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An Assessment of Financial Viability of Recycled Carbon Fibre in Automotive Applications

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Abstract

Carbon fibre (CF) recycling has been demonstrated to achieve reductions in environmental impacts compared to virgin CF production, but there is limited understanding of the financial viability of recycling and reutilisation of recycled CF (rCF). In this work, cost analysis and identification of market opportunities for rCF are performed by evaluating the cost of recycling, composite manufacture, and applications in automotive industry. Cost impacts of using rCF as a substitute for conventional materials and competitor lightweight materials are assessed over the full life cycle, including in-use implications. Recovery of CF can be achieved at $5/kg and less across a wide range of process parameters, approximately 15% of the cost of producing virgin carbon fibre. The life cycle cost results show that rCF composites, especially aligned rCF composites, give substantial cost reductions relative to virgin CF composites and even steel and aluminium.

Key words

Carbon fibre recycling, life cycle cost analysis, fluidised bed, lightweighting

1 Introduction

Vehicle lightweighting is a potentially effective method to reduce energy consumption in the transportation sector. Due to its low density and high mechanical performance, carbon fibre (CF) has been widely used in lightweighting applications. The global demand for carbon fibre reinforced plastic (CFRP) in automotive industries values $2.4 billion in 2015, and is expected to increase to $6.3 billion by 2021 with an average increase of 17.5% [1]. However, compared to conventional steel and aluminium, the high cost of the manufacture of virgin CF (vCF) has limited the net benefits of lightweighting. It is estimated that the global demand of vCF would be 1.23 million tonnes if it was available at $11/kg [1]; however recent prices are estimated in the range of $33–66/kg [2, 3]. Recycled carbon fibre (rCF) can potentially provide similar lightweighting performance as vCF at a lower cost; however there is limited understanding of the overall financial viability of producing automotive components from rCF.

The generation of CFRP-based wastes is correspondingly increasing along with the increasing demand of CFRP, arising from manufacturing, where up to 40% of the CFRP can be waste arising during manufacture [4-6] and end-of-life products/components. For instance, 6000-8000 commercial aircraft are expected to come to their end-of-life by the year of 2030 [3, 7]. Treatment of CFRP waste must account for environmental and cost impacts. Conventional methods to treat the CFRP wastes, such as landfilling and incineration, incur costs while recovering little value, and are discouraged by policies aimed at reducing waste sent to landfill [8] and increasing the recovery and recycling of materials from end-of-life products, including automobiles under the End-of-life Vehicle Directive [9]. Opportunities to recover CF could thus extract greater value from CFRP waste streams while contributing to a range of policy objectives.

There is very little publicly available cost information regarding the performance of commercial-scale/pilot-scale facilities associated with CF recovery or other waste management options. Mechanical recycling is a mature technology but is only employed at commercial scale to recycle glass fibre reinforced plastics [10]. Significant scale CF recycling plants, based on a pyrolysis process, have been built in Japan, Europe, and US with capacities of 1000–2000 t/yr [11-14]. In contrast, the fluidised bed and chemical processes (supercritical fluid; subcritical fluid) are still transitioning from lab scale to pilot plant, including a fluidised bed pilot plant representative of commercial scale developed at the University of Nottingham. The fluidised bed technology is particularly suitable for dealing with end-of-life CFRP wastes which are likely to be contaminated with other materials [5, 15, 16]. Energy related cost data for CFRP recycling is either based on hypothesis or literature for lab-scale operation. This results in uncertainties/limitations of the financial results as a comprehensive assessment of recycling processes can only be implemented when high quality data is available.

The knowledge gap also exists in the subsequent manufacturing processes of rCFRP in considering the rCFRP applications. Recycled CF are typically in a discontinuous and filamentised form with random orientation and low bulk density, but without tow structures. Therefore, it is difficult in handling and processing compared to vCF with a continuous tow form, which has limited the penetration of rCF into vCF markets so far. A range of techniques have been explored for preparing composite materials from rCF, including rCF conversion processing including wet papermaking process [17, 18] and fibre alignment [18-20]; final composite manufacturing including compression moulding [6, 17], and injection moulding [21]. CFRP using rCF shows retention of excellent mechanical properties, in specific, tensile performance relative to vCF [18, 21, 22]. However, gaps exist in current understanding of rCF conversion techniques for opportunities to produce high performance rCFRP materials in a cost-effective way (e.g. processing time, temperatures, pressures, capacity) and no cost analysis has been conducted previously.

Limited studies have examined the viability of CFRP recycling and utilisation of rCF. Materials produced from rCF can significantly reduce key environmental impacts (greenhouse gas emissions, fossil energy use) in automotive applications when used in place of conventional materials (steel) and alternative lightweighting materials (vCF, aluminium) [4, 16, 23, 24]. However, there is little understanding of the financial performance of recycling and remanufacturing routes to assess CFRP technologies capable of producing rCF suitable for vCF displacement. To date, only one work [25] evaluated the financial viability of mechanical recycling of CFRP waste and use of rCF in place of raw glass fibres, finding that this low value use of rCF provided insufficient revenue to compensate for the costs of CFRP waste collection and CF recovery.

For the full implications of any use of rCF to be considered, technical and financial viability of utilising rCF-based composite materials needs to be evaluated for automotive component manufacture. In this work, a techno-economic analysis is undertaken to determine the financial viability of producing automotive components from rCF. The analysis considers: 1) the minimum rCF selling prices based on key operating parameters of a fluidised bed recycling process; 2) cost of manufacturing automotive components from rCF, competitor lightweight materials (vCF, aluminium) and conventional materials (steel); and 3) in-use fuel costs due to mass-induced fuel consumption in a typical light duty passenger vehicle. Comparisons with conventional and competitor lightweight materials are made to assess financial viability, and provide insights to rCF use in automotive applications.

2 Methods

Techno-economic models are developed to assess the feasibility of rCF use in automotive applications. The techno-economic analysis includes cost modelling of: 1) CF recycling by the fluidised bed process, 2) processing of rCF, 3) manufacture of rCFRP automotive components, and 4) mass-induced fuel consumption. A set of rCFRP manufacturing routes are considered:

(1) Random structure – Compression Moulding: rCF is processed by a wet papermaking process prior to impregnation with epoxy resin and compression moulding. Fibre volume fractions (vf) of 20%, 30%, and 40% are considered.

(2) Aligned – Compression Moulding: rCF is processed by a fibre alignment process prior to compression moulding with epoxy resin. 50%vf and 60%vf are considered.

(3) Random structure – Injection Moulding: rCF is processed by wet papermaking and subsequently chopped prior to compounding with polypropylene (PP); rCF–PP pellets are subsequently injection moulded. Fibre volume fraction is 18%.

The overall life cycle cost of rCFRP components are compared to conventional material (steel) and competitor lightweight materials (aluminium, vCFRP) to assess the relative financial performance of utilising rCF for automotive component manufacture while meeting the same component design criteria (see Section 2.6). The first considers autoclave moulded vCF material typical of high-performance applications wherein bi-directionally woven vCF is autoclaved moulded from prepreg with epoxy resin with a fibre volume fraction of 50%. A second, a similar process wherein chopped, unaligned fibres are compounded with PP and vCF–PP pellets are subsequently injection moulded with a fibre volume fraction of 18%. The CF-based materials are also compared with mild steel manufactured by stamping process, as a conventional automotive material, and potential lightweight materials (aluminium manufactured via casting process) as described in Section 2.5. Vehicle assembly is excluded as costs are assumed to be similar for all materials considered. The end of life stage is also excluded.

The techno-economic models are developed to account for capital cost (CAPEX) such as equipment and financing, and operational cost (OPEX) such as fixed operating and maintenance, utilities costs (e.g., energy), depreciation and overheads. Taxes, subsidies, and profit margins are not included in the analysis. The minimum rCF selling price is determined based on estimated costs of CFRP recycling and key operating parameters of a fluidised bed process (see Section 2.2). Overall life cycle costs of manufacturing automotive components and their in-use fuel costs are calculated for all materials to determine the relative financial performance of rCF-based materials.

Techno-economic modelling is highly sensitive to the accuracy of the input data. A sensitivity analysis is performed to evaluate the impact of uncertainty in the model input parameters. Key parameters such as in-use fuel consumption, vehicle lifetime, fuel price, raw material price are considered in the analysis in Section 3.3.

The comparison analysis is taken to ensure functional equivalence of producing automotive components from the set of materials based on the material design index (λ) [26, 27] in order to broadly understand the financial viability of rCF materials in potential applications. The component thickness is variable and is adjusted based on each material's mechanical properties and the specific design material index (see Section 2.6 for further details). Financial results are presented on a normalised basis (relative to the mild steel reference material), and can thereby be easily applied to subsequent analyses that are undertaken for specific components where the material design index is known.

2.1 Capital and Operational Costs

The CAPEX estimation is undertaken for hypothetical CFRP recycling, rCF processing, and rCFRP manufacturing facilities. Equipment costs are estimated with insights from the Nottingham fluidised bed demonstration plant and laboratory-scale processes developed for rCF processing (papermaking, fibre alignment). Installed costs are estimated for standard equipment, sized to required capacity, and non-standard equipment with indicative cost data from the demonstration plant, using the factor method [28, 29] as shown in Table 1. All major equipment items are designed and costed based on the process information described in Section 2.2-2.5. Costs are then extrapolated to those of year 2015 based on the Chemical Engineering Plant Cost Index [30]:

$$C_{p,v,2015} = C_{p,u,r}\left(\frac{v}{u}\right)^{n}\left(\frac{I_{2015}}{I_r}\right) \tag{1}$$

where $C_{p,v,2015}$ is the equipment CAPEX with capacity v in the year of 2015, $C_{p,u,r}$ is the reference equipment cost at capacity u in year r, I_{2015} is cost index in the year of 2015., I_r is cost index in year r. A scaling factor (n) of 0.6 is assumed. An exponential relationship as shown in Eq. (1) is used to estimate equipment capital costs for different plant capacities. Normalised annual CAPEX is calculated assuming a 15% of return tax rate for a plant life of 10 years [31].

The annual operational cost is calculated as the sum of operating costs (labour, material, utility), plant overheads, and maintenance cost as shown in Table 1 but OPEX information is updated based on actual component of pilot plant or standard equipment where available. The labour cost is estimated based on an hourly pay rate of £18.20 ($27.70) in 2015 [32] for plant operation requirement of 3 shifts per day across 250 days per year (see Table 1). Other operational costs including materials, utilities, plant overheads and maintenance are obtained from publicly available data and, where appropriate, are adjusted to the plant capacities.

2.2 **CF Recycling**

The overall fluidised bed process consists of two main sub-processes: waste CFRP size reduction (shredder, hammer mill) and a fluidised bed process. In the fluidised bed reactor, the epoxy resin is oxidised at a temperature above 500 °C. The gas stream is able to elutriate the released fibres and transport them out of the fluidised bed for separation by cyclone. After fibre separation, the gas stream is directed to a high-temperature oxidiser to complete oxidation of resin decomposition products. Energy is recovered to preheat inlet air to the fluidised bed. Process models of the fluidised bed recycling plant have been developed in our previous study [16, 33], and are used in this work to calculate utilities cost. The rCF minimum selling price is calculated for a set of operational parameters including plant capacity (100–6000 t/yr) and feed rate per fluidised bed area (3–12 kg/hr m^2).

