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FUTURE AIRCRAFT WING STRUCTURES USING RENEWABLE MATERIALS

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Abstract

Ambitious targets for the reduction of CO_2, the pursuit of independence from fossil resources and the demand for cost control has driven efforts to search for raw materials from renewable resources. In general, polymer composites reinforced with endless fibers offer good mechanical properties and their low densities, which make them ideal candidates for lightweight design. Advanced fiber composites made from regenerative resources would therefore contribute to lower fuel-burn in operation because of reduced weight and additionally have the potential to decrease the overall carbon footprint of the aircraft. However, alternative materials lack in mechanical properties, and usually do not meet reliability requirements. In a previous investigation a method including non-linear deformation and critical sizing check for maximum maneuver, gust, roll and buckling loads for the structural design of a defined conventional wing was used for wing mass calculations. This introductory study showed that some composites with natural fibers could represent alternative materials for aircraft design. In the present work, a future wing design for a single-aisle aircraft consisting of an in-plane cantilevered slender wing made of selected sustainable materials is assessed regarding wing weight and other critical aircraft related aspects. In a first aircraft level assessment, using the Airbus A320neo as reference, one of the selected sustainable materials leads to an outcome comparable to carbon fiber reinforced polymer with epoxy matrix in terms of aircraft performance increase.

1. NOMENCLATURE

Acronyms

AR	*Aspect Ratio*
CF	*Carbon Fiber*
CFRP	*Carbon Fiber Reinforced Polymer*
CO_2	*Carbon Dioxide*
FEM	*Finite Element Method*
MTOW	*Maximum Take-Off Weight*
NCF	*Nanocellulosic Fibers*
NF	*Natural Fibers*
OWE	*Operating Weight Empty*
PAX	*Passenger*
PLA	*Polylactic Acid*

Symbols

b	*wingspan (m)*
C	*Aerodynamic coefficient (-)*
E	*Elastic modulus (GPa)*
G	*Shear modulus (GPa)*
e	*Oswald efficiency number (-)*
m	*mass (kg)*
ρ	*Density (kg/m³)*
S	*Wing area (m²)*
σ	*Yield stress (MPa)*

Subscripts and Indices

Di	*Vortex-induced drag*
D0	*Zero-lift drag*
L	*Lift*
y	*Axis direction*

2. INTRODUCTION

In the last decades the awareness for the environment, climate changes and the limitation of fossil resources increased. Aspects of ecological sustainability came more into focus of research and development, leading to sustainability targets in aviation formulated by the European Commission [1] and the International Air Transport Association [2]. The spotlight there is on better fuel efficiency of air vehicles, which also includes an improved, lightweight design of the vehicle structure. A further step beyond these goals is the application of lightweight high-strength materials from renewable resources.

The use of renewable raw materials reduces the dependency on fossil resources and on their price volatilities. Furthermore, when considering the environmental impact, materials based on renewable resources can be advantageous; their carbon footprint (i.e. the total amount of Carbon Dioxide (CO_2) that goes with the production, use phase and end-of-life) is reduced, because plants grow by absorbing carbon in form of CO_2 from the atmosphere, thus sequestering carbon. When renewables-based materials are produced, this carbon is withdrawn from the atmosphere for the duration of the whole use (and re-use) phase of the component and can be recycled in closed loops. Note that sustainable materials can (hypothetical) complementary be produced from non-biogenic feedstock as CO_2 as well [3].

However, sustainability of a material is not only dictated by its feedstock but has to be determined along the whole life-cycle (production, use-phase, end-of-life-phase) of a structural component.

The idea of using materials based on renewable feedstock for aircraft wings was first presented in [4]. In summary, the potential of a possible weight reduction has been demonstrated for one natural fiber composite, consisting of ramie fibers and a matrix of polylactic acid (PLA) for a state-of-the-art wing.

However, in order to increase the aerodynamic efficiency of the wing and to reduce the fuel burn of the aircraft the current wing design needs to be revised. One alternative to increase aerodynamic efficiency of the wing is to proceed to high aspect ratio wings, which exhibit an increased wingspan and a decreased wing chord. For example, the next generation of the Boeing 777 wide-body aircraft will have an increased wingspan of around 10% compared to the former version [5].

