From aviation to aviation: environmental and financial viability of closed-loop recycling of carbon fibre composite

Fanran Meng[1*], Yuanlong Cui[2], Steve Pickering[1], Jon McKechnie[1]
[1]Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK
[2]Department of Built Environment, College of Engineering and Technology, University of Derby, Derby, DE22 3AW, UK
* Corresponding author: Email: Fanran.Meng@nottingham.ac.uk

Abstract:

By 2050, the aviation sector is expected to generate about 500,000 tonnes of accumulated carbon fibre reinforced plastic waste from the production and end-of-life phase. In this study, aircraft interior applications of recycled carbon fibre (rCF) replacing virgin glass fibre are examined over the full life cycle in terms of environmental and financial viability. The viability of rCF for closed-loop aviation applications are demonstrated across rCF conversion (papermaking; fibre alignment) and composite manufacture (compression moulding; injection moulding)The results show that rCF composites, especially aligned rCF composites, give reasonable environmental (4-31%) and cost reductions (5-31%) relative to virgin glass fibre composites.

Key words:

Carbon fibre, Recycling, Compression moulding, Injection moulding

1 Introduction

The aviation industry is a key element of transportation and is responsible for 12% of CO_2 emissions from all transports sources compared to 74% from road transport [1]. Carbon fibre reinforced polymers (CFRP) has been widely used for weight reduction in aviation applications (e.g., the Boeing 787 Dreamliner and Airbus A350) towards fuel efficiency objectives. For instance, Boeing 787 has used up to 50% weight of CFRP materials in the body structure [2]. The global demand for carbon fibres are expected to increase from 63,500 tonnes (approximately 2.34 billion US$) in 2016 to 117,000 tonnes by 2022, corresponding to an annual growth rate of 8.7% [3]. By 2050, the aviation sector will generate approximately 500,000 tonnes of accumulated CFRP waste from the production and the end-of-life phase in total [4]. In anticipation of the growth of waste arising from increasing demand in the future, it is necessary to create a waste management system delivering minimal negative environmental and cost impacts.

Existing EU regulations also drive the aviation industries to make efforts in carefully dealing with production and end of life waste materials. The European Waste Framework Directive (2008/98/EC) requires the adoption of the waste management hierarchy (3R strategy): Reduce, Reuse, Recycling and Disposal. The European Commission's Circular Economy Policy Package seeks to increase recycling rates of municipal waste to 65% by 2035 and reduce landfill rate to 10% by 2035. The End-of Life Vehicle Directive (ELV, 2000/53/EC) sets targets which currently (as of 1 January 2015) require 85% by weight of vehicles to be reused or recycled [5]. Although this is not similar for aerospace, there are industry initiatives to minimise waste generation and achieve recycling targets [6, 7]. Airbus already sets up plans to distribute 95% of the CFRP waste that comes from its process to the recycling industry between 2020 and 2025. They also plan to use 5% out of the 95% for aircraft parts [7]. Landfill tax in UK at £94/tonne ($122.7/tonne) (2020-2021 rate), makes the cost of landfill, including the gate fees and transport, up to £130-£140/ tonne ($170-$183/tonne) making landfill as the least option for waste disposal [8].

The nature of CFRP, a fibre-reinforced cross-linked thermoset polymer structure, gives excellent stiffness, strength and durability, however, it also makes them difficult to recycle [9, 10]. Solutions have emerged and continue to be improved for recycling value from end-of-life composite materials, contributing to a circular economy. Current CFRP recycling techniques are based on either mechanical recycling processes, in which the waste is reduced in size to produce fibrous or powdered materials, or thermal processes in which the polymer is removed to yield a clean CF recyclate [11, 12]. Recovery of CF instead of landfilling has shown multiple benefits with regards to reduced energy consumption and reduced greenhouse emissions relative to virgin CF (vCF) production (198-595 MJ/kg) or even virgin glass fibre (GF) production (13–54 MJ/kg) [13]. It is found from our previous study that the CF recycling could be achieved at $5/kg or less, which is approximately 15% of the cost of the vCF [14]. However, up until now, there have been almost no cases where recycled CFs (rCFs) have been used for mass production, only demonstrators (prototypes), such as aircraft seat arm rests and car seat base, have been produced [15].

Life cycle assessment (LCA) is a standardised method to assess a trade-off of existing and emerging technologies/materials by comparing the environmental impacts over the full life cycle [16, 17]. The applications of LCA methodologies are growing in the composite material field in which they have been adopted to investigate the environmental and cost impacts of substituting conventional material types with virgin CFRP (vCFRP) or recycled CFRP (rCFRP) in transport applications [18-21]. Our previous study applied LCA methods to use rCF in place of vCF in automotive applications, concluding that CF recycling is far less impacting than vCF manufacture which can potentially reduce the environmental impacts across the full life cycle [22]. These assessments could provide a basis for identifying environmentally beneficial applications for rCFRP materials. Integrating LCA with financial analysis enables further understanding of trade-offs between cost and environment factors to guide material selection [18, 19, 23, 24]. Opportunities to use rCF materials exist in automotive components such as vertical pillar and car hood under bending conditions as demonstrated using material indexes. Achieving high rCF fibre volume fraction is necessary to reduce the life cycle costs as it is dependent very much on material properties achievable with rCFRP and the design requirements of the application in automotive sector. However, so far, there is no study assessing the environmental and financial viability of using rCF in aviation applications.

In aviation industries, cost and weight considerations for aircraft interiors have traditionally had different driving mechanisms than that for any other transportation systems. Weight savings gained during the initial design and development of an aircraft in one area can have a savings multiplier effect in operating cost considering the cost versus performance benefit. In this study, we focus on aircraft interior applications for rCF replacing virgin fibre which has not been covered in most of literatures. The aim is to examine the environmental and financial viability of using rCF in aviation industries to close the loop of CFRP material. A set of rCFRP manufacturing approaches including the compression moulding and injection moulding are proposed, and the production and usage of material are evaluated in an aircraft during its lifetime period. The effects of the life cycle environmental and cost can be quantified and integrated in decision making systems for sustainable use of CFRP in aviation industries and beyond.