The capital and operational costs associated with rCF are estimated for a fluidised bed plant with a hypothetical throughput of 1000 t/yr as a base case while a range of 100–6000 t/yr is considered in the sensitivity analysis. The main components of the fluidised bed plant are shown in Fig. 1. Cost for shredding is estimated for processing particle size to 25–100 mm and finally to 5–25 mm [28, 29]. An indicative oxidiser capital cost is obtained based on the pilot plant. Fixed costs for all other equipment are estimated based on processing parameters (e.g., flow rate, temperature and pressure) for best operation of the pilot plant using standard equipment and appropriate cost indices, installation factors and other costing factors [28]. All capital costs are adapted for required capacity in the year of 2015 and normalised to annual capital costs.

The OPEX of the selected recycling plant is calculated based on a nominal operating labour of three persons per shift, utility inputs (natural gas, electricity) calculated previously [16], and costs associated with maintenance, supervision and indirect costs as detailed in Section 2.1. Heat recovery from the exhaust stream is assumed to provide additional revenue by displacing natural gas used for an onsite/offsite heating system. The financial value of recovered heat is assumed to be 80% that of the avoided natural gas consumption to account for costs of a heat recovery system. Heat recovery, however, depends on having a customer for the heat; this is discussed further in the results section.

A discounted cash flow analysis is used to determine the rCF minimum selling price (MSP) ($/kg) to achieve a net present value of zero:

$$MSP = \frac{OPEX + ACAPEX - OR}{AO} \tag{2}$$

where OPEX is the operational cost ($/yr), ACAPEX is annualised capital cost ($/yr), OR is other revenue ($/yr), e.g. heat sales, and AO is annual rCF output (t/yr)

2.3 Processing of rCF

Due to its discontinuous, filamentised form and low bulk density, rCF cannot be directly manufactured into CFRP. Currently, there are two methods to convert rCF into intermediate mats: wet papermaking process for random rCF mats and fibre alignment process for aligned rCF mats. In the papermaking process, CF is metered and dispersed in a viscous aqueous solution to form a fibre suspension. The volume fraction of rCF in the suspension is 0.1% based on the best performance to avoid agglomeration tested so far. 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 CF roll. The main equipment of papermaking process consists of mixer, belt conveyer, vacuum dryer and thermal dryer. Capital costs are estimated based on standard equipment, sized to required capacity and non-standard equipment with processing parameters from lab-scale plant. Plant capacity required can be related to quantity of rCF required in final CFRP part manufacture volume. An energy analysis of the papermaking process has been performed based on the processing parameters previously [16] and energy consumption (4 kWh/kg) is used for energy cost estimation in this study. Viscosity modifier cost is estimated assuming a recycling rate of 99.5%, which is achieved by complete recovery during vacuum drying and minor losses during thermal drying. The papermaking process is assumed to need 1.5 labourers per operational shift.

Fibre alignment processes are under development and show promise to allow rCF to be manufactured into CFRP with high fibre volume fractions for high value applications [34]. Similar to the papermaking process, discontinuous rCF is dispersed in a viscous aqueous liquid to form a fibre suspension. The suspension is then pumped into a pressure pot and then pressurized to form a consistent flow via a convergent nozzle. The nozzle is located above a nylon mesh inside a rotating drum. The mesh screen filtered the fibre dispersion to separate the CF. Vacuum suction is employed under the mesh to accelerate the dewatering step. As the alignment process is under development, no cost information is available for fibre alignment rig yet. Instead, we calculate a target cost for alignment to compete financially with competitor materials and randomly oriented rCF materials. Additional alignment costs could be acceptable due to the improved mechanical performance that can be achieved from aligned, high volume fraction rCFRP materials relative to unaligned materials. Target fibre alignment costs are determined in order for aligned rCFRP materials to achieve the same life cycle cost as a conventional steel component and the best performing randomly aligned rCFRP material.

2.4 Component Manufacture

After rCF processing, rCF can be manufactured into the final CFRP products by either compression moulding or injection moulding from random/aligned rCF mats.

A compression moulding method has been utilised to produce rCFRP components from either random or aligned CF at lab scale. In this process, CF mats and epoxy resin film are cut to fit into the mould. The main equipment consists of a compression moulding press and a trimming machine of which fixed capital is \$1.88 million for a 200 t/yr plant [35] and scaled up to the required capacity of component production and extrapolated to 2015. Energy analysis of the process (i.e. heating stage, curing stage, pressure build-up stage and finishing stage) based on heat transfer and force analysis has been reported in a previous publication [16] and used for utilities estimation. The process is assumed to require 1.5 labourers per operational shift.

Injection moulding is also an efficient way to process rCF leading an outstanding mechanical performance when compared to vCF counterparts [21]. The CF is compounded with polymer matrix to produce pellets for injection moulding. The injection moulding facility is made up of compounding, injection and trimming machines and the equipment capital cost ($24.8m for a 144 t/yr plant) [35] and scaled up to the required capacity of component production and extrapolated to 2015. Operational cost is based on material requirements as in the discussion of material substitution under equivalent stiffness, manufacturing energy use (based on previously presented models of energy consumption [23]). This process is assumed to require 1.5 labourers per shift.

The reference component is assumed to be made of hot rolled steel coil. The manufacturing devices are assumed to include a coil handling and a stamping equipment (CAPEX is $18.2m for a 460 t/yr plant), and the manufacturing energy is 0.34 MJ/kg [35]. Aluminium is assumed to be manufactured by wrought methods including casting, punching and machining units (CAPEX is $6.24m for a 210 t/yr plant) and the total energy requirement is 18.43 MJ/kg [36]. Virgin CF is either manufactured by autoclave moulding (CAPEX is $4.50m for 210 t/yr [37]) into woven vCFRP or by injection moulding into chopped vCFRP similar as for rCFRP. Publicly available operational cost data are used to evaluate, including materials, labour and utilities for these manufacturing processes, obtained from process models, literature and online database [36-39] (see Table 2).

2.5 **Use Phase**

In the use phase, the automotive part will influence vehicle fuel consumption due to its weight. Mass-induced fuel consumption is calculated for a typical midsize passenger vehicle (Ford, Fusion) with the Physical Emission Rate Estimator model [40] and a mathematical model [41]. As a base case, a typical vehicle life of 200000 km [35, 42] is assumed. Fuel prices are regionally dependent; as a base case we consider the average 2015 U.K. petrol price (£1.11/litre or approximately $1.70/litre) [43] but consider a range of fuel costs in typical of other jurisdictions. To compare with upfront costs, use phase fuel costs are converted to a present value assuming a 5% discount rate and a vehicle life of 10 years.

2.6 Automotive Component Design Criteria

Automotive components produced from different materials must meet the same design criteria in order to be suitable for their application. In this study, a generic automotive component with requirements of bending and torsion stiffness, assumed to be produced from mild steel, is selected as the reference component and allocated a normalised thickness and mass of 1. When evaluating alternative materials, it is ensured that each meets the component design criteria measured by component stiffness by considering the design material index (λ) and varying component thickness to account for differences in each material's mechanical properties. Properties of rCFRP materials, vCFRP materials, mild steel, and aluminium are obtained from experiments and online databases as in [23] (see Table 3). The mass and thickness ratio among components made of different materials is expressed below:

$$\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/\lambda} \tag{3}$$

$$\frac{t_2}{t_1} = \left(\frac{E_1}{E_2}\right)^{1/\lambda} \tag{4}$$

where E_1, t_1, ρ_1 are the tensile modulus, thickness and density of reference materials (i.e. mild steel), E_2, t_2, ρ_2 are the tensile modulus, thickness and density of replacing material, (e.g. aluminium, CFRP), λ is the component-specific design material index.

Depending on design purposes, the structural index λ value may vary between 1 and 3. λ=1 is for columns and beams under tension conditions; λ=2 is for beam under bending and compression conditions in one plane; and λ =3 is for beam and panel when loaded in bending and buckling conditions in two planes. In order to meet design constraints, finite element simulation is required for actual component designs to identify the material design index. For instance, vehicle structural components have a λ value range of 1.2–2.0 [26] while other car body structural parts have a λ value range of 1.21–2.4 based on finite element analysis [48]. In this work, a range of λ values (1-3) is considered to assess the financial viability of rCF applications across a broad range of potential automotive component applications.

The relative thickness of the components impacts costs for raw material procurement as thicker CFRP components require greater quantities of fibre and matrix materials for functional equivalence. Larger weight components also require higher cost for manufacturing. Moreover, they incur greater in-use fuel consumption associated with mass as will be discussed in the following sections.

3 Results and Discussion

3.1 CF Recovery

Recovery of CF from CFRP wastes can be achieved at under \$5/kg across a wide range of process parameters. Fig. 2 shows the minimum selling price of rCF with a breakdown costs at a range of capacities between 50 and 6000 t/yr. The cost includes all variable and fixed costs associated with the construction and operation of the fluidised bed recycling plant and revenue from heat recovery. The relative contribution of fixed and operational costs is highly dependent upon the plant capacity for recycling. At capacities in excess of 500 t/yr, an rCF minimum selling price of less than \$5/kg can be achieved. Operation at smaller capacities is detrimental to financial viability: at relatively low capacity of 100 t/yr, rCF would have to achieve a market value of \$15/kg to be financially feasible. This is primarily because of the higher relative share of fixed capital and labour costs. At all plant capacities, operational cost accounts for over 50% of the total cost of recycling. As labour cost is determined by the operation requirement of the recycling process itself, and is independent of plant capacity, its relative contribution therefore reduces when the plant capacity grows. For a fixed feeding rate (kg/hr m^2), larger equipment capacities result in lower specific capital cost (\$/t yr) due to economies of scale. Heat recovery from exhaust contributes to reducing the rCF minimum selling price by \$0.17/kg for all capacities. At the base case capacity of 1000t/yr, heat sales represent 6% of rCF recovery costs. If a customer for the heat is not available, rCF recovery cost would correspondingly increase. Sorting, dismantling and transport of waste CFRP to the facility are not included in this analysis, but this could represent significant costs, particularly if manual disassembly is required. However, publicly available data of dismantling cost is limited or lacking for aerospace industries, bringing uncertainty in the total recycling cost. It is reported to cost between £60,000 to £120,000 to dismantle a Boeing 747 airplane giving about £0.33-£0.65/kg [49, 50]. Previous study [25] displays dismantling cost for automotive CFRP waste is £1.38/kg CFRP waste. Transportation costs vary due to waste availability and regional factors when high capacities can be achieved. However, transport costs are expected to be quite small as stated in [25] that £0.043/t-km and 200 km travelling distance making only £0.0086/kg CFRP waste. Therefore, further work is suggested to investigate disassembly cost for aerospace industry and types, locations and quantities of CFRP wastes when data is available to better understand these costs and their impact on financial viability.