The aim of the present paper is to investigate, if such a future wing with better aerodynamic efficiency might be implemented with the application of light-weight material that is made entirely of renewable resources. Possible future wing layouts with high Aspect Ratios (ARs) are discussed that may be a feature of a future narrow-body aircraft. The investigated wing designs are dimensioned with a computational tool to estimate the wing weight, which also depends on the used material properties.

Furthermore, a first assessment at aircraft level for a possible narrow-body aircraft with new wing designs is conducted and compared to the Airbus A320neo as reference [6]. The assessment shows the influence of the selected wing layout, i.e. aerodynamic performance, wing weight and design weight, on block fuel for a given mission.

3. MATERIALS

Materials made from high-strength endless fibers (in the form of fabrics) embedded in a polymeric matrix are advantageous when aiming at high strength to density ratios. Therefore such composites based on carbon fibers and thermosetting matrices like epoxy resin found broad application in lightweight structures. The targeted reduction of CO_2 and other climate-damaging anthropogenic gases requests the use of lightweight vehicles in order to increase fuel efficiency. Today, both fibers and matrices are based on petrochemical feedstock. Regarding sustainability over the whole life-cycle, alternative resources should be discovered; furthermore, increased independence from fossil resources is desirable to reduce dependence from price volatilities and shortages in supply. We therefore seek materials that can be produced from renewable feedstock.

Composites consisting of natural fibers were analyzed for conventional wing structure in a previous study [4]. The use of a quasi-isotropic composite of ramie-fibers and polylactic acid (PLA) for an aircraft wing indicated a potential weight reduction. PLA is based on lactic acid, which can be synthesized from starch. It is a common biological thermoplastic with the ability of being biodegradable. Belonging to the class of thermoplastics, it can be molded and more easily processed and also recycled than thermosets. As a matrix material for composites thermoplastics are already used in automotive, their application for aviation structures are under investigation [7]. Unfortunately the mechanical properties of PLA are rather poor. However, they can be enhanced by addition of nanocellulosic fibers (NCF). Cellulose is the main constituent of vegetable cell walls, accounting for structural stability. Nanocellulosic fibers can be obtained from any cellulose source material like woodpulp or cotton. It could be demonstrated that admixtures of 1 to 3 wt% nanocellulose to PLA can be advantageous for the mechanical performance [8]; by adding more, the Young's Modulus further increases, but the materials become very brittle and strength is not positively affected.

Conventional fiber composites for aircraft structures are made of another class of polymers, the thermosets. These polymers are typically resins that solidify after chemical reaction. Thus processing routes are completely different from thermoplast composites and typically involve curing, which requires time, and defined pressurisation. Epoxy resins are resistant against environmental degradation and have mechanical properties that make the resin system especially attractive to the aircraft industry. However, at present the substitution of epoxy constituents for sustainable alternatives succeeded only to some extent. This is the reason why we opted for another thermoset system: phenolic resins. They exhibit excellent fire, smoke and toxicity properties and are therefore often the resin of choice in interior components. There exist various phenolic systems, but all involve a chemical reaction of phenol and an aldehyde during production. Phenol can be derived from renewable resources, e. g. lignin or tannin [9]. A commonly used aldehyde with good properties for production is formaldehyde, a highly volatile and toxic organic compound. Therefore recent research focuses on the use of other aldehydes like glyoxal [10] or furfural [8, 10]. Both can also be obtained from natural sources.

The matrix of a fiber composite determines the geometrical shape of the component and its overall durability, but structural loads are carried mainly by the reinforcing fibers. Stiffness and strength of the composite are thus dominated by the choice of fibers.

Concerning fibers from plants, ramie fibers show very good mechanical properties at low density. Like any vegetable fibers they also have some major disadvantages, like variation in physical properties depending on growth, harvest and processing conditions, sensitivity to moisture and their hydrophilic nature, which makes the incorporation into polymeric matrices difficult. Still, after suitable modifications [12] they have great potential as natural reinforcing fibers in composites.