2 Methodology

The life cycle model begins where the waste CFRP has been collected (Figure S1). For recycling, to the system boundary includes fibre recovery, the production of composite materials from rCF and the use in aviation, but no collection of waste CFRP. The overall life cycle environment and cost of rCFRP components are compared to GFRP and competitor lightweight materials (vCFRP) to assess the relative environmental and financial performance of utilising rCF for aircraft component manufacture while meeting the same component design criteria. Process models are developed to estimate the mass and energy balance of production pathways. Material substitution is used for component design from the set of materials to meet performance criteria (i.e., equivalent stiffness). The following composite production pathways are considered:

1) Reference GFRP material is produced by compression moulding and the fibre volume fraction is 30%vf: vGF PR_40%.
2) Random structure – Compression Moulded rCFRP: rCF is processed by a wet papermaking process prior to impregnation with epoxy resin (EP)/phenolic resin (PR) and compression moulding. Fibre volume fractions of 30%are considered: Random rCF PR_30% vf, Random rCF EP_30%.
3) Random structure – Injection Moulded rCFRP: rCF is processed by wet papermaking and subsequently chopped prior to compounded with polypropylene (PP); rCF-PP pellets are subsequently injection moulded. Fibre volume fraction is 18%vf: Random rCF PP_18%.
4) Aligned – Compression Moulded rCFRP fabric: rCF is processed by a fibre alignment process prior to compression moulded with epoxy resin. 50%vf is considered: Fabric Aligned rCF EP_50%.
5) Fabric – Autoclaved vCFRP: bi-directionally woven vCF preimpregnated (prepreg) is autoclave moulded with epoxy resin; fibre volume fraction is 50%vf [25]: Fabric vCF EP_50%

This life cycle inventory data is supplemented with databases to estimate impacts of producing and using material and energy inputs (e.g., Gabi [26], Ecoinvent [27], GREET [28]) assuming all activities to occur in the UK. The manufacture of composite from virgin CF is also modelled based on processing parameters similarly to provide inventory data for comparative analysis. Two environmental impacts are quantified: primary energy demand (PED) in terms of MJ and (GHG) emissions, reported as gram CO_2 equivalents ($gCO_2eq.$) based on the most recent IPCC 100-year global warming potential (GWP) [29]. The functional unit is galley cabinet door flat sandwich panel with a mass of 2.54 kg and a thickness of 15 mm. Each skin thickness is 1.5 mm, made of glass fibre reinforced plastic (GFRP) comprising GF and phenolic resin (MTM 82S-C) [30] and the core thickness is 12 mm, made of Nomex honeycomb (ANA-3.2-48) (the density is 48 kg/m^3) [31]

The capital and operational costs are estimated as previously [14] and then extrapolated to those of year 2019 based on the Chemical Engineering Plant Cost Index. The capital costs (CAPEX) is annualised over the production life as below to calculate the life cycle cost,

$$A_c = CAPEX \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad 1$$

where A_c is the annualised cost ($); n is the production life of the project (year); i is the discount rate (%).

Figure 1 The overview of closed-loop recycling of aviation carbon fibre composite waste

2.1 Fluidised bed recycling process

The fluidised bed recycling process requires a shredding process before feeding CFRP wastes into the reactor. The silica sand bed is used to volatilise the shredded scrap material and thus to decompose the epoxy resin and release the fibres. The fluidising air can elutriate the released fibres while degraded material remains in the bed. The operating temperature above 500 °C of the reaction is chosen to be sufficient to decompose polymer, leaving clean fibres, but not too high to degrade the fibre properties substantially. The fibres can then be removed from the gas stream by a cyclone and collected [32]. Finally, the gas stream after fibre separation is directed to a combustion chamber to fully oxidise the polymer by-products from the process. Heat is recovered to pre-heat inlet air input before being exhausted through the stack. Fluidised bed recycling is in technology readiness level 6 with pilot plants in Nottingham UK.

Inventory data is extracted from the process model and the operating conditions are given including 500 t rCF/yr annual capacity, 9 kg CF/hr-m^2 fluidised bed feed rate and 5% air in-leakage. These parameters correspond to an energy requirement of 7.7 MJ/kg rCF, comprised of 1.9 MJ/kg (natural gas) and 5.8 MJ/kg (electricity) [33]. CO_2 emissions resulting from the oxidation of the epoxy matrix material are calculated on a stoichiometric basis assuming all carbon is fully oxidised to CO_2.

2.2 Carbon Fibre Conversion Process

rCF is converted into an intermediate form suitable for composite manufacture by a) wet papermaking to produce a random non-woven mat and b) fibre alignment to produce an aligned fibre mat. In the wet papermaking process, rCF is metered and dispersed in a viscous aqueous solution to form a fibre suspension. The suspension is then filtered out onto a moving mesh to form a wet mat. The mat is later subjected to binder application, drying and winding onto a fibre roll. Capital and operational costs were estimated based on standard equipment, sized to required capacity and non-standard equipment as previously. An energy requirement of 14.3 kWh/kg for a 100 tonne/yr capacity is used in the analysis.

In the fibre alignment process, the rCF suspension is injected onto a mesh screen inside a rotating drum and the convergent nozzle filters and aligns the fibres. Vacuum suction is employed under the mesh to accelerate the dewatering/drying step. As the alignment process is under development, a best estimation of energy consumption of 22 MJ/kg rCF mat is used in the analysis based on a target for technology development. Target fibre alignment costs are determined in order for aligned rCFRP materials to achieve the same capital and operational costs as the best performing randomly aligned rCFRP material.

2.3 Composite manufacture

A demonstrator component was made using prepreg from ACG made using a phenolic resin for fire retardence [34]. This was a sandwich panel construction compression moulded. The demonstrator was finished as a typical door for a compartment within an aircraft galley. The part was made successfully, and the performance approached that achievable from virgin materials, although a higher fibre volume fraction in the prepreg would be required to achieve commercial viability.

Compression moulding or injection moulding from random/aligned rCF mats is assumed to be utilised to manufacture equivalent components. The fixed capital cost of the compression moulding process is \$1.88million for a 200 tonne/yr plant [18] with 1.5 labourers per operational shift based on a rate of £21.8/hour (\$28.5/hour). The injection moulding facility consists of compounding, injection and trimming machines and the equipment capital cost (\$24.8million for a 144 tonne/yr plant) [18] with 1.5 labourers per shift.