The impacts of feed rate per unit fluidised bed area on the minimum selling price of rCF and the breakdown of the costs for a 1000 t/yr plant are shown in Fig. 3. The minimum selling price per kg rCF varies from \$4.9 to \$2.5 with respect to feeding rate of 3 kg/hr m^2 to 12 kg/hr m^2. Prior analysis [16] also shows feeding rate is a key factor for environmental impact which is correlated to the energy input. For a fixed plant capacity, with the increase of feed rate per unit bed area the size of equipment can be reduced. Therefore, the annualised capital cost reduces relative to the increase of feeding rate. Also, plant with higher feeding rate consumes less energy (i.e. natural gas and electricity), and thus, has less utilities cost while the other costs including labours remain unchanged. For instance, the utilities cost is \$0.73/kg (15% of the total) at 3 kg/hr m^2 but reduces to \$0.18/kg (4% of the total) at 12 kg/hr m^2. While cost effectiveness gains are identified to be achievable by increasing feed rate, there are potential trade-offs in terms of resulting rCF properties. To avoid agglomeration in the recycling process at high feed rates, fibre length must be reduced [51]. However, fibre length may also affect the downstream rCFRP manufacturing process and resulting rCFRP properties. The feeding rate has to balance recycling cost and subsequent rCFRP properties.

3.2 Complete Life Cycle Cost

CFRP materials manufactured from rCF can offer cost savings and weight reductions relative to steel and competitor lightweight materials in some cases, but is dependent on the specific application, e.g., material design index, as this drives the weight reduction/in-use fuel consumption and material requirements (see Fig. 4).

With the increasing fibre content, rCFRP materials show better mechanical performance. Thus increasing the fibre volume fraction in CFRP materials is beneficial in reducing component mass for functional equivalence with steel. For design material index λ=2, for instance, significant weight reductions are seen in increasing the fibre content of random rCFRP components from 20%vf (54% reduction) to 30%vf (58% reduction); however, further increase to higher volume fractions of 40%vf compromises the weight reductions due to fibre damage during the manufacturing process while it achieves the same weight reduction as for 30%vf (see scattered dots in Fig. 4). Although achieving further high fibre volume fractions of 50% and 60% provides 65%-67% weight reductions, this requires new fibre alignment techniques.

Weight savings achieved during material substitutions result in in-use fuel saving, and thus, potential life cycle cost benefits. However, the net financial benefits can be compromised for high cost of raw materials. For instance, due to high cost of vCF ($41/kg), the total life cycle cost of vCFRP does not present significant benefits especially for low fibre volume fraction ($1.6/part for vCF 18%) for λ=2 . The normalised life cycle costs including vehicle use for material substitution under different design indices (i.e. λ=1, 2, 3) are shown in Fig. 4, where life cycle cost of the parts made of rCFRP and other alternative lightweight materials are compared relative to steel.

For design index λ =2, which is typical for components under bending and compression conditions in one plane (vertical pillars, floor supports), rCFRP components show slight cost reductions relative to steel over the full life cycle. For random rCFRP parts with different fibre volume fractions, total normalised cost varies between $0.93/part for 20%vf, $0.82/part for 30%vf and $0.81/part for 40%vf. It is noted that for random rCFRP, from 30%vf to 40%vf, the life cycle cost is not expected to be reduced as from 20% to 30%. This is primarily because of different weight reductions achieved between 20-30% and 30-40% as discussed above. Raw material costs account for a large part of the life cycle cost (28-36%) primarily due to the high cost of epoxy resin. On the contrary, although use phase cost of random rCFRP parts is 42–46% that of steel part, these benefits do not compensate the material and manufacturing cost.

Compression moulding random rCFRP part costs only 59–67% of that for injection moulded random rCFRP part in the full life cycle. Compression moulding random rCFRP part with higher fibre volume fraction (20–40%vf) shows better mechanical performance than injection moulded part, which results in greater weight reductions relative to steel. Therefore, injection moulded random rCFRP part with 18%vf has less fuel savings and as such higher life cycle cost compared to compression moulded rCFRP part.

For a panel loaded in bending and buckling conditions in two planes (λ=3), following trends similar to that for λ=2, larger weight savings for rCFRP in replacement of steel are observed and as such more fuel savings can be achieved in the use phase. For random rCFRP components, normalised life cycle costs are $0.70/part for 20%vf, $0.65/part for 30%vf and $0.66/part for 40%vf, respectively (equivalent to cost reductions of 16–21% relative to the reference steel component).

For λ=1, for columns and beams under tension conditions (e.g., a window frame), there is limited scope for lightweighting with any of the materials considered in this work. Even though, fibre alignment could still potentially improve financial performance of rCFRP provided that the target value of $1.3/kg for fibre alignment technique is met.

3.2.1 Cost Target for Fibre Alignment

To achieve high rCF fibre volume fraction, which is necessary to achieve similar mechanical performance as woven vCFRP, fibre alignment is necessary. The life cycle cost results are used to set targets for the development of fibre alignment technologies that are currently under development. Hatched columns on Fig. 4 show the target cost that aligned rCF intermediate materials must achieve to compete with best available random rCFRP (i.e. rCFRP with 30%vf) for λ=2 and λ=3 or with steel for λ=1. Therefore, for instance, life cycle cost for aligned rCFRP component is assumed to be $0.65/part, giving a corresponding target alignment cost of $0.18/part for 50%vf and $0.21/part for 60%vf respectively (λ=3). If rCF can be produced at a cost of $3/kg at an annual throughput of 1000 t/yr as discussed in Section 3.1, higher processing costs (i.e. fibre alignment cost) could be accommodated for high quality aligned rCFRP products to achieve the same cost level as the random rCFRP products or steel under different design constraints in the full life cycle. The target fibre alignment cost is $10-16/kg aligned rCF mat compared to $11.6/kg random rCF mat via papermaking process under λ=2, 3 while the target value has to be as low as $1.3/kg in order to achieve the same life cycle cost with steel under λ=1.

In Fig. 5, the general performance trends of life cycle cost relative to weight savings are presented for rCFRP materials and compared to steel and other lightweight materials. Cost data for members of a particular group of material (e.g. vCFRP, rCFRP) cluster together and can be enclosed by an envelope. As previously discussed, greater weight and life cycle cost reductions can be achieved at higher design criteria indices. With the increase of lambda values, using rCF materials to replace steel show more life cycle cost reductions as well as weight reductions. This demonstrates the more appropriate cost effective applications of rCF materials in beam/panel part manufacture under bending conditions. Results also indicate larger cost savings together with weight savings can be achieved by using high-fibre-volume-fraction rCFRP. Compared to vCFRP, providing the same weight reduction, aligned rCFRP materials potentially lead to larger life cycle cost reductions in replacement of steel in automotive parts. This demonstrates fibre alignment could potentially improve financial performance provided technology development targets are met.

3.2.2 Cost Effectiveness of Reducing GHG Emissions

The normalised financial costs of components (relative to steel) are compared with previously reported life cycle GHG emissions (including material production, component manufacture, and use-phase emissions) and also normalised against emissions from conventional steel components [23] (Fig. 6). Materials in the lower half of the figure reduce life cycle cost relative to the reference steel component while materials in the left-hand side of the figure can reduce GHG emissions relative to steel; materials capable of reducing both cost and GHG emissions are therefore located in the lower left quadrant. With higher lambda values, using rCF materials to replace steel achieves greater life cycle cost reductions as well as GHG emission reductions. Relative to vCFRP components, rCFRP can achieve both lower life cycle costs and greater avoided GHG emissions. Compared to lightweight aluminium, compression moulded random rCFRP materials enable greater GHG emissions reductions; and they exhibit lower cost at varying fibre volume fractions for λ=3, only lower cost at higher fibre volume fractions (no less than 30%vf as observed) for λ=2, but higher cost for λ=1. Therefore, for λ=2 and 3, unaligned rCFRP materials can save cost and provide an added benefit of reducing GHG relative to aluminium, giving negative carbon abatement costs of -\$52.9/t CO_2eq. (λ=2) and -\$178.9/t CO_2eq (λ=3), respectively . Although rCFRP is able to reduce GHG emissions relative to aluminium for λ=1, the higher relative cost of rCFRP components in this case results in an overall cost of avoided CO_2eq. emissions of in excess of \$900/t CO_2eq., which far exceeds estimates of the social cost of carbon (~\$40/t CO_2eq. in 2015)[52] and thus is not a cost-effective means of reducing GHG emissions.

3.3 Sensitivity Analysis

The cost analysis entails uncertainties, as not all costs of stages of the life cycle are known in the design process. Variation in key parameters in the life cycle (in-use fuel consumption, vehicle lifetime, fuel price, raw material price) would incur sensitive results.

Uncertainty associated with mass-induced fuel consumption and vehicle lifetime does not alter the finding that rCFRP components significantly reduce the life cycle cost among the lightweight substitution materials from a life cycle perspective (see Fig. 7). Mass-induced fuel consumption is estimated to be

0.26–0.44 L/(100 km·100 kg) for different brands of midsized light duty vehicles. Mass-induced fuel consumption of 0.38 L/(100 km·100 kg) for Ford Fusion vehicle in 2015 is selected as the base case for life traveling distance of 200000 km as presented in Fig. 6. Across the range of values considered herein, rCFRP materials maintain the lowest life cycle cost impact. Aligned rCFRP materials offer possibilities for further life cycle cost savings than random rCFRP and weight reductions while maintaining good mechanical properties, but fibre alignment technique is still under development. It is also noted that due to the high energy intensity of vCF production, vCFRP with low fibre volume fraction (18%) only exhibit cost savings when the mass induced fuel consumption is larger than 1.48 L/(100 km·100 kg).

Similarly, life cycle cost increases with traveling distance, depending on the mass of the substitution alternatives, the initial cost of raw material and part manufacturing. At extended vehicle lifetime (up to 300000 km), cost advantages of lightweight materials become more pronounced. Aligned rCFRP components reduce life cycle cost relative to steel by up to 60% excluding fibre alignment; fibre alignment could potentially improve financial performance (see dashed lines in Fig. 7) provided technology development targets are met, demonstrating lowest cost from use of high volume fraction rCFRP. CFRP components from vCF become favourable to steel when vehicle life exceeds 566000 km (λ=2). Conversely, shorter vehicle life reduces in-use fuel savings and is therefore detrimental to the performance of lightweight materials. However, rCF components can reduce life cycle cost relative to conventional steel components even with relatively short distances travelled (~180000 km). Conventional lightweight aluminium also shows cost reductions from the very start of the life.