At present the reinforcement of choice for lightweight and high-strength applications is carbon fiber (CF). They are based today on petrochemical raw materials, however, the base chemicals also can be produced from natural resources [13]. Thus bio-based carbon fibers are a second option of reinforcement for the present study; we postulate that these naturally derived CF have similar mechanical and physical properties as conventional ones. One key step towards such fibers is the replacement of petrochemically derived acrylonitrile (the precursor block-chemical of conventional carbon fibers) by a renewable precursor. For instance, acrylonitrile can be synthesised from glycerin that is obtained during the production of biodiesel or from synthesis gas that forms during the gasification of biomass. The analysis and assessment of these alternative production pathways is part of future studies.

For calculating the mechanical properties of the used composite, the main parameters like Young's Modulus E, the yield strength σ_y and the density ρ for selected matrices and fibers are given in Table 1.

Table 1: Material characteristics of naturally derived fiber and matrix materials used in the present study (Data from 1: [14], 2: [15], 3: [8], 4: [16]).

	E (GPa)	*σ_y (MPa)*	*ρ (kg/m³)*
Fiber Material			
Ramie [1]	44	612	1450
Carbon fiber [2]	230	3530	1760
Matrix Material			
PLA + 3wt% NCF [3]	1.20	33	1220
Novolac furfural phenolic resin [4]	3.18	50	1250

From these material data mechanical parameters for the composite material were calculated, supposing 60% fiber content. The method is described in [4].

Fiber composites are inherently highly anisotropic, with properties in fiber direction differing much from parameters perpendicular to the fibers. Combining several fiber plies with varying orientation angles to a laminate, however, can result in a quasi-isotropic material, which is the best choice for a multi-axle stress state. The mechanical properties of this material are estimated by employing the "10% rule" investigated by Hart-Smith, assuming that each composite ply contributes only 10% to the overall strength and stiffness of the composite except for the plies that have the fibers oriented in direction of the load [17].

Results for mechanical parameters for the composite laminates are shown in Table 2, together with parameters for the reference materials conventional carbon fiber reinforced polymers (CFRP) (epoxy resin with carbon fibers) and an aluminium alloy of the 6000-series. The laminate build-up was chosen to be symmetric [0°/+45°/90°/-45°/0°], with equal amounts of plies (25% each) in each direction. The wing mass was evaluated for all given materials.

Table 2: Ramie-fiber and carbon fiber (CF) composites input parameters and data for conventional CFRP (Ref1) and aluminium (Ref2: Data from [18]) for wing mass calculations.

Material	*E GPa*	*G GPa*	*σ_y MPa*	*ρ kg/m³*
PLA+3%NCF/Ramie	8.7	5.5	124	1357
PLA+3%NCF/CF	40	27	540	1573
Phenolic Res./CF	42	27	543	1586
EpoxyRes./CF (Ref1)	75	47	550	1576
Al 6061 T6 (Ref2)	69	26	276	2700

4. WING MASS CALCULATION

In order to determine the wing weight of a possible future wing layout a MATLAB program was used [18, 19]. The method of the program works as follows: The vortex lattice method, namely "Tornado" [21], is used to calculate the aerodynamic forces on a wing, which are defined by the user. The aerodynamic forces must be high enough to produce sufficient lift to bear the assumed aircraft weight in the given flight state. Then the aerodynamic forces are applied on a Finite Element Method (FEM)-beam model that represents the load bearing structure, i.e. the skin, spars and stringers, of the wing. Through the applied forces the FEM-beam is deformed. The wingbox is dimensioned according to the deformation. The deformed wing leads to new aerodynamic forces that cause new wing deflection. This iterative process is carried out until the wing structure is dimensioned for the corresponding load. Hence, the weight of the wing can be estimated. Figure 1 displays the grid for the calculation of the aerodynamic forces, which is used in "Tornado", and the FEM-beam model. Figure 2 shows the structural components, which are dimensioned according to the occurring loads. The spars, skin and stringers are fit into the used airfoil.

The aerodynamic loads are calculated for different load cases such as the maximum maneuver load, roll and gust according to the certification specifications for large aero planes (CS-25 and FAR 25) [21, 22].