2.4 Mechanical properties of composite materials

2.4.1 Mechanical properties of random oriented rCFRP

In the material substitution design, the material properties are significant inputs to be determined to meet the functional requirements and geometries constraints. The Halpin-Tsai equations [35, 36] use empirical relationships to calculate the mechanical properties of the composite in terms of properties of the fibre and the matrix and geometries. The equation can be expressed as followed:

$$P_c = P_m \frac{1 + \zeta \eta v_f}{1 - \eta v_f} \quad 2$$

where P_c is the property of a composite, P_m is the corresponding property of the matrix, P_f is the property of fibre, ζ is a factor curved fitted to specific modulus calculations, v_f is the volume fraction of fibre, and the efficiency factor is:

$$\eta = \frac{\frac{P_f}{P_m} - 1}{\frac{P_f}{P_m} + \zeta} \quad 3$$

2.4.2 Mechanical properties of aligned rCFRP

Compared to random oriented rCFRP, the aligned rCFRP normally show better mechanical performance due to the higher fibre volume fraction (40% or over). The properties of rCF from fluidised bed process and epoxy resin used in the manufacture are shown in **Table S2**. The volume fraction of CF can be determined using Eq. 4. The multi-laminate composite used in this study is assumed to be a layup $[0°/90°]$. Based on the Classical Lamination Theory [37], we have developed a micromechanics model as in section 1.1 in SI to predict their modulus.

$$V_f = \frac{N_f G_f / \rho_f}{(N_f G_f)/\rho_f + N_R G_R / \rho_R} \quad 4$$

where N_f= number of layers of fibre mat; G_f=fibre ply areal density; ρ_f=fibre density, kg/m^3; N_R=number of layers of resin film; G_R=resin film areal density; ρ_f=epoxy resin density, kg/m^3.

2.5 Functional unit

The demonstration component selected was a GFRP galley cabinet door of generic construction utilizing the same manufacturing processes common to flat panel parts processed for aircraft interior construction with requirements of bending and torsion stiffness. When evaluating alternative materials, functional equivalence measured by component stiffness is maintained by considering the design material index of 1/3 and varying face thickness to account for differences in each material's mechanical properties (modulus in this study) according to [38-40]. The Nomex honeycomb core thickness is kept the same as 12 mm.

$$R_m = \frac{m}{m_{ref}} = \frac{\rho}{\rho_{ref}} \left(\frac{E_{ref}}{E}\right)^{1/3} \quad 5$$

where Rm is the ratio of component mass between the substitution material (t) and the reference (GFRP, t_{ref}=1.5 mm), ρ is the density of the two materials (kg/m^3), and E is the modulus of the two materials (GPa).

2.6 Aircraft use phase

In the use phase, the aircraft part will influence fuel consumption due to its weight. The fuel consumption of an aircraft depends on airframe drag power, engine fuel use, flying distance, vertical flight route and its weight. Most fuel consumption models are mainly based on the widely-used Base of Aircraft Data (BADA) models [41]. According to BADA model, fuel consumption for aircraft is expressed in Thrust Specific Fuel Consumption (TSFC) based on an energy balance of thrust (see section 1.2 in SI). The mass induced fuel consumption can be defined as the energy per unit weight per unit distance as below.

$$MIF = \frac{F}{m} = \frac{(C_D f_A)^{\frac{1}{2}}}{\varepsilon} g \qquad 6$$

where f_A is the filling factor, ε is the efficiency of real jet engine (~1/3), C_D is coefficient of drag, m is the mass of the plane and g is the gravitational acceleration.

The mass induced fuel consumption is a dimensionless factor multiplied by the gravitational acceleration. The dimensionless factor depends on a plane's geometry, the drag coefficient and the engine efficiency rather than the size or mass of the plane or air density. For an aircraft component LCAs, the component is assumed to be designed for an aircraft (Boeing 747-300 in this study the parameters are shown in the Table S3 [42]). The lifetime is assumed to be initially 5 years with a daily distance of 14,000 km, while a sensitivity of 1 years and 10 years is considered. Therefore, the total life cycle distance is estimated at about 25 million km. The parts can be considered as load that have to be carried by the aircraft during each flight.

3 Results and discussion

3.1 Mechanical properties of rCFRP

When evaluating alternative materials in substitution, functional equivalent stiffness is maintained by varying component mass to account for differences in each material's mechanical properties. The mechanical properties of rCFRP calculated in this study are shown in Figure 2 (which align well with the experimentally and publicly reported data (the discrete markers) and Table S4. The referenced GFRP (30%vf GF-PR) has a modulus of 22.7 GPa [30]. Increasing fibre volume fraction, rCFRP materials generally show better mechanical performance. Random structure-injection moulded rCFRP (18%vf-PP) can achieve a modulus of 16.3 GPa using 5%wt maleic anhydride grafted polypropylene coupling agent [43]. Random structure-compression moulded rCFRP with epoxy resin show higher modulus of 37.1 GPa for 30%vf [44]. As rCF are in a fluffy, discontinuous, 3D random and highly entangled structure with a typically low bulk density (~50 kg/m^3), it is difficult to manufacture CFRP with the same high modulus as unidirectional part. However, relatively high fibre volume fractions can be achieved by fibre alignment process [45, 46] and thus high mechanical performance (60.8 GPa for 50%vf; 73.9 GPa for 60%vf) similar with woven vCFRP (70 GPa for 50%vf) [25]. Due to differences of fibre volume fractions and resin used in component manufacturing, the composite density is also different. These differences would determine the relative masses between rCFRP and reference GFRP during material substitution.

Figure 2 Tensile properties of an epoxy recycled carbon fibre composite experimentally measured. Solid and dotted lines represent the theoretical modulus calculated using the generalized rule for randomly distributed and aligned fibres, respectively.

3.2 Life cycle energy use and greenhouse gas emissions

All substitution materials are capable of significantly reducing component weight relative to the referenced GFRP sandwich panel. Higher proportions of CF in a composite give better properties and lighter components. Thus, CFRP materials with increased fibre volume fraction achieve the greatest weight reductions relative to GFRP (Figure 3). 5%-27% overall weight reductions or 6%-34% surface panel weight reductions are seen in random rCFRP with fibre volume fractions of 18% - 30%vf. Weight reductions vary depending on resin types used in composite manufacture: random rCF (18%vf) using polypropylene achieves 20% overall weight reduction (26% surface panel weight reduction); random rCF (30%vf) using the same phenolic resin as referenced GFRP achieves 5% overall weight reduction (6% surface panel weight reduction), random rCF (30%vf) using epoxy resin achieves 27% overall weight reduction (34% surface panel weight reduction). Achieving higher fibre content of 50%vf by aligning rCF can result in significant reductions in component weight (231% overall weight reduction or 39% surface panel weight reduction). Like the aligned rCFRP, woven vCFRP achieves very low component weight (33% overall weight reduction or 42% surface panel weight reduction).