Life cycle costs are sensitive to fuel price similar with the variations in mass-induced fuel consumption (see Fig. 8). Life cycle cost shows linear relationships with fuel price, but rCFRP materials continue to show significant cost reductions across the range of values considered in this study. For each material type, cost variations between -60% and +30% is shown. This is based on historic fuel price range of \$1.22 –2.07/L (£0.8–1.35/L) in the UK from 2000 to 2015 [43] with a reference price of \$1.70/litre (£1.11/L) in 2015. Considering proportional relationship between the fuel consumption and the part mass, for functional equivalence, weight savings mean cost reductions in the replacement and therefore fuel price directly impact quantities of fuel savings. The total life cycle cost varies –7% – +5% for rCF 30% compared to -13% –+10% for steel relative to the base case (\$1.70/L) mainly due to larger mass-induced fuel consumption for steel part. Results are compared for regional variations amongst US, Canada, EU average and Netherlands due to different fuel prices in 2015. Because of regional variations in transport fuel tax rates, rCFRP show variations in net cost savings relative to steel, for instance, the net cost saving of using rCFRP to replace steel in the US is smaller than that in Netherlands.

Uncertainty in raw material prices brings sensitivity of life cycle cost results depending on the material types (Fig. 9). The price range is mostly considered under historic figures from 2000 to 2015. For rCF, the prices vary depending on the plant capacities and feeding rate as discussed in Section 3.1 in the region of \$1.2–5/kg under common industrial scales (500–6000 t/yr). As raw material costs account for a relatively small part, the total life cycle cost of steel part has only -0.3%–+0.3% variations corresponding to variations of -13%–+13% for the steel price. Variations of rCF price also have an impact on the total life cycle cost of rCFRP components: -58%–+78% variations of rCF price result in -6%–+7% variations for random rCFRP with 30%vf. Excluding alignment cost, life cycle costs for aligned rCFRP components is sensitive to rCF price showing relatively high variations of -8%–+9% with high rCF content (60%). Virgin CFRP components are sensitive to vCF prices (-25%–+25% variations) that the life cycle cost shows -10%–+8% variations for woven vCFRP primarily due to the large proportion of vCF production cost in the full life cycle.

4 Conclusions

The need for a systematic identification of the utilisation of rCF materials in order to reduce life cycle costs has been addressed. In this work, techno-economic models have been developed for cost impact assessment of a hypothetical commercial-scale fluidised bed recycling plant and rCFRP manufacturing technologies to identify the market opportunities for rCF. Recovery of CF from CFRP wastes can be achieved at \$5/kg or less across a wide range of key process parameters including plant capacity (100 t/yr–6000 t/yr) and feeding rate per unit bed area (3 kg/hr m^2 – 12 kg/hr m^2), approximately 15% of the cost of producing vCF. At all plant capacities, operational cost accounts for over 50% of the total cost of recycling. Increasing feeding rate is beneficial to reducing the capital and operational cost but it has to balance recycling cost and subsequent rCFRP properties.

The manufacture of rCFRP is selected for case studies in terms of material selection and substitution for steel under different design indices. Case studies are used to assess the life cycle cost performance of rCFRP which is required to be addressed before it is used widely in applications in automotive industries.

The comparative assessment showed that rCFRP can be a competitive material that can replace conventional metal materials and vCFRP materials in automotive applications. It is observed that significant weight savings are achieved by rCFRP materials in substituting steel materials while providing the same mechanical properties. Random rCFRP shows significant life cycle cost reduction for λ=3 (30-35%) and for λ=2 (7-19%), but cost increase for λ=1. Aligned rCFRP as the lightest substitution alternative could potentially improve financial performance for all material indexes (more than 35% cost reduction) provided technology development targets are met. Financial credits are primarily from the vehicle in-use fuel cost savings due to mass-induced fuel consumption associated with mass reduction. The cost is already competitive with the conventional steel component, prior to monetising the environmental benefits of rCF materials (e.g. social cost of carbon).

Injection moulded rCFRP parts cost 33-41% more than those manufactured by compression moulding. However, injection moulding process allows for close tolerances in small parts with complex geometries at high production rates, and it requires little post-production work as parts have a finished shape after ejection, which is very suitable for CF/matrix part formation.

Uncertainty associated with mass-induced fuel consumption, vehicle lifetime, and fuel price does not alter the findings of life cycle cost reductions obtained by using rCFRP materials to replace conventional steel components relative to aluminium and vCFRP materials.

This is one of a few studies on CFRP recycling that offers financial assessment of CFRP recycling and reutilisation of rCF. It offers an extensive list of environmental and financial impact categories, and a set of valuable data to cover some gaps of data availability for the CFRP recycling process as well. While developed to assess financial viability of fluidised bed recycling process in automotive application, the method could be applied to any CFRP recycling technologies and reutilisation of rCFRP materials in other structural and/or non-structural applications.

The findings of this study together with previous life cycle assessment results provide insight for decision-makers seeking to use rCF composite materials, especially considering for reductions in weight, energy intensity, greenhouse gas emissions and life cycle costs. Opportunities to use rCF materials exist in automotive components such as vertical pillar and car hood under bending conditions as demonstrated using material indexes. The results are in particular important as they support the emerging commercialisation of CF recycling technologies, identify significant potential market opportunities in the automotive sector, and set critical development targets for rCF processing to improve cost and environmental performance.

In terms of applications of rCFRP, not restricted to automotive industries, future research could evaluate in more detail specific applications of rCFRP materials, such as aerospace, wind energy and sporting industries. Their environmental and financial impacts could be assessed for a creation of reutilisation pathway databases and trade-off strategies for waste management of CFRP wastes.

Appendix A.

Table A1

Manufacturing costs of 1000 t/yr rCF recycling plant

Conflicts of interest

There are no conflicts to declare.

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References

[1] Mazumdar S. The road to success in carbon composites for the automotive market. JEC composites magazine2016. p. 21-3.

[2] Meng F, McKechnie J, Pickering SJ. Towards a circular economy for end-of-life carbon fibre composite materials via fluidised bed process, In 21st International Conference on Composites Materials (ICCM-21). Xi'an, China, 20-25 August 2017, 2017.

[3] Carberry W. Airplane Recycling Efforts benefit boeing operators. Boeing AERO Magazine QRT. 2008;4(08):6-13.

[4] Witik RA, Teuscher R, Michaud V, Ludwig C, Manson J-AE. Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. Composites, Part A. 2013;49:89-99.

[5] Pickering SJ. Recycling technologies for thermoset composite materials—current status. Composites, Part A. 2006;37(8):1206-15.

[6] Pimenta S, Pinho ST. Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. Waste Manage (Oxford). 2011;31(2):378-92.

[7] McConnell VP. Launching the carbon fibre recycling industry. Reinf Plast. 2010;54(2):33-7.

[8] European Council. Directive 1999/31/EC on the landfill of waste. Off J Eur Union L. 1999;182:1-19.

[9] European Council. Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles. Off J Eur Union L. 2000;L.269:34-269.

[10] Oliveux G, Dandy LO, Leeke GA. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. Prog Mater Sci. 2015;72:61-99.

[11] Carbon Conversions. <http://www.carbonconversions.com/>, (accessed June 2016).

[12] KARBOREK RCF. <http://www.karborekrcf.it/home/en/>, (accessed July 2016).

[13] CFK Valley Stade Recycling GmbH and Co KG. <http://www.cfk-recycling.com>, (accessed July 2016).

[14] ELG Carbon Fibre Ltd. <http://www.elgcf.com/>, (accessed September 2016).

[15] Pickering SJ, Turner TA, Meng F, Morris CN, Heil JP, Wong KH, et al. Developments in the fluidised bed process for fibre recovery from thermoset composites, In CAMX 2015 - Composites and Advanced Materials Expo. 2015; pp 2384-94.
[16] Meng F, McKechnie J, Turner TA, Pickering SJ. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Composites, Part A. 2017;100:206-14.
[17] Wong KH, Pickering SJ, Turner TA, Warrior NA. Compression moulding of a recycled carbon fibre reinforced epoxy composite, In SAMPE 2009 Conference. Baltimore, Maryland, 2009.
[18] Wong KH, Turner TA, Pickering SJ. Challenges in developing nylon composites commingled with discontinuous recycled carbon fibre., In 16th European conference on composite materials. Seville, Spain, 2014.
[19] Yu H, Potter K, Wisnom M. A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method). Composites, Part A. 2014;65:175-85.
[20] Liu Z, Wong K, Thimsuvan T, Turner T, Pickering S. Effect of fibre length and suspension concentration on alignment quality of discontinuous recycled carbon fibre, In 20th International Conference on Composite Materials. Copenhagen, 2015.
[21] Wong KH, Syed Mohammed D, Pickering SJ, Brooks R. Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite. Compos Sci Technol. 2012;72(7):835-44.
[22] Meredith J, Cozien-Cazuc S, Collings E, Carter S, Alsop S, Lever J, et al. Recycled carbon fibre for high performance energy absorption. Compos Sci Technol. 2012;72(6):688-95.
[23] Meng F, McKechnie J, Turner T, Wong KH, Pickering SJ. Environmental aspects of use of recycled carbon fibre composites in automotive applications. Environ Sci Technol. 2017;51(21):12727–36.
[24] Meng F, Pickering SJ, McKechnie J. Environmental aspects of recycled carbon fibre composite products, In SAMPE Europe Conference & Exhibition. Liege, Belgium, September 2016, 2016.
[25] Li X, Bai R, McKechnie J. Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes. J Cleaner Prod. 2016;127:451-60.
[26] Patton R, Li F, Edwards M. Causes of weight reduction effects of material substitution on constant stiffness components. Thin Wall Struct. 2004;42(4):613-37.
[27] Ashby MF. Materials Selection in Mechanical Design(3rd edition). Butterworth-Heinemann, Oxford, UK2005.
[28] Ulrich GD. A Guide to Chemical Engineering Process Design and Economics: Wiley New York; 1984.
[29] Gerrard A. Guide to Capital Cost Estimating: IChemE; 2000.
[30] Chemical Engineering. Chemical Engineering's Plant Cost Index. 2015.
[31] Pickering SJ, Kelly RM, Kennerley JR, Rudd CD, Fenwick NJ. A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. Compos Sci Technol. 2000;60(4):509-23.
[32] Eurostat Statistics Explained. Estimated labour costs for the whole economy in EUR, 2015. <http://ec.europa.eu/eurostat/statistics-explained/index.php/Main_Page>, (accessed July 2016).
[33] Meng F, Pickering SJ, McKechnie J. Inventory analysis of fluidised bed recycling of carbon fibre reinforced polymers, In SAMPE Europe Conference & Exhibition. Amiens, France, September 2015, 2015.
[34] Wong KH, Turner TA, Pickering SJ, Warrior NA. The potential for fibre alignment in the manufacture of polymer composites from recycled carbon fibre. SAE Int J Aerosp. 2010;2:225-31.
[35] Witik RA, Payet J, Michaud V, Ludwig C, Månson J-AE. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Composites, Part A. 2011;42(11):1694-709.
[36] Sullivan J, Burnham A, Wang M. Energy-consumption and carbon-emission analysis of vehicle and component manufacturing. Argonne National Laboratory (ANL); 2010.