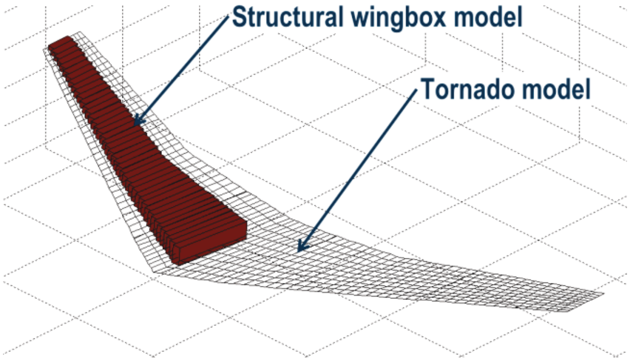


Figure 1: Finite element model with "Tornado"-mesh for aerodynamic calculations

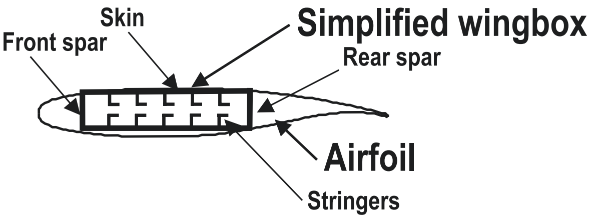


Figure 2: Definition of the wingbox for finite elements calculations.

5. FUTURE WING LAYOUT

The increase in aerodynamic efficiency, i.e. the reduction of drag is one objective of a future wing of a next generation aircraft. The aerodynamic drag of a wing can be described as follows

$$C_D = C_{D0} + C_{Di} \tag{1}$$

where C_D is the drag coefficient, C_{D0} is the zero-lift drag coefficient and C_{Di} is the vortex-induced drag coefficient. The vortex-induced drag produces around 35% of the total drag and is coupled with the Aspect Ratio (AR) of the wing. For example, for a parabolic polar, the induced-vortex drag coefficient can be calculated as

$$C_{Di} = \frac{C_L^2}{\pi e AR} \tag{2}$$

where C_L is the lift coefficient, e is the Oswald efficiency number. From this it follows that it is possible to reduce the vortex-induced drag by increasing the AR. AR is defined as

$$AR = \frac{b^2}{S} \tag{3}$$

where b is the wingspan and S is the reference area of the wing. Therefore, the AR can be increased by increasing the wingspan and keeping the wing reference area constant. This leads to a decrease in wing chord and to a more slender wing.

In Figure 3 several wing layouts are displayed for ARs of 9, 12, 15 and 18 respectively. Also, an AR of 9.4 is displayed, which corresponds to the AR of an Airbus A320-200 aircraft.

A first study was carried out to show the behavior of wing weight and aerodynamic drag with increasing AR. The key figures used in this study were aligned with data for the Airbus A320-200 [24]. The key figures are displayed in Table 3. A constant Maximum Take-Off Weight (MTOW) was assumed. In Figure 4 the results of the study are displayed. It can be seen that an increase in AR from 9 to 18 reduces the vortex-induced drag by ~44%. This means a total drag reduction of ~15% (assuming that 35% of the total drag is vortex-induced drag, as stated above). The wing weight is increased by ~140%. That means that the span is increased by only ~41%, but the weight of the wing has more than doubled. The reason for this is that the different wing layouts are dimensioned using the same load cases, but for a more slender wing the structural properties change. For example, for a more slender wing the second moment of inertia of the wingbox is smaller, which leads to an increase in spar and skin thickness.

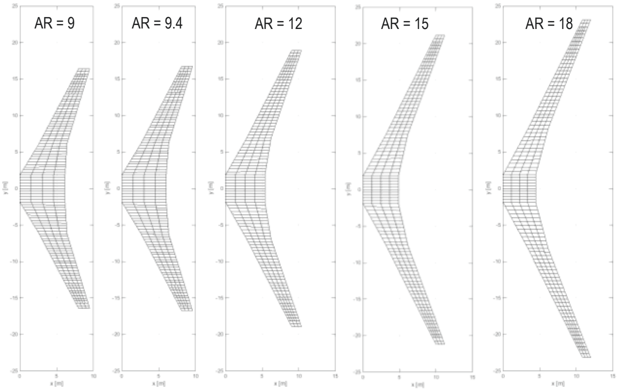


Figure 3: Several wing layouts with increasing aspect ratios from 9 to 18.