The referenced GFRP has a production PED of 228 MJ/part and GHG emissions of 8.7 kgCO$_2$eq/part (Figure 3). The Nomex honeycomb core material has the same PED (39.8 MJ/kg) and GHG emissions (0.9 kgCO$_2$eq/kg) for all selected materials thus would not change the comparison. GHG emissions associated with the production of rCFRP components generally represent similar or even lower value relative to GFRP. CF recycling is associated with very low GHG emissions. Production of matrix material, rCF processing, and final manufacture represent the largest shares of production emissions. Increasing the fibre volume fraction of rCFRP contributes to lower production GHG emissions due to reduced contribution of more GHG-intensive matrix material than rCF. Random structure-compression moulded rCFRP (30%vf) can achieve lower GHG emissions (4% reduction) than that of GFRP. Alignment of fibre is the only way to achieve further higher fibre volume fraction of rCFRP (50%vf) but has a 11% increase of production GHG emission due to high emissions related to autoclave moulding. Although Random rCF PP_18% has lower fibre volume fraction, due to less GHG-intensive polypropylene and injection moulding manufacturing method, the lowest production GHG emission can be achieved at 4.4 kgCO2eq/part, approximately 49% emission reduction. Similar with GHG results, the results show production PED decreases with the increasing fibre volume fractions of rCFRP. Results of vCFRP component presents relatively high production PED (821 MJ/part) and GHG emissions (37.0 kgCO_2eq/part) primarily due to the high environmental impacts of vCF manufacture.

Figure 3 Production a) primary energy demand; b) greenhouse gas emissions; and mass of components made of different materials achieving equivalent stiffness in aircraft components

Use phase dominates the full life cycle impacts and therefore the environmental impact is driven by component weight, not embodied emissions (Figure 4). The environmental benefits from substitution are highly dependent on weight reductions achieved: the greater weight reduction, the lower mass-induced fuel consumption during the use phase as well as lower material requirements during manufacture. We separately consider the life cycle impacts over 1 year, 5 years and extended 10 years lifetime travelling distance. The base lifetime is assumed to be 5 years with a daily distance of 14,000 km. Embodied emissions are only 0.1-4.5% of total environmental impact: 0.1-0.8% for GFRP, 0.5%-4.5% for vCFRP, and 0.1%-1.0% for rCFRP, respectively. Impacts associated with rCFRP components vary depending on the production route and fibre volume fractions.

There is no major difference of relative life cycle GHG emission of rCFRP to that GFRP for 1 year, 5 year and 10 year travelling distance. Random structure, compression moulded rCFRP components using epoxy resin can reduce GHG emission relative to GFRP by 126% (30%vf); similar trends are seen in PED. Compression moulded rCFRP using phenolic resin, however, can only reduce 4-5% GHG emissions primarily due to less fuel savings associated with less weight reduction as shown above. Injection moulded rCFRP components using polypropylene achieves lower reduction of PED (~21% reduction) and GHG emissions (~21% reduction) although they have the lowest production PED and GHG emission. Further PED and GHG emissions reductions of up to 31% for 50%vf can be achieved through fibre alignment conversion process. In comparison, despite the high energy intensity for vCF production, fabric vCFRP components still achieve GHG reduction by 27% (1 year lifetime travelling) to 32% (10 year lifetime travelling). This is mainly attributed to the similar largest weight reduction (33%) with aligned rCFRP achieved in the substitution.

Figure 4 Life cycle with use phase a) primary energy demand; b) global warming potential of components made of different materials achieving equivalent stiffness in aircraft components for different lifetime years

A breakeven analysis of PED and GHG emissions of all substitution scenarios is shown in Figure S2. Generally, over any realistic operating life, lighter materials deliver lower impact. Random injection moulded rCFRP (18%vf) and rCFRP (30%vf) using epoxy resin already has lower production PED and GHG emissions and thus do not need a distance to breakeven the life cycle impacts. Random compression moulded rCFRP components using phenolic resin need 136292 km to breakeven the GHG emissions. The fabric vCFRP components require a longer breakeven distance of 391420 km for life cycle GHG emissions but in the context of reasonable lifetime. This is approximately 28 days flying distance (14000 km/day).

3.3 Life Cycle Cost

The production cost savings from substitution are highly dependent on weight reductions achieved: the greater weight reduction, lower material requirements during production phase. Although Nomex honeycomb core materials are at a high cost of $25.6/kg [47, 48], it does not affect the overall results as all components have the same mass of core material(Figure 5). Material cost of rCFRP using epoxy resin ($13.6/kg) is generally more expensive than those using polypropylene ($1.5/kg) and phenolic resin ($2.3/kg) even at the same fibre volume fraction. In material substitution, the varied mass is achieved by varying component thickness to account for differences in each material's mechanical properties. The relative thickness of the components impacts costs for raw material as thicker CFRP components require greater quantities of fibre and matrix materials for functional equivalence. Due to high cost of vCF ($40/kg versus $2.2/kg rCF), vCFRP (50%vf) requires an overall material cost of $43.1/part compared to $16.1/part for GFRP ($2/kg GF).

Manufacture costs include wet papermaking cost for random rCFRP, fibre alignment for aligned rCFRP and composite manufacture (i.e., injection moulding, compression moulding, and autoclave moulding) as previously [14]. Similar with material costs, larger weight components also require higher cost for manufacturing. Manufacture costs account for 23.5% for referenced GFRP while for vCFRP they are only 8.6%. Aligned rCFRP components ($5.2/part) require higher manufacture costs than most random rCFRP components ($4.6-6.1/part) primary due to high energy cost related to fibre alignment and autoclave moulding processes.

Figure 5 The production cost of aircraft component materials ($/part)

Use phase dominates the life cycle cost which is driven by mass-induced fuel consumption: the greater weight reduction, the lower mass-induced fuel consumption during the use phase. In Figure 6, the use phase costs over 5 years are already converted to net present values for life cycle cost. The referenced GFRP has a life cycle cost of $85,563/part (production cost accounts for 0.02%). With the increasing fibre content, rCFRP materials show better mechanical performance which is beneficial in reducing component mass for functional equivalence with GFRP. All rCFRP materials can offer both cost savings and weight reductions relative to GFRP: random structure compression moulded rCFRP using epoxy resin (30%vf) can achieve 26% life cycle cost reduction and aligned rCFRP can achieve up to 31% life cycle cost reduction for the highest fibre volume fraction of 50%. Despite an increased cost of vCFRP during manufacture, it shows a significant reduction in life cycle cost. In-use fuel saving achieved from weight savings far outweigh the high cost of vCF material, enabling vCFRP to achieve a 33% life cycle cost savings.

Figure 6 The life cycle cost of aircraft component materials ($/part) for a period of 5 years

Similar with results of environmental metrics, the cost impacts are entirely driven by component weight: lighter materials deliver lower cost over any realistic operating life (Figure S3). vCFRP components become favourable to GFRP when travelling distance exceeds 18390 km which is just less than two days flight time. rCFRP components can achieve life cycle cost reduction at a relatively short distances of 5950 km for compression moulded rCFRP with 30%vf and 2860 km for aligned rCFRP with 50%vf, respectively.