[37] Witik RA, Gaille F, Teuscher R, Ringwald H, Michaud V, Månson J-AE. Economic and environmental assessment of alternative production methods for composite aircraft components. J Cleaner Prod. 2012;29–30(0):91-102.

[38] Ingarao G, Deng Y, Marino R, Di Lorenzo R, Lo Franco A. Energy and CO2 life cycle inventory issues for aluminum based components: the case study of a high speed train window panel. J Cleaner Prod. 2016;126:493-503.

[39] InfoMine. Charts and Data for the Mining Industry. <http://www.infomine.com/ChartsAndData/>, (accessed August 2016).

[40] US EPA. Dynamometer Drive Schedules. <http://www.epa.gov/nvfel/testing/dynamometer.htm>, (accessed June 2016).

[41] Kim HC, Wallington TJ, Sullivan JL, Keoleian GA. Life Cycle Assessment of Vehicle Lightweighting: Novel Mathematical Methods to Estimate Use-Phase Fuel Consumption. Environ Sci Technol. 2015;49(16):10209-16.

[42] Helms H, Lambrecht U. The potential contribution of light-weighting to reduce transport energy consumption. Int J Life Cycle Assess. 2007;12(1):58-64.

[43] UK Department of Energy & Climate Change. Typical retail prices of petroleum products and a crude oil price index. 2015.

[44] MatWeb. Technical Data Sheet-AISI 1017 Steel, cold drawn. <http://www.matweb.com/>, (accessed July 2016).

[45] Kelly JC, Sullivan JL, Burnham A, Elgowainy A. Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions. Environ Sci Technol. 2015;49(20):12535-42.

[46] ASM Aerospace Specification Metals Inc. Aluminum 6061-T6. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6>, (accessed December 2015).

[47] GoodFellow. Technical Information - Carbon/Epoxy Composite. <http://www.goodfellow.com/>, (accessed August 2016).

[48] Cui X, Zhang H, Wang S, Zhang L, Ko J. Design of lightweight multi-material automotive bodies using new material performance indices of thin-walled beams for the material selection with crashworthiness consideration. Mater Des. 2011;32(2):815-21.

[49] Cacciottolo M. 2010, How do you recycle a jumbo jet? <http://news.bbc.co.uk/1/hi/magazine/8542482.stm>.

[50] Boeing. Boeing 747-400/-400ER. <http://www.boeing.com/resources/boeingdotcom/company/about_bca/startup/pdf/historical/747-400-passenger.pdf>, (accessed January 2018).

[51] Jiang G, Wong W, Pickering S, Rudd C, Walker G. Study of a fluidised bed process for recycling carbon fibre from polymer composite, In 7th world congress for chemical engineering, Glasgow, UK. 2005.

[52] US EPA. The Social Cost of Carbon. <https://www.epa.gov/climatechange/social-cost-carbon>, (accessed April 2017).

[53] MEPS (International) LTD. MEPS - WORLD CARBON STEEL PRICES. <http://www.meps.co.uk/World%20Carbon%20Price.htm>, (accessed July 2016).

[54] Warren C. Low cost carbon fiber overview. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 2011.

[55] Easy Composites Ltd. EL2 Epoxy Laminating Resin. <http://www.easycomposites.co.uk/#!/resin-gel-silicone-adhesive/epoxy-resin/EL2-epoxy-laminating-resin.html>, (accessed September 2016).

[56] MRC Ltd. Price report: polypropylene. <http://www.mrcplast.com/reports/icis-mrc-price-report-polypropylene.html>, (accessed July 2016).

[57] Dempsey N, Barton C, Hough D. Energy prices- Commons Briefing papers SN04153. 2015.

[58] PlastiComp Inc. 30% Long Carbon Fiber Reinforced PP – Complēt LCF30-PP. <http://www.plasticomp.com/complet-lcf30-pp/>, (accessed June 2016).

Table 1.

Summary of the cost model input data.

Items		Values
CAPITAL COSTS		
Fixed capital, C_{FC}		C_{FC}=Purchase cost $(1+f_{10}+f_{11}+f_{12})$
Working capital, C_{WC}		C_{WC}=15% C_{FC}
Total capital investment, C_{TC}		$C_{TC}=C_{FC}+C_{WC}$ /available data
OPERATIONAL COSTS		
Direct		
Raw materials	Steel	\$0.43/kg [53]
	Aluminium	\$1.65/kg [39]
	vCF	\$41/kg [54]
	Epoxy resin	\$16/kg[55]
	Polypropylene	\$1.35/kg [56]
Utilities	Electricity cost	£0.09 (\$0.14)/kWh [57]
	Natural gas cost	£0.007(\$0.011)/MJ[57]
Maintenance		5-10% of fixed capital (6% used)
Operating labour	Labour costs	£18.20 (\$27.70) per hour [43]
	Working days per year	250
	Shifts	8 h/3 per day
Indirect		
Plant overheads		60% of operating labour
Insurance		0.5% of the fixed capital
General expenses		
Administrative costs		25% overhead
Distribution and selling costs		5% of total expense
Research and development		5% of total expense
Production volume		50000 parts/yr
Production period		10 yrs
Depreciation time		10 yrs (estimated machine lifetime)
Use		Premium unleaded gasoline in 2015: \$1.70/litre [32]

Table 2.

Summary of cost data of manufacturing routes

Items		Steel	Aluminium	CFRP		
Manufacture type		Stamping	Casting	IM	CM	AM
Part manufacture	Equipment	$18.2m [35]	$6.24m [35]	$24.8m [35]	$1.96m [35]	$4.50m [37]
	Plant capacity	460 t/yr	210 t/yr	144 t/yr	200 t/yr	210 t/yr
	Energy	0.34 MJ/kg	18.43 MJ/kg	3-4 MJ/kg	15-20 MJ/kg	33 MJ/kg
	Labour	4	2	1.5	1.5	2

CM = compression moulding, IM = injection moulding, AM = autoclave moulding

Table 3.

Material properties of selected materials in the study

Material	Matrix	Manufacture	Density, g/cm3	Modulus, GPa	Strength, MPa	References
Mild steel	-	Stamping	7.81	207	350	[44]
Aluminum	-	Wrought	2.70	69	276	[46]
Random rCF 20%	Epoxy resin	Compression molding	1.32	27.6	260	[17]
Random rCF 30%	Epoxy resin	Compression molding	1.38	37.1	341	[17]
Random rCF 40%	Epoxy resin	Compression molding	1.44	39.8	302	[17]
Aligned rCF 50%	Epoxy resin	Compression molding	1.50	60.8	-	calculated
Aligned rCF 60%	Epoxy resin	Compression molding	1.56	73.9	-	calculated
Woven vCF 50%	Epoxy resin	Autoclave molding	1.6	70	570	[47]
Random rCF 18%	PP	Injection molding	1.17	16.3	125	[20]
Chopped vCF 18%	PP	Injection molding	1.07	16.2	117	[58]

Table A2

Manufacturing costs of 1000 t/yr rCF recycling plant

Job title: Fluidised bed recycling plant
Location: Nottingham

Date estimate carried out: September 2016
Capacity: 1000 t/yr rCF
Cost index type: Chemical Engineering in 2015
Cost index value: 557.91

CAPITAL COSTS		
Fixed capital, C_{FC}	\$4,117,108	$C_{FC}=PPC*(1+f_{10}+f_{11}+f_{12})$
Working capital, C_{WC}	\$617,566	$C_{WC}=15\%\ C_{FC}$
Total capital investment, C_{TC}	\$4,734,674	$C_{TC}=C_{FC}+C_{WC}$
OPERATIONAL COSTS		
Direct	\$/yr	
Raw materials		CFRP waste
Miscellaneous materials		10% of maintenance
Utilities	254,914	Electricity and natural gas
Maintenance	247,026	5–10% of fixed capital (6% used)
Operating labour	499,378	from manning estimate
Supervision	74,907	15% of operating labour
Operating Supplies	24,703	10% of maintenance
Laboratory charges	49,938	10% of operating labour
Royalties		1% of the fixed capital
Total, A_{DME}	1,150,866	
Indirect		
Plant overheads	492,787	60% of operating labour
Insurance	20,586	0.5% of the fixed capital
Total, A_{IME}	554,543	
Total manufacturing expense (excluding depreciation), $A_{ME}=A_{DME}+A_{IME}$	1,725,995	
General expenses		
Administrative costs	123,197	25% overhead
Distribution and selling costs	102,733	5% of total expense
Research and development	102,733	5% of total expense
Total, A_{GE}	328,662	
Total expense, A_{TE}	2,031,785	$A_{TE}=A_{ME}+A_{BD}+A_{GE}$
Revenue from sales, As		
rCF/ \$2.83/kg	2,805,710	MSP
Process steam/ \$0.009/kg rCF	169,467.66	

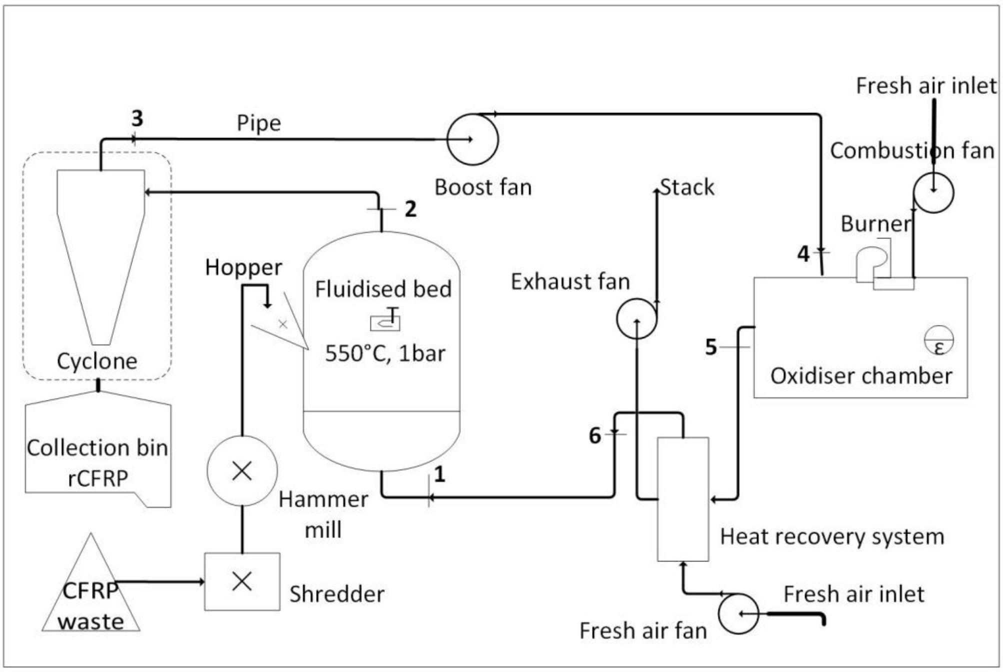


Fig. 1. Main components and flow directions of the fluidised bed CFRP recycling process