Table 3: Key figures for wing weight versus aerodynamic improvement study.

Aircraft / Wing Property	***Unit***	***Value***
Maximum Take-Off Weight	kg	78000
Number of Passengers	-	180
Cruise Speed	-	M0.76
Cruise Altitude	ft	35000
Wing loading	kg/m²	645
Wing area	m²	121
Leading edge sweep	deg	25

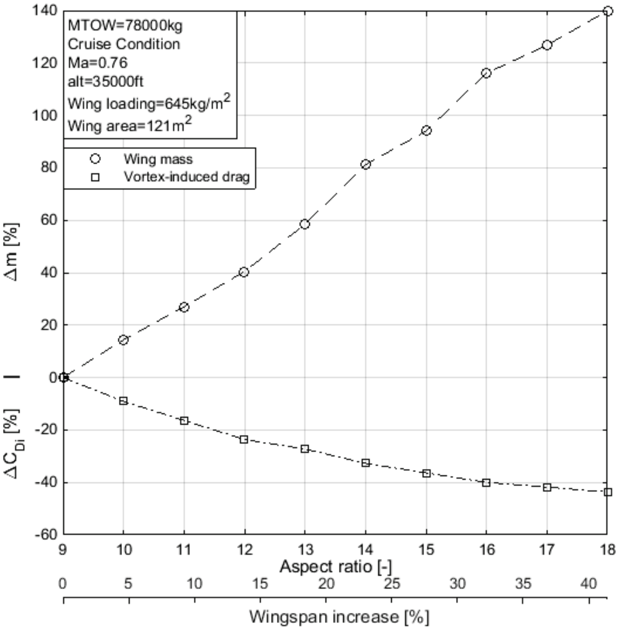


Figure 4: Aerodynamic improvement and increase in wing weight for increasing wing aspect ratio

6. OVERALL DESIGN SIZING AND BENCHMARKING

In accordance with materials options of all-aluminium (Al, “Ref2”), conventional CFRP with epoxy matrix (CFRP, “Ref1”), CFRP with an alternative phenolic matrix (Phenol-CF) for comparison, with a ramie-fiber composite with phenolic matrix (Phenol-NF), and another composite of ramie fibers and polylactic acid (with added nanocellulosic fibers) (PLA-NF), sized design candidates employing in-plane wings only were considered, i.e. no polyhedral wing morphologies or aerodynamic devices like winglets. Each candidate MTOW design was defined as one in which 180 PAX at 100 kg per PAX can be accommodated with useable fuel that delivers 2750 nm (5093 km) assuming suitable reserves and contingencies. Performance constraint criteria, such as payload-range working capacity, en route and low-speed operational performance were applied and subsequently identified feasible solutions were reviewed. To round off this section, a parametric benchmarking of each design candidate to that of the state-of-the-art A320neo is presented.

6.1. Aircraft Top-Level Requirements and Sizing Heuristics

A set of Aircraft Top-Level Requirements were stipulated for the sizing and optimisation of design candidates employing wing material options of Al, CFRP, Phenol-CF, Phenol-NF and PLA-NF. Apart from the introduction of advanced materials to the wing structure technology down-selection was limited to state-of-the-art: those indicative of the Airbus A320neo equipment type employing Geared Turbo-fan propulsion. The A320neo (MTOW = 79000 kg) was chosen as the baseline aircraft as opposed to the A320-200 (MTOW = 78000 kg) because it is considered to be the contemporary standard for operational performance of the A320 platform. Furthermore, in view of the significantly improved A320neo vehicular efficiency compared to the A320-200, as discussed in [25], any implementation of new technology will need to exhibit aggressive performance attributes since each percentage-point of vehicular efficiency enhancement becomes increasingly challenging.