3.4 Discussion

rCFRP components can achieve weight reductions while reducing the impacts of primary production due to the low energy-, GHG emission-, and cost- intensive recycling and rCF processing activities. Random structure, injection moulded rCFRP with relatively low fibre volume fraction can reduce both life cycle environmental and cost impacts, however, injection moulding is normally used to manufacture relatively small parts and might not be the most appropriate manufacturing technique for larger components in aircraft. The results provide a comparable alternative manufacturing route for rCF for better environmental and financial benefits.

Although the findings present high performance vCFRP is still better than rCFRP materials primary due to less weight reduction associated with mechanical degradation during recycling, diverting CFRP waste from conventional landfill/incineration for secondary application is beneficial in addressing waste management issues. Currently waste landfilling in the UK will be charged a gate fee at a cost of £24/tonne ($31.3/tonne) excluding landfill tax and £113/tonne ($147.5/tonne) including landfill tax, while tipping fees for incineration are £93/tonne ($121.4/tonne) in 2018/2019 [8]. Seeking application markets for rCF is significantly contributing to a circular economy. The market development of CFRP recycling, however, requires collaborations between all stakeholders across upstream (recyclers), midstream (intermediate substrate manufacturers), downstream (end-product manufacturers) and end-users. It is believed to be effective through mutual cooperation among intermediate substrate manufacturers to identify the better type between nonwoven and aligned mats, resin manufacturers, and processing manufacturers.

Moreover, as aircraft interiors only have a life of about 5 years and thus are replaced regularly. Over their realistic operating life, aligned rCFRP is found to have comparable environmental and financial benefits relative to high performance vCFRP, indicating new fibre alignment techniques are required.

In aircraft design, weight saving is not always a reliable indicator of system performance as this single metric ignores the impacts associated with material production and other aircraft design criteria such as fatigue properties, durability and safety issues. Future work shall link component design criteria including modulus, strength, fatigue properties and durability of components to life cycle environmental and cost impact to integrate this approach with whole aircraft design considerations and optimisation tools in order to identify the most promising applications.

Waste reduction at the highest level of waste management hierarchy is still the most demanding option than recycling. In aerospace industry, the ‘buy-to-fly’ ratio (the ratio of materials weight procured to the weight of the finished product) is a key concern and lots of efforts at reducing manufacturing waste generation are in progress. It includes the manufacturing technology developments such as out of autoclave and novel curing. Moreover, high performance fibre reinforced thermoplastic composites and more sustainable single-polymer-composites have been developed for aircraft industries. As they are recyclable via direct melting while proving high mechanical performance in forms of sandwich panels, they can be considered in replacing the high-cost and high-energy-intensity fibre reinforced thermoset composite materials to some extent and this will be the on-going technologies under development.

It shall be noted that end of life phase of all the candidate materials are excluded in the system boundaries. The conventional incineration of waste plastic would emit about 3.1 $kgCO_2eq/kg$ waste, although advanced recycling of these materials can significantly reduce the GHG emissions [49]. Taking into account of component weight, incineration of all these material waste at the end of life would only result in about 4.7 – 7.0 $kgCO_2eq/part$, which would not alter the finding as use phase dominates the overall environmental impacts. However, the end of life treatment option cannot be easily applied to all selected candidate materials as GFRP and vCFRP waste can be mechanically/thermally recycled but rCFRP may not be able to be similarly recycled as the rCF is already in short sizes (6-20 mm) after primary recycling. Future research can look at how to achieve the best secondary life of rCFRP materials in terms of optimised environmental and financial impacts.

It shall also be noted that what considered in this study is not necessarily closed-loop – as it is for a less demanding application (although still in aviation industry) and unsure if further recycling would be viable. Innovation is needed to achieve true closed-loop solutions for aviation industries: e.g., the thermoplastic composites as above which would enable simpler recovery of CFRP while maintaining high mechanical properties and so could be suitable for same demanding applications. However, this still needs to be able to meet design requirements for strength/stiffness/durability.

4 Conclusions

This study presents a complete life cycle environmental and cost analyses by using the rCF from fluidised bed process in aviation industries. The viability of rCFRP materials for closed-loop aviation applications are demonstrated and compared with vCFRP to replace conventional GFRP. rCF materials have significant effect on the environmental benefits and cost-effectiveness in terms of the material selection processes and empower eco-friendly light weighting strategies in the aviation sector. It offers a list of environmental and financial impact categories and a set of valuable data to cover gaps of data availability for the closed-loop recycling and reuse of CFRP material. Results reveal that the specific components of the rCFRP materials could achieve the substantial reduction of weight and optimise the potential environmental and cost benefits.

The mathematical models can be used to predict the material properties of rCFRP and contribute to better understand and optimise emerging technologies in composite fields. It can also be applied to look at other potential rCF markets.

The overall finding identifies significant potential market opportunities in the aviation sector. It can enable industry and policy makers to comprehensively understand the environmental and financial impacts in comparison with conventional material groups in particular at product design stage for weight reduction in aviation industry. It has the potential to support the development of relevant policies to encourage suitable utilisation of rCF materials.

Use phase dominates the overall life cycle cost for aviation application and therefore the environmental impact is driven by component weight: the greater weight reduction during substitution, the lower in-use fuel consumption as well as lower material requirements. The decision making in looking at lightweight vCFRP or rCF markets shall be made carefully between upfront cost and overall life cycle environmental and cost impacts as demonstrated in this study.

Future research can be focused on balanced market application opportunities between high market volume like automotive and low market volume like aerospace given level of scrap available (e.g. milled fibre / speciality non-woven products). It is also highly demanded for the establishment of standards for CF recycling, full LCA database and the policy support from the government and cooperation between upstream and downstream firms under CF supply chain. This can link all stakeholders across upstream and downstream industry partners and end-users to drive sustainable development of CFRP material markets.

Notes

The authors declare no competing financial interest.