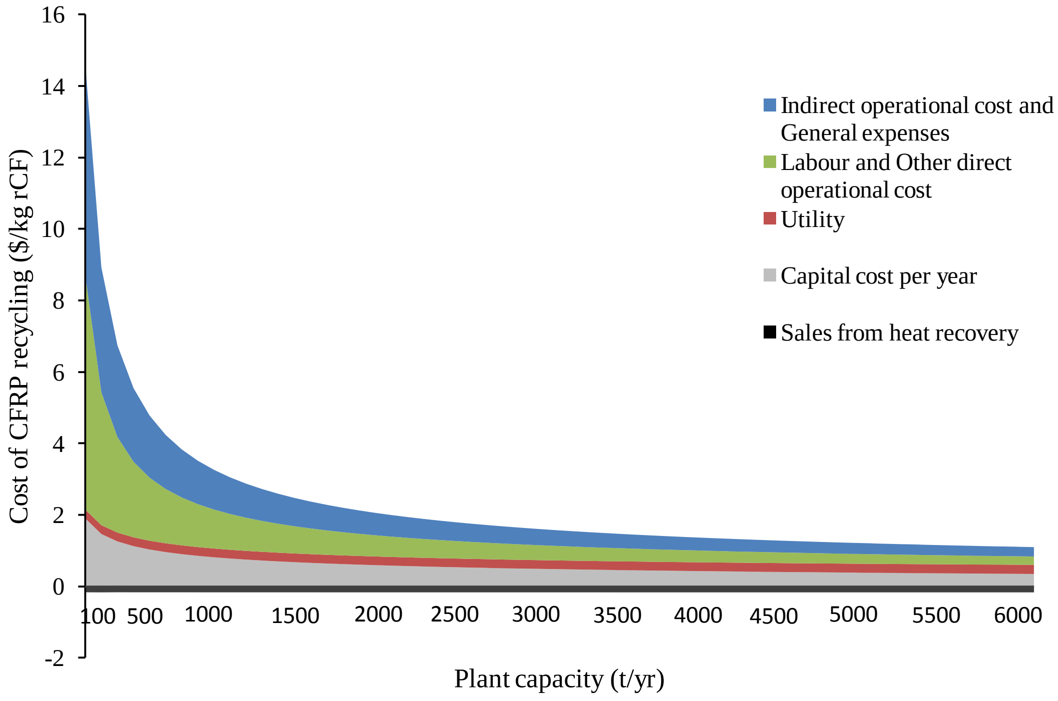


Fig. 2. Minimum selling price of rCF and breakdown cost components for different plant capacities at feed rate of 9 kg/hr m^2.

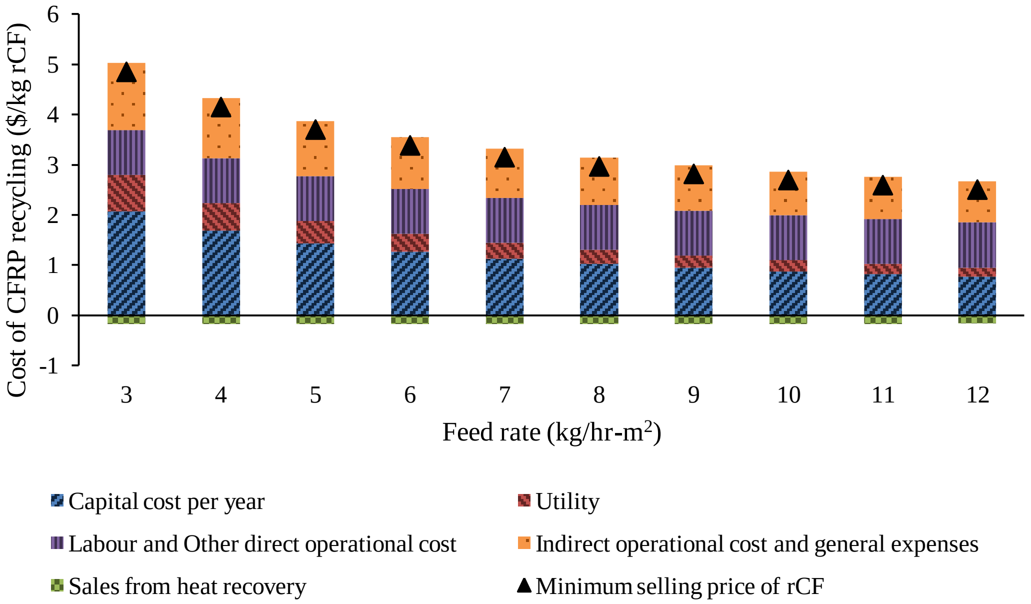
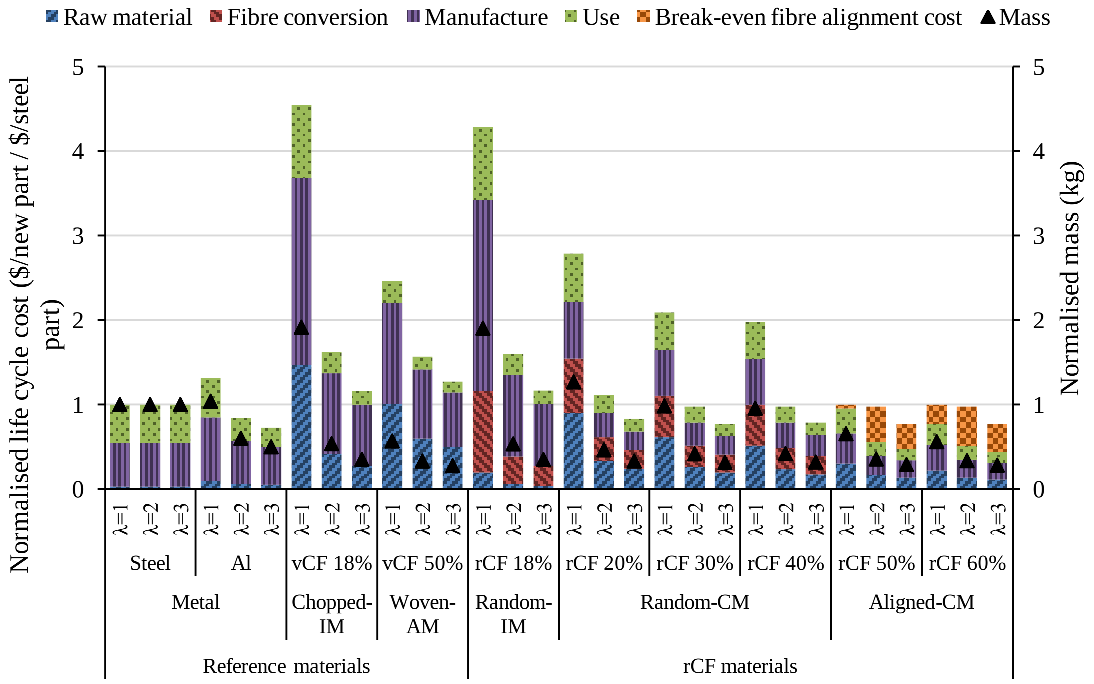
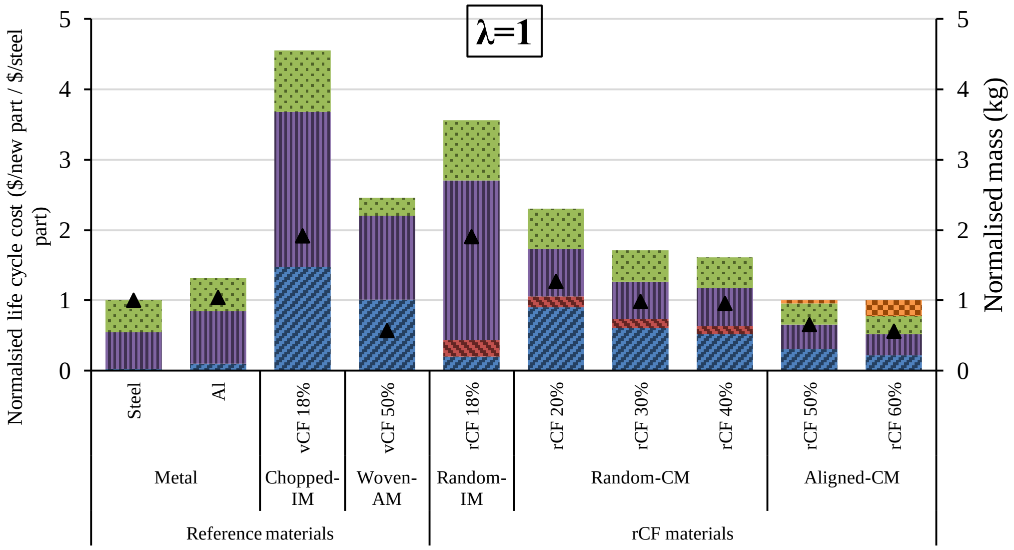
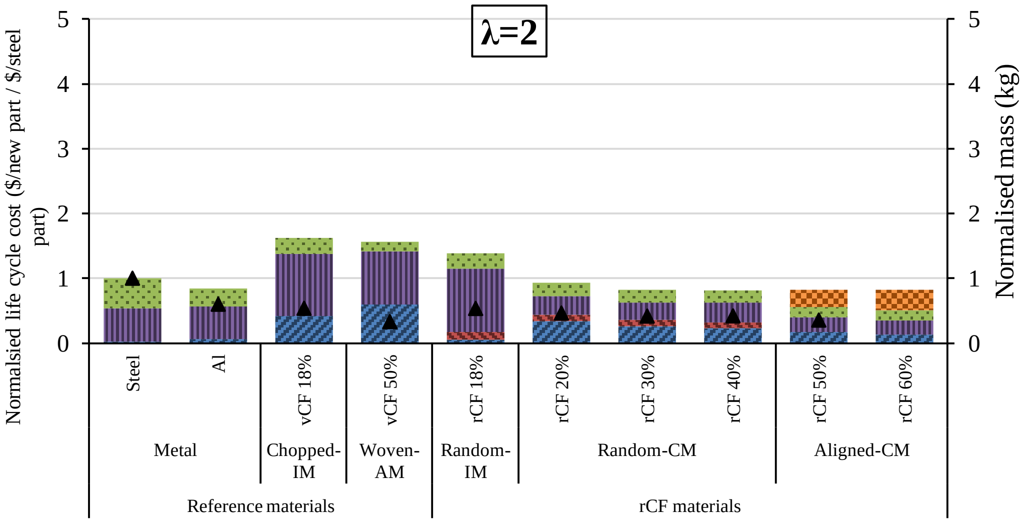


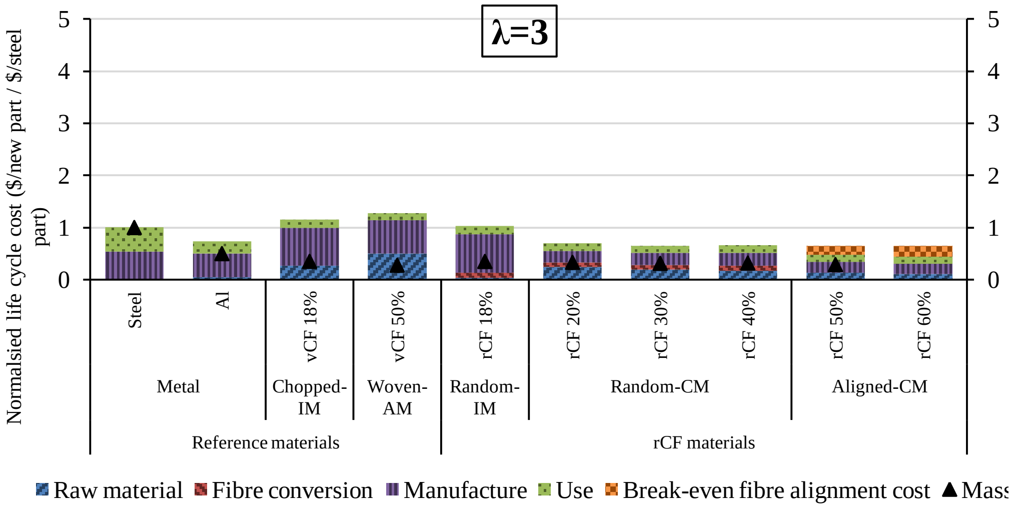
Fig. 3. Minimum selling price and breakdown costs of rCF for different feeding rates (kg/hr m^2) for 1000 t/yr.