The design payload is 180 PAX assuming 100 kg per PAX and the cabin including outfitting/interiors allowance was adopted from the A320neo (fuselage geometry was kept fixed for all variations away from the seed aircraft). Compliance with the airworthiness regulations CS-25 and FAR 25 transport category were also administered. In accordance with gathered intelligence and associated technical modelling, A320-200 [24] and A320neo [6] specifications reflecting Outer Mould Line definition, propulsion system characteristics, corresponding weights breakdown, payload-range working capacity, and, en route/low-speed operational performance attributes were gleaned from Ref. [26]. Mimicking the A320neo, design range was designated as 2750 nm (indicative of a US trans-continental city pair), design field performance characterised by a Take-Off Field Length at ISA, sea-level not being greater than 1930 m at MTOW, Regulated Take-Off Weight of MTOW under ISA+20°C, 5000 ft airport elevation conditions, and, an approach speed less than or equal to 136 KCAS at Maximum Landing Weight. Additionally, the time-to-climb to initial cruise altitude was limited to 25 min.

The defined mission profile consisted of a taxi-out, take-off at sea level and ISA+10°C ambient conditions, climb at ISA+10°C with speed schedule 250 KCAS / 300 KCAS / M0.76 until an Initial Cruise Altitude of FL350. The cruise was then performed at M0.76 at ISA+10°C, followed by a climb speed schedule mirrored descent, landing and taxi-in. Reserves and contingency fuel was in accordance with International Reserves, namely, 10% en route flight time overshoot contingency cruise, 30 min hold at 1500 ft and 200 nm alternate.

Apart from parametric wing geometry optimization provided by the high-end-low-fidelity numerical methods discussed in Section 4, all aircraft variations away from the seed or baseline aircraft reflected constant wing loading to that of the A320neo, thereby retaining the same en route buffet onset characteristics and a measure of original low-speed performance. All wing design candidates conformed to an inequality constraint of wing span not violating ICAO Code C airport compatibility (maximum of 36.0 m). Takeoff thrust-to-weight was also taken to be synonymous with the A320neo. The empennage was scaled with wing geometric variation according to a constant volume coefficient approach. All functional sensitivities included the effect of cascade re-sizing, i.e. appropriate changes in Manufacturer's Empty Weight due to alteration in loads (for structures). Finally, aircraft balance and any associated impact to trim were neglected.

In order to gauge indirectly the impact to vehicular efficiency, block fuel predictions for a 1000 nm (1852 km) stage length is given; although longer in distance this particular stage length can be construed as being representative of the maximum utilisation stage length together with stage lengths up to the design range of 2750 nm.

The aircraft sizing algorithm was based upon methods published in [27], utilising full analytical fractional change transformations. The fractional change prediction method is based upon a combination of analytical correlations, as well as synthetic, intermediary and macro-objective functions with fractional change analytical constructs. The analytical component of the fractional change method operates with the underlying premise that the designer/analyst begins with a seed condition or aircraft. By considering an increment in variable x as dx or Δx, a fractional change to a new value, x_1, small or otherwise, from a seed parameter x_o is defined as

$$\triangleleft\, x = \frac{\Delta x}{x_o} = \frac{x_1 - x_o}{x_o} = \frac{x_1}{x_o} - 1 \qquad (4)$$

Recent examples of the fractional change methodology used to good effect with regards to aircraft sizing, optimisation and integrated en route/low-speed performance can be found in [24, 27–30].

7. RESULTS AND DISCUSSION

Table 4 and Figure 5 display sizing and optimisation exercise results of design candidates employing wing material options covering Al (Ref2), CFRP (Ref1), Phenol-CF, Phenol-NF and PLA-NF relative to the A320neo reference aircraft. For purposes of additional comparison, information specific to the A320-200 equipment type is also provided. It is highlighted the 180 PAX design range of the A320-200 is limited to approximately 2480 nm (4592 km) due to fuel useful load restrictions as a result of certified design weights.