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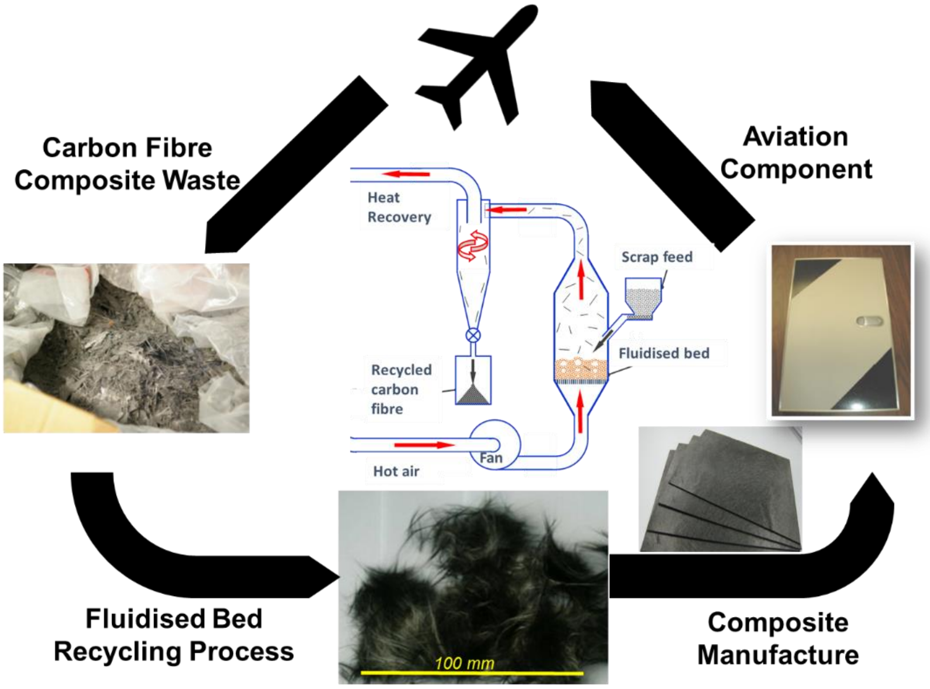


Figure 1 The overview of closed-loop recycling of aviation carbon fibre composite waste.

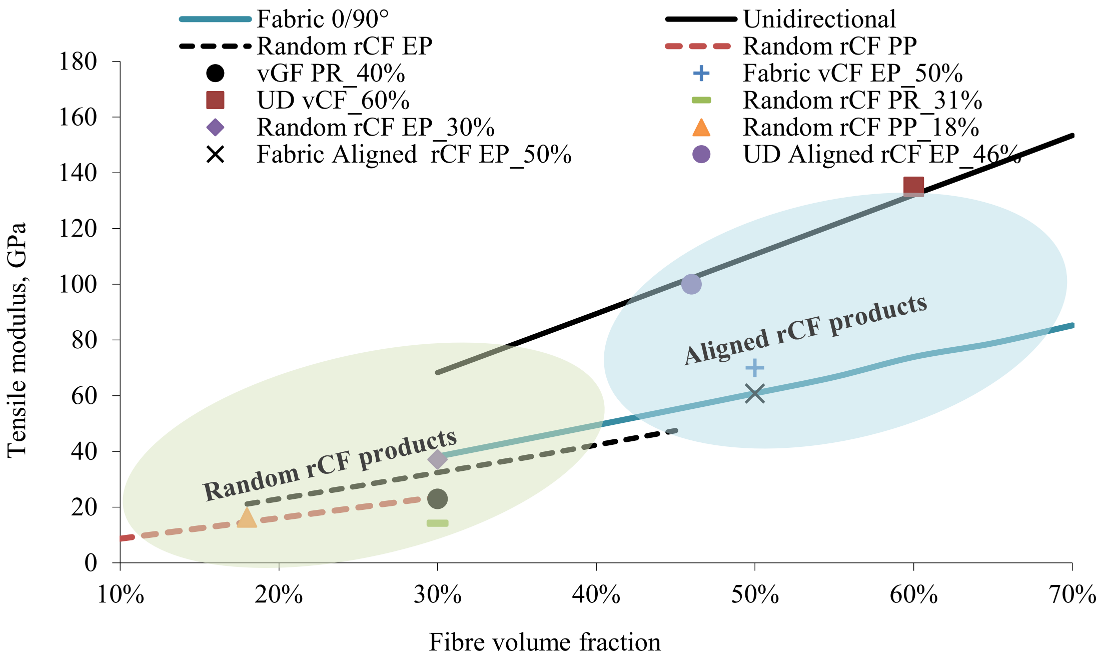
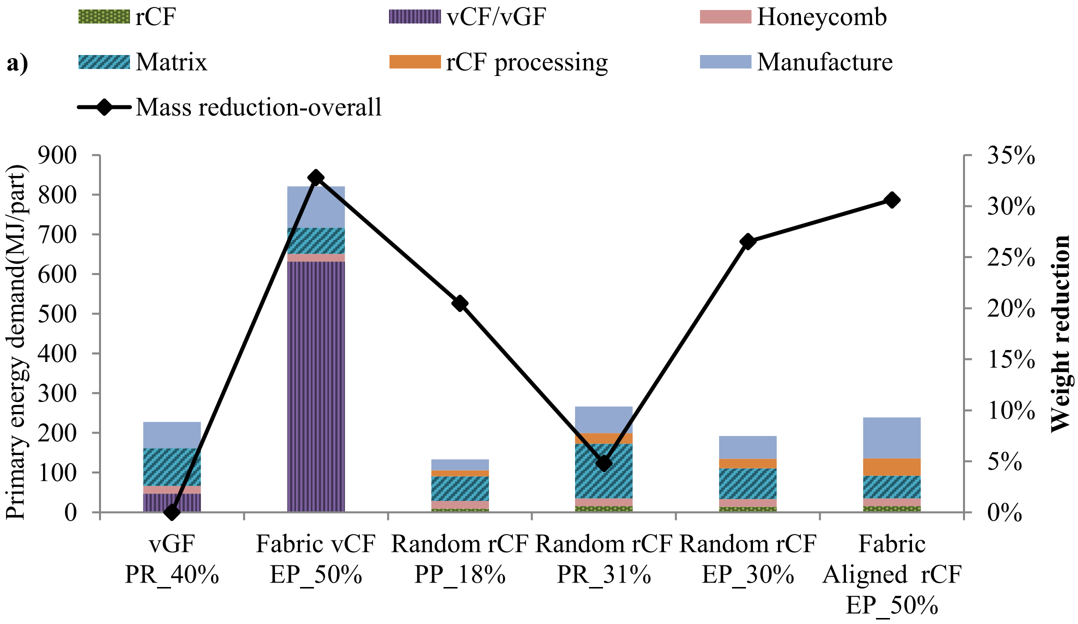


Figure 2 Tensile modulus properties of an epoxy recycled carbon fibre composite experimentally measured. Solid and dotted lines represent the theoretical modulus calculated using the generalized rule for randomly distributed and aligned fibres, respectively.