λ=1
Normalsied life cycle cost ($/new part / $/steel part)
Normalised mass (kg)
0
1
2
3
4
5
Steel
Al
vCF 18%
vCF 50%
rCF 18%
rCF 20%
rCF 30%
rCF 40%
rCF 50%
rCF 60%
Metal
Chopped-IM
Woven-AM
Random-IM
Random-CM
Aligned-CM
Reference materials
rCF materials

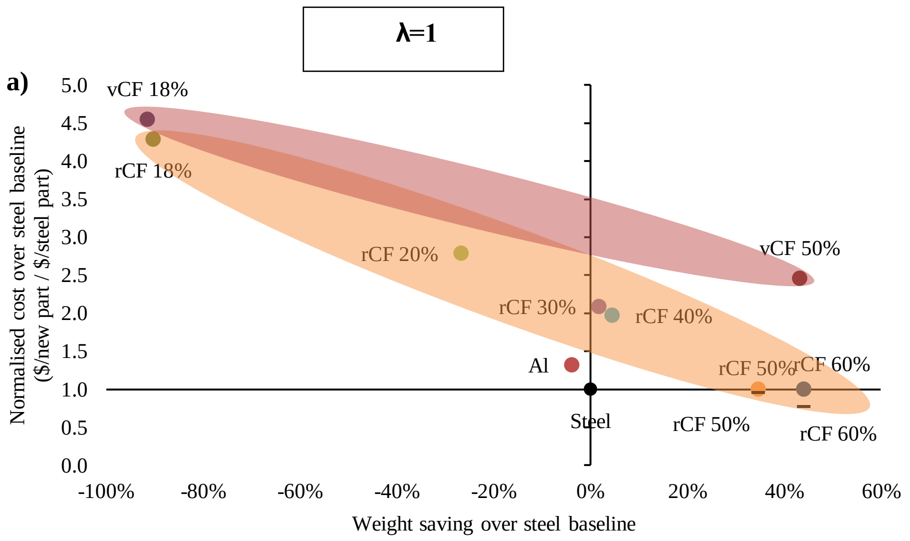
4.1.1

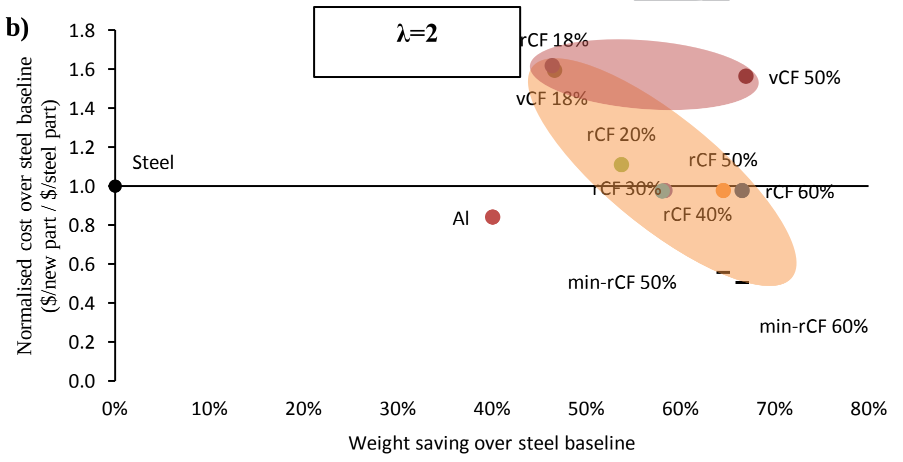

λ=2
Normalsied life cycle cost ($/new part / $/steel part)
Normalised mass (kg)
0
1
2
3
4
5
Steel
Al
vCF 18%
vCF 50%
rCF 18%
rCF 20%
rCF 30%
rCF 40%
rCF 50%
rCF 60%
Metal
Chopped-IM
Woven-AM
Random-IM
Random-CM
Aligned-CM
Reference materials
rCF materials



5

Fig. 4. The normalised life cycle cost ($/new part / $/steel part) of the automotive components made of steel and substitution materials under different design indices (i.e. λ=1, 2, 3). The orange columns represent fibre alignment cost range allowed to breakeven with conventional steel components and randomly oriented rCF components competitors.


λ=1
a)
Normalised cost over steel baseline ($/new part / $/steel part)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
vCF 18%
rCF 18%
rCF 20%
rCF 30%
rCF 40%
vCF 50%
Al
rCF 50%
rCF 60%
Steel
rCF 50%
rCF 60%
-100%
-80%
-60%
-40%
-20%
0%
20%
40%
60%
Weight saving over steel baseline


b)
λ=2
Normalised cost over steel baseline ($/new part / $/steel part)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
rCF 18%
vCF 50%
vCF 18%
rCF 20%
Steel
rCF 50%
rCF 30%
rCF 60%
Al
rCF 40%
min-rCF 50%
min-rCF 60%
0%
10%
20%
30%
40%
50%
60%
70%
80%
Weight saving over steel baseline

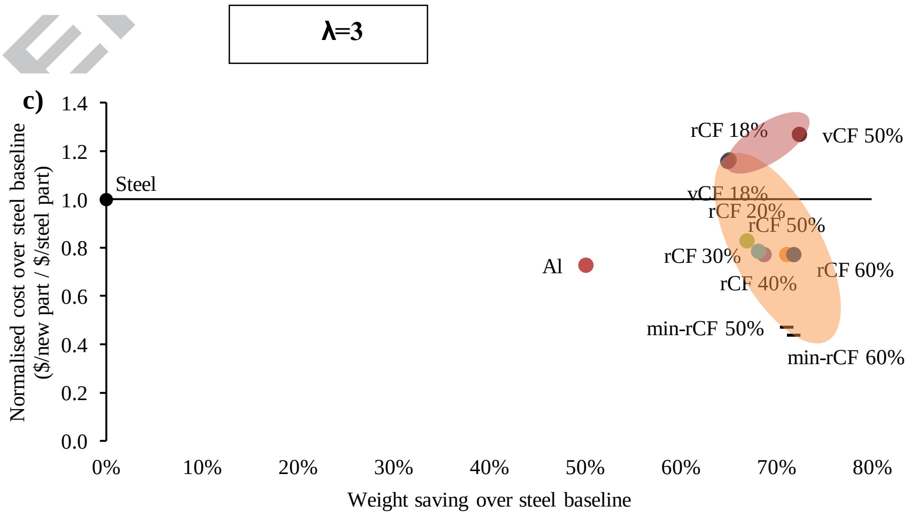
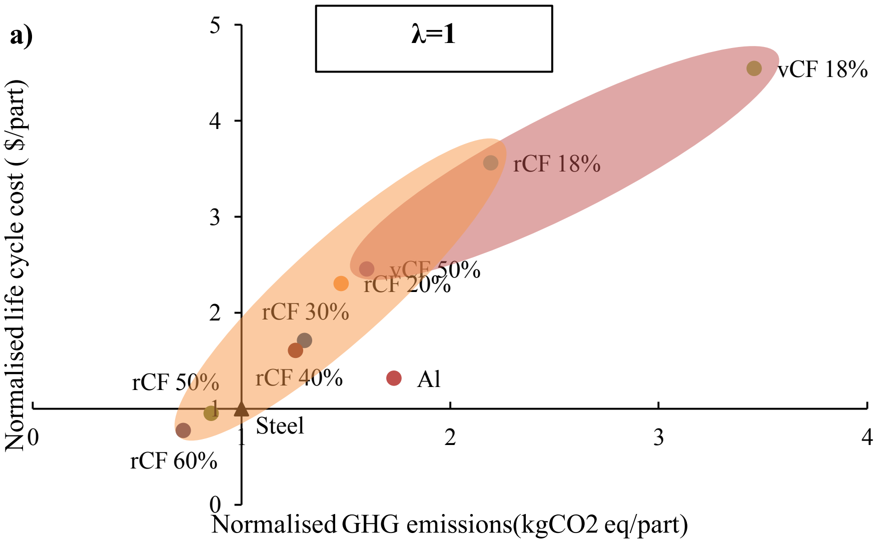

λ=3
c)
Normalised cost over steel baseline ($/new part / $/steel part)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
rCF 18%
vCF 50%
Steel
vCF 18%
rCF 20%
rCF 50%
rCF 30%
Al
rCF 60%
rCF 40%
min-rCF 50%
min-rCF 60%
0%
10%
20%
30%
40%
50%
60%
70%
80%
Weight saving over steel baseline

Fig. 5. The weight saving for components against normalised cost target relative to steel baseline for a) λ=1, b) λ=2, c) λ=3.