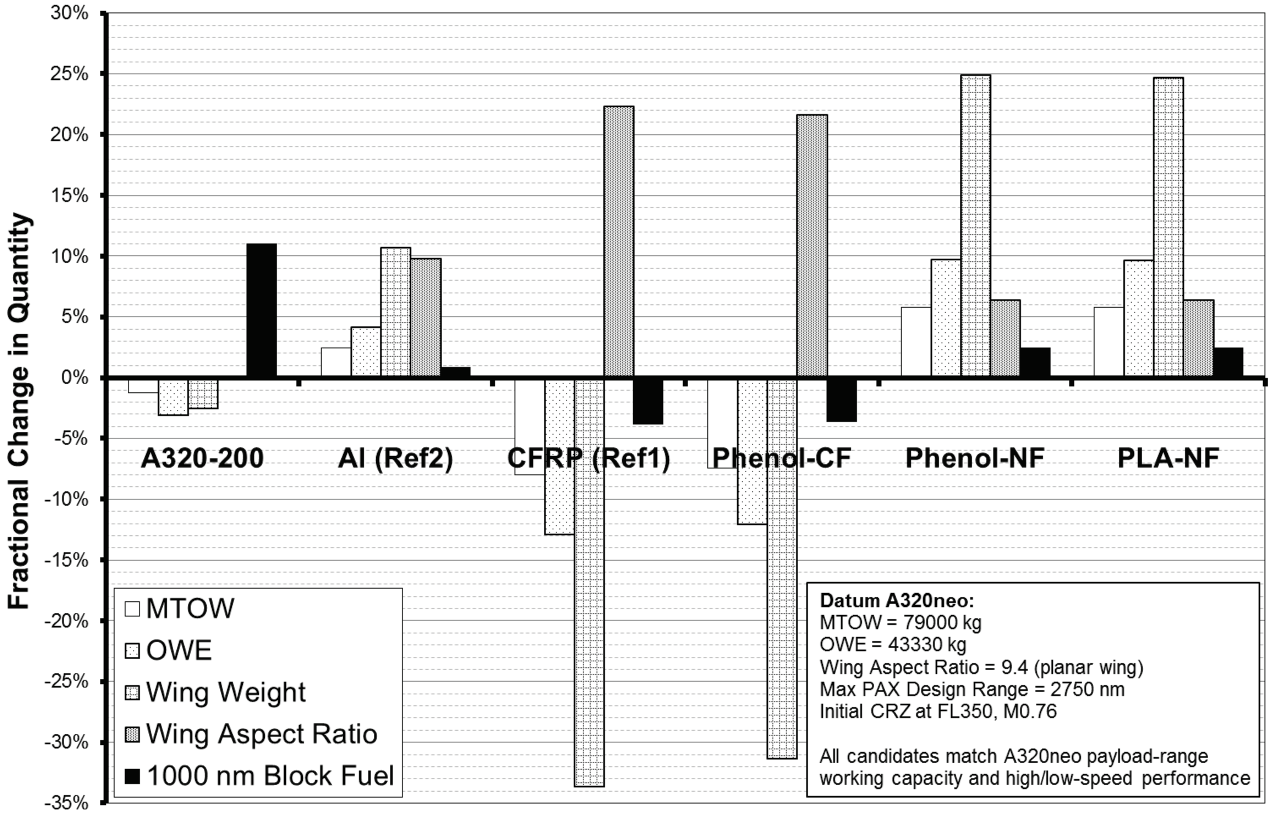
As it can be discerned in Figure 5, conventional CFRP with epoxy matrix materials technology yields the best outcome leading to almost 4% reduction in 1000 nm block fuel. This prediction together with the weights reduction outcome bodes well with results posted in [31, 32], where it was argued that the substitution of aluminum primary structures by CFRP can lead to at least a 30% weight reduction. In this case an isotropic composite behavior is assumed.

The CFRP constrained wing AR = 11.5 contrasts against the A320neo planar wing AR of 9.4 – recall, the A320neo utilises winglet aerodynamic devices (producing a fictitious in-plane equivalent AR = 10.6), whereas, the study presented here assumes in-plane wing morphologies only. Phenol-CF has generated an outcome very close to the reference CFRP. We assumed these carbon fibers to be produced from renewable feedstock; it was also postulated that the sustainable carbon fibers used in Phenol-CF have mechanical properties similar to conventional CF applied in Ref1 CFRP. As mentioned before, the mechanical properties of the composite are primarily dependent on the choice of reinforcing fibers, therefore this result is as expected and sustainable composites with alternative, high-performance carbon fibers can be considered to be a worthwhile future option. It was observed that for the sizing of the wing the dimensioning load for the Phenol-CF version of the wing was buckling.