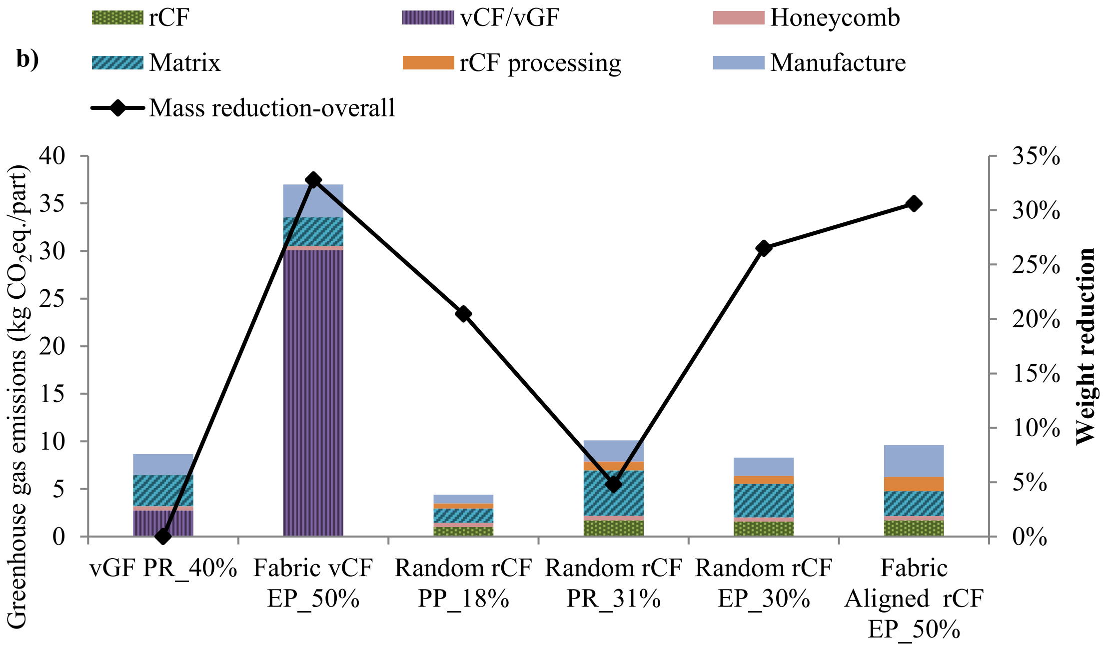
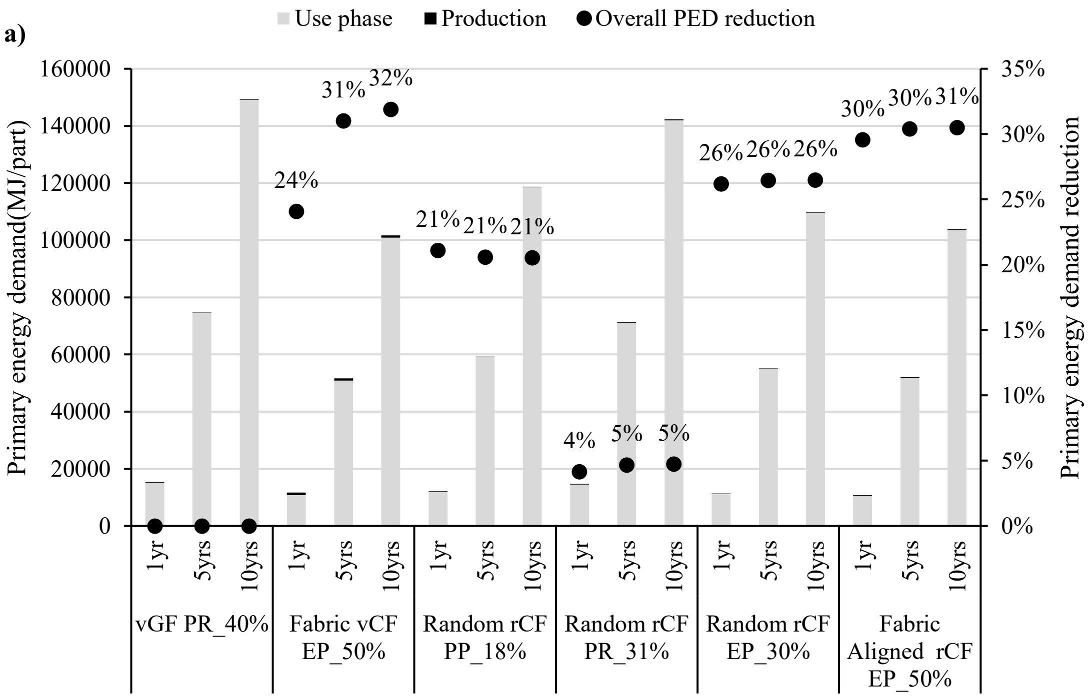


Figure 3 Production a) primary energy demand; b) greenhouse gas emissions; and mass of components made of different materials achieving equivalent stiffness in aircraft components.



