz, V. Mathes, and E. Witten, Eds., "*Handbuch Faserverbundkunststoffe*," AVK-Industrievereinigung Verstärkter Kunststoffe, Frankfurt am Main, 2010.

[18] M. C. Y. Niu, “Laminate Design Practices,” in *Composite Airframe Structures*, Conmilit Press Ltd, Hong Kong,1992.

[19] H. Jäger and T. Hauke, "*Carbonfasern und ihre Verbundwerkstoffe*," Bibliothek der Technik, Verlag Moderne Industrie, München, 2010.

[20] P. R. Teagle, “The Quality Control and Non-Destructive Evaluation of Composite Aerospace Components,” *Composites*, vol. 14, no. 2, pp. 115-128, 1983.

[21] T. H. Courtney, "*Mechanical Behavior of Materials*," McGraw-Hill, Singapore, 2000.

[22] J. Rösler, H. Harders, and M. Bäker, "*Mechanisches Verhalten der Werkstoffe*," Vieweg und Teubner, Wiesbaden, 2003.

[23] M. R. Wisnom, “The Effect of Specimen Size on the Bending Strength of Unidirectional Carbon Fibre-Epoxy,” *Composite Structures*, vol. 18, no. 1, pp. 47-63, 1991.

[24] E. F. Bruhn, “Practical Strength Analysis & Design of Structural Components,” in *Analysis and Design of Flight Vehicle Structures*, Jacobs Publishing, Inc, Indianapolis,1973.

[25] “Federal Aviation Regulations,” vol. 25, §23.729, 1964.

[26] Report of the World Commission on Environment, “*Towards Sustainable Development*,” From A/42/427: Our Common Future.

[27] United Nations General Assembly, Resolution A/60/1, World Summit Outcome, 2005.

[28] Parliamentery Office of Science and Technology, “Carbon footprint of electricity gerenation,” *Carbon*, no. 383, pp. 1-4, 2006.

[29] M. F. Ashby, "*Materials and the Environment*," Butterworth-Heinemann, Oxford, 2013.

[30] Datenblatt zur Ökobilanz von Primäraluminium in Europa im Bezugsjahr 2004, www.*probas.de*, 20.8.2013

[31] O. Faruk, A. K. Bledzki, H.-P. Fink, and M. Sain, “Biocomposites Reinforced with Natural Fibers: 2000-2010,” *Progress in Polymer Science*, 2012.

[32] J. M. Chard, G. Creech, D. A. Jesson, and P. A. Smith, “Green Composites: Sustainability and Mechanical Performance,” *Proceedings of the 18th International Conference on Composite Materials*, 2009.

[33] M. Saxena, A. Pappu, A. Sharma, R. Haque, and S. Wankhede, “Composite Materials from Natural Resources: Recent Trends and Future Potentials,” *InTechOpen*, 2011.

[34] T. G. Schuh, “Renewable Fibes for Automotive Applications," *www.ienica.net/fibresseminar/schuh.pdf*, 2004.

[35] S. V. Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, “Are Natural Fiber Composites Environ-Mentally Superior to Glass Fiber Reinforced Composites?,” *Composites: Part A*, vol. 35, pp. 371-376, 2003.

[36] I. Norberg, “Carbon Fibres from Kraft Lignin,” PhD Thesis, KTH Royal Institute of Technology, Stockholm, 2012.

[37] J. Luo, “Lignin-Based Carbon Fiber,” Master Thesis, University of Maine, 2010.

[38] T. A. Edison, “Manufacture of Filaments for Incandescent Electronic Lamps,” *U.S. Patent 470,925*, 1892.

[39] K. Sudo and K. Shimizu, “A New Carbon Fiber from Lignin,” *Journal of Applied Polymer Science*, vol. 44, pp. 127-134, 1992.

[40] J. F. Kadla, S. Kubo, R. A. Venditti, R. D. Gilberst, A. L. Compere, and W. Griffith, “Lignin-Based Carbon Fibers for Composite Fiber Applications,” *Carbon*, vol. 40, pp. 2913-2920, 2002.

[41] S. Kubo and J. F. Kadla, “Lignin-based Carbon Fibers : Effect of Synthetic Polymer Blending on Fiber Properties,” *Polymers and the Environment*, vol. 13, no. 2, 2005.

[42] “http://www.innventia.com,” *6.8.2013.*

[43] Y. Nordström, R. Joffe, and E. Sjöholm, “Mechanical Characterization and Application of Weibull Statistics to the Strength of Softwood Lignin-Based Carbon Fibers,” *Journal of Applied Polymer Science*, pp. 1-9, 2013.

[44] Z. P. Xia, J. Y. Yu, L. D. Cheng, L. F. Liu, and W. M. Wang, “Study on the Breaking Strength of Jute Fibres Using Modified Weibull Distribution,” *Composites Part A*, vol. 40, no. 1, pp. 54-59, 2009.

[45] I. M. D. Rosa, M. Kenny, D. Puglia, C. Santulli, and F. Sarasini, “Tensile Behavior of New Zealand Flax (*phormium tenax*) Fibers,” *Journal of Reinforced Plastics and Composites*, pp. 1-5, 2010.

[46] S. Das, “Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites,” *International Journal of life cycle Assesses*, vol. 16, pp. 268-282, 2011.

[47] CAAFI, “http://www.caafi.org/resources/glossary.html,” *30.7.2013.*

[48] ASTM Standard D7566, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," ASTM International, West Conshohocken, 2013

[49] W.C. Chueh, C. Falter, M. Abbott, D. Scipio , P. Furler, S. M. Haile, A. Steinfeld,“High-Flux Solar-Driven Thermochemical Dissociation of CO_2 and H_2O using Nonstoichiometric Ceria,” *Science*, vol. 330, pp. 1797-1801, 2010.

[50] W. C. Chueh and S. M. Haile, “Ceria as a Thermochemical Reaction Medium for Selectively Generating Syngas or Methane from H_2O and CO_2,” *ChemSusChem*, vol. 2, pp. 735-739, 2009.

[51] Solar Chemical Reactor Demonstration and Optimization for Long-term Availability of Renewable JET fuel,“European Collaborative Research Project SOLAR-JET,” *FP7-AAT-2011-RTD-1, GANo. 285098*, 2011.