Wing designs incorporating composites with natural fibers, Phenol-NF and PLA-NF, tended to produce undesirable results: not only is the 1000 nm block fuel 2-3% higher than the A320neo datum, but the significantly increased design weights would tend to generate moderate increases in cash operating cost due to incremental penalties relating to airport charges, navigation fees and Direct Maintenance Cost. Also, further modest increases in so-called Additional Operating Cost covering community noise and emissions fees would be characteristic of integrated Phenol-NF and PLA-NF materials technology for the future wing.

Table 4: Parametric review between design candidates and the A320neo (datum) reference aircraft.

Aircraft Properties	*Unit*	*A320neo [datum]*	*A320-200*	*Al (Ref2)*	*CFRP (Ref1)*	*Phenol-CF*	*Phenol-NF*	*PLA-NF*
MTOW	kg	**79000**	-1.3%	+2.4%	-8.0%	-7.5%	+5.8%	+5.8%
OWE	kg	**43330**	-3.1%	+4.2%	-12.9%	-12.0%	+9.7%	+9.7%
OWE / MTOW	%	**54.9**	53.9	55.8	51.9	52.1	56.9	56.9
Aspect Ratio (planar)	-	**9.4**	9.4	10.3	11.5	11.4	10.0	10.0
Estimated W_{wing}	kg	**9379**	-2.4%	+10.7%	-33.6%	-31.4%	+24.9%	+24.7%
W_{wing} / MTOW	%	**11.9**	11.7	12.8	8.6	8.8	14.0	14.0
Estimated 1000 nm Block Fuel, M0.76	kg	**5740**	+11.0%	+0.9%	-3.8%	-3.6%	+2.5%	+2.4%



Datum A320neo:
MTOW = 79000 kg
OWE = 43330 kg
Wing Aspect Ratio = 9.4 (planar wing)
Max PAX Design Range = 2750 nm
Initial CRZ at FL350, M0.76

All candidates match A320neo payload-range working capacity and high/low-speed performance

Figure 5: Parametric review between design candidates and the A320neo (datum) reference aircraft.

8. CONCLUSION AND OUTLOOK

Our results indicate that for future wing designs sustainable composites with ramie fibers are not a suitable material option, as they lead to increased wingbox weight and thus higher block fuel and operating costs. However, with natural fibers probably emerging from some few niche applications for load-bearing structures in the next decade, efforts will increase to enhance their mechanical performance and their processability, leading to improved composites. Additionally, we assumed an isotropic composite design; an optimization regarding laminate fabrication taking into account active loads may lead to further weight reduction (which is, by the way, not limited to sustainable materials).

In contrast to natural fibers, notably in the case of alternative carbon fiber composites, the application of advanced composites for load-bearing aircraft structures made from renewable resources is competitive to existing materials. Note, however, that the sustainable carbon fibers are assumed to have similar mechanical parameters as conventional ones. To date, attempts to produce carbon fibers from non-petrochemical feedstock did not lead to values of high-performance conventional carbon fibers.

A first assessment on aircraft level with the different selected sustainable materials and accordingly optimized aspect ratio of the wing was conducted. While the composites made of biologically derived matrix and vegetable fibers did not lead to an improvement, the material selection of the phenolic resin with carbon fibers from renewable feedstock generated a positive outcome and even a block fuel reduction of -3.6% compared to the reference Airbus A320neo for a 1000 nm mission. Although a further substantial reduction of fuel burn cannot be expected, the overall carbon footprint of an aircraft would decrease considerably. Additionally, once technologically established, composite components made from renewable feedstock might help to lower high composite costs, thus stimulating the extensive use of composites and promoting new lightweight design options. In this paper only an increase in aspect ratio for planar wings, which do not violate the ICAO Code C airport compatibility was considered as a possible way to increase the aerodynamic performance of the wing. However, wings with even higher aspect ratios that are not accordant to ICAO Code C, or non-planar wings, such as wings equipped with winglets or even C-wings, provide the possibility of aerodynamic improvement as well. Therefore, these wing designs combined with suitable sustainable materials could be an option for future aircraft.

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