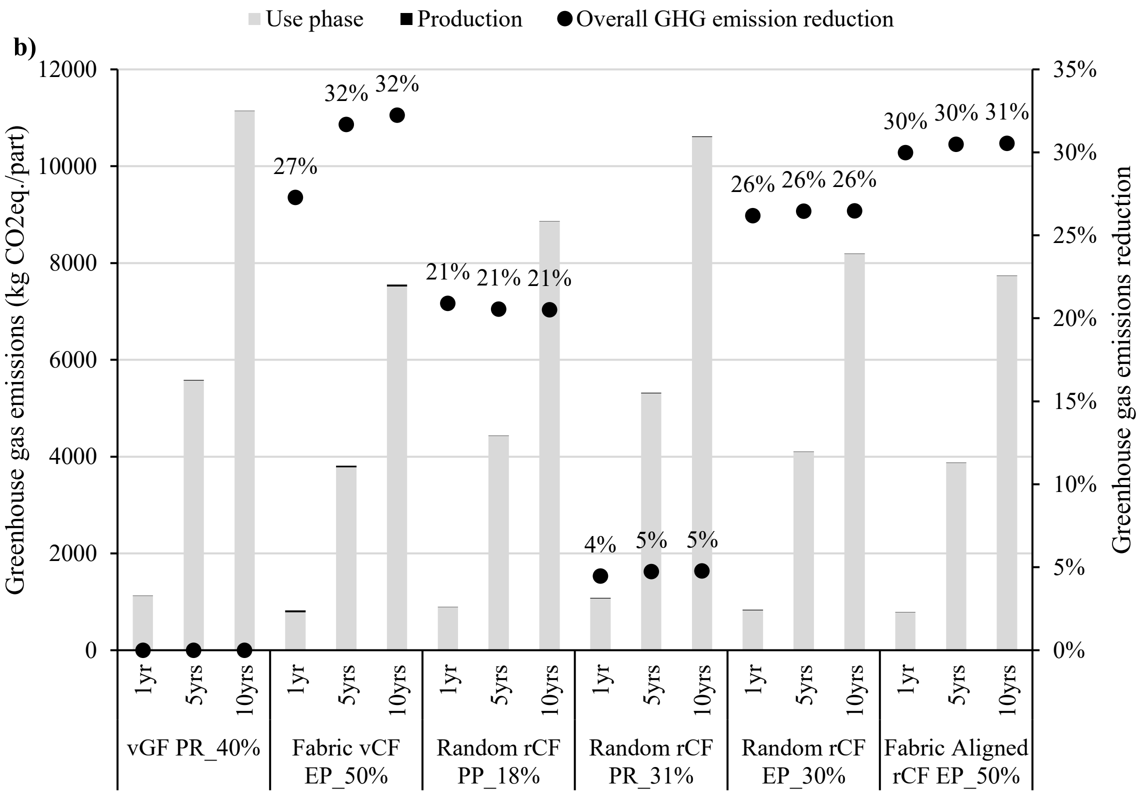


Figure 4 Life cycle with use phase a) primary energy demand; b) global warming potential of components made of different materials achieving equivalent stiffness in aircraft components for different lifetime years.

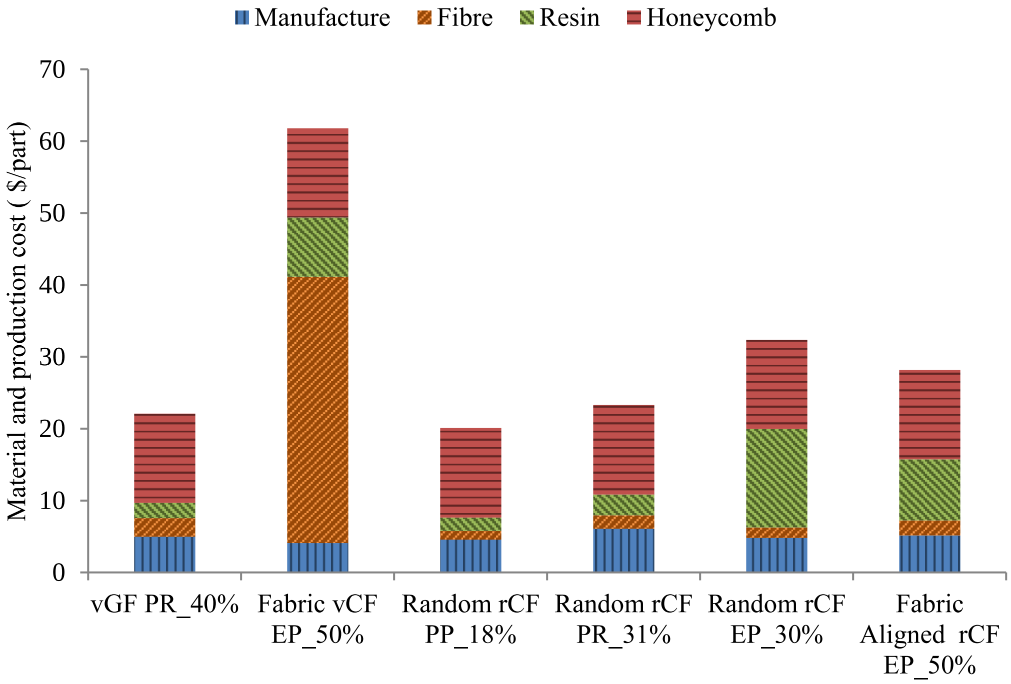


Figure 5 The production cost of aircraft component materials ($/part).

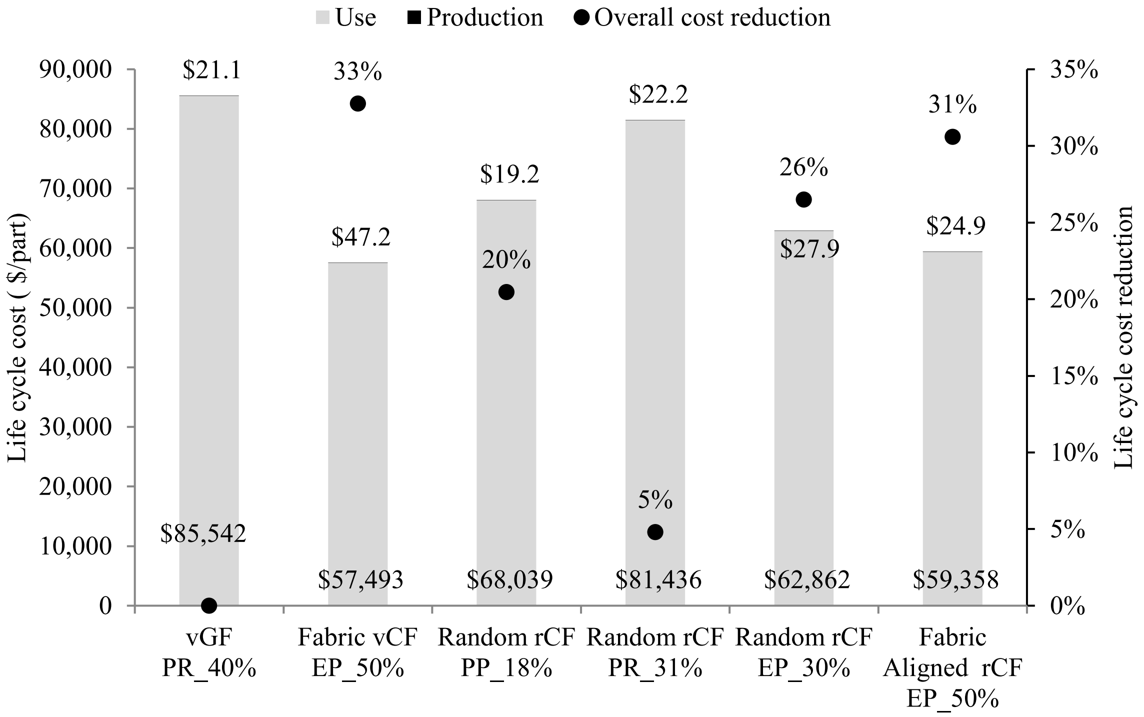


Figure 6 The life cycle cost of aircraft component materials ($/part) for a period of 5 years.