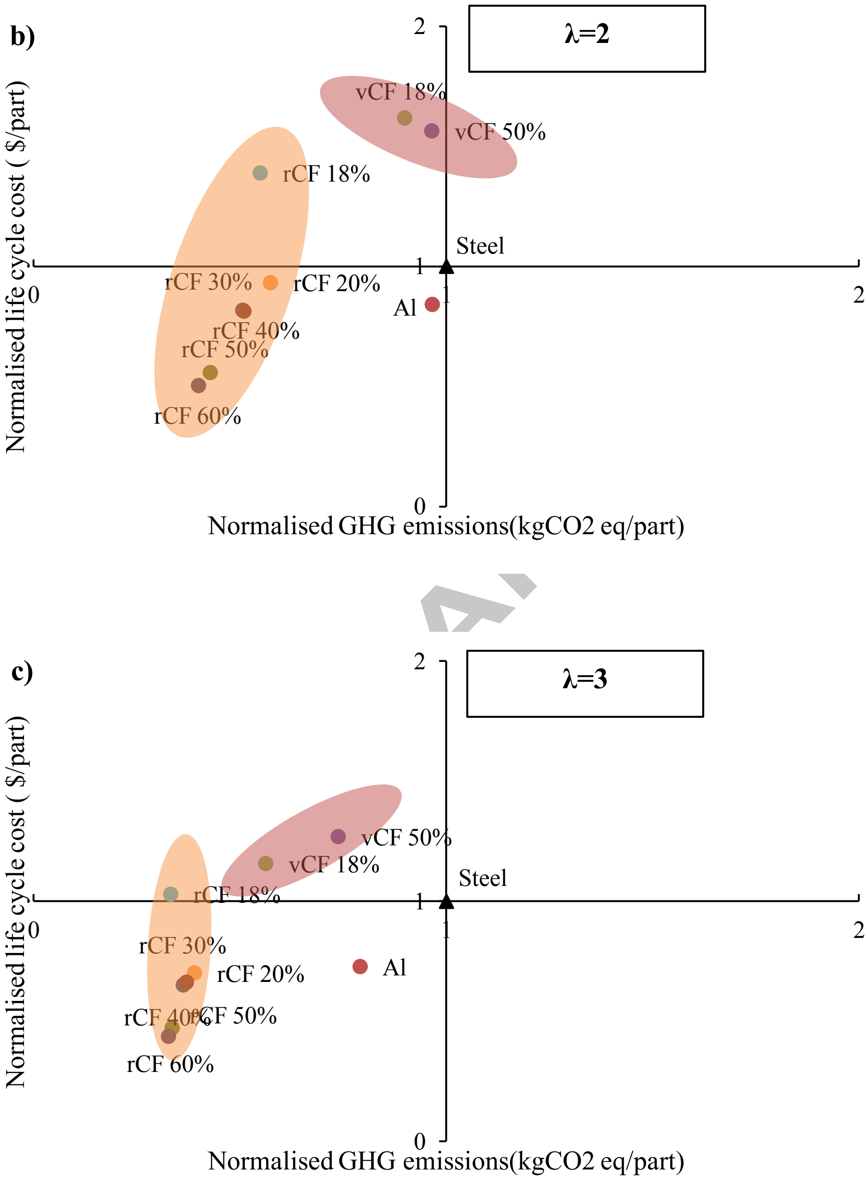


Fig. 6. The normalised life cycle cost savings ($/new part relative to $/steel part) for components against normalised GHG emissions relative to steel baseline (kg CO_2eq./new part relative to kg CO_2eq./steel part) for a) λ=1, b) λ=2, c) λ=3. GHG emission results are from [23].

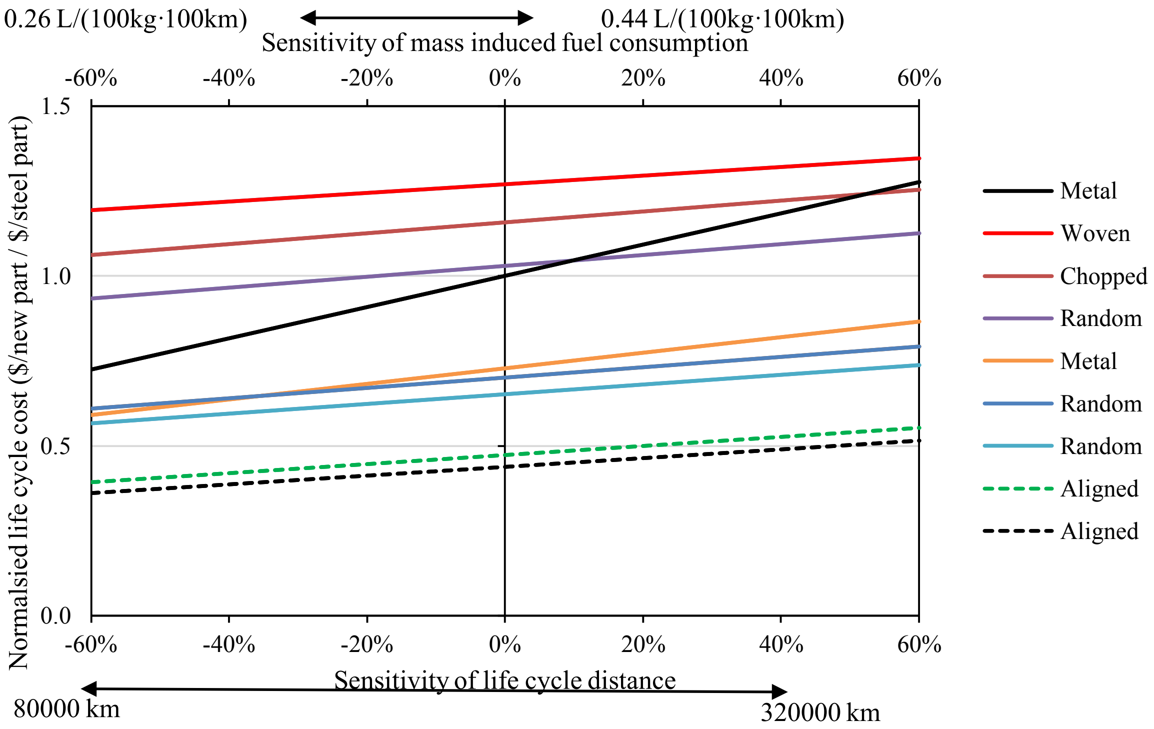


Fig. 7. The life cycle cost of automotive component materials with varied life cycle distances (80000–320000 km) and mass induced fuel consumption (0.26–0.44 L/(100 kg·100 km)) (λ=2).

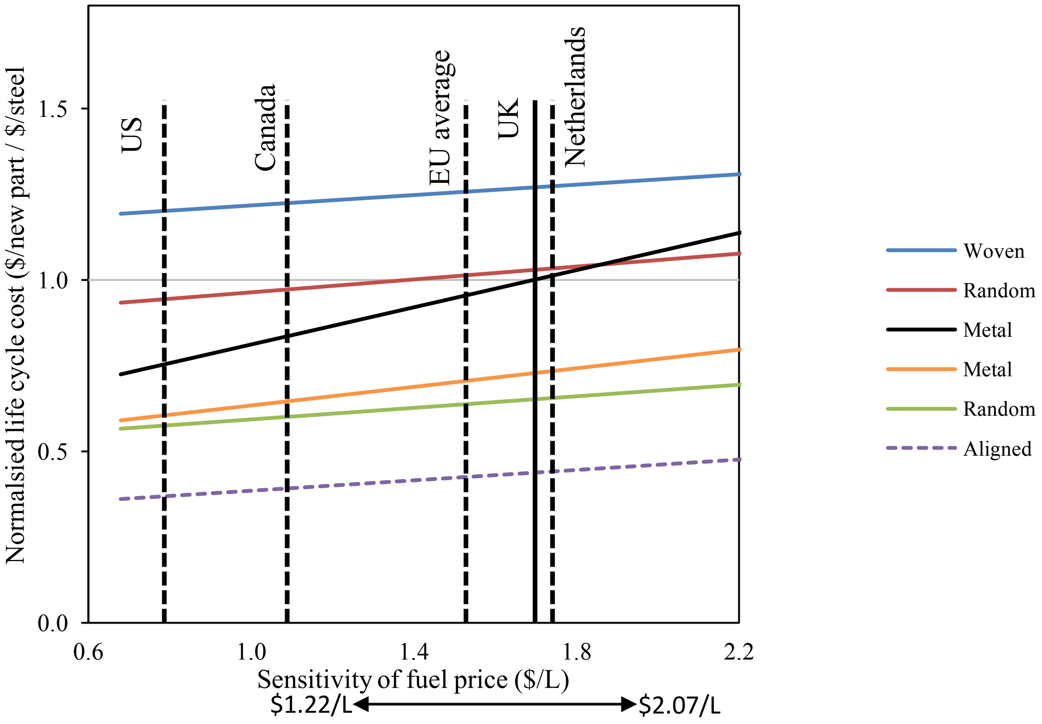


Fig. 8. The life cycle cost of automotive component materials with varied fuel prices ($1.22–2.07/L) based on historic prices in the UK from 2000 to 2015 and geographical locations (λ=2).

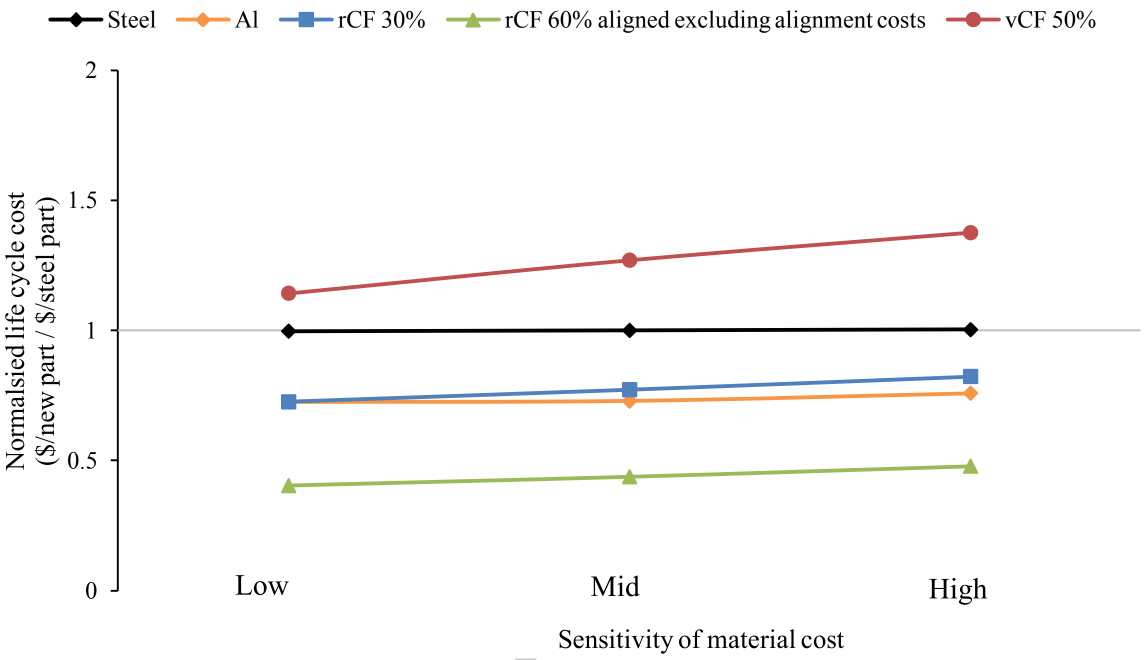


Fig. 9. The life cycle cost of automotive component materials with varied raw material prices (low, medium and high) (λ=2).