A holistic End-of-Life (EoL) Index for the quantitative impact assessment of CFRP waste recycling techniques

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Abstract. In the present study, a holistic End-of-Life (EoL) Index is introduced to serve as a decision support tool for choosing the optimal recycling process among a number of alternative recycling techniques of CFRP waste. For the choice of the optimal recycling process, quality of the recycled fibers as well as cost and environmental impact of the recycling methods under consideration, are accounted for. Quality is interpreted as the reusability potential of the recycled fibers; that is quantified through the equivalent volume fraction of recycled fibers that balances the mechanical properties of a composite composed of a certain volume fraction of virgin fibers. The proposed Index is offering an estimated balanced score, quantifying a trade-off between the reusability potential of the recycled fibers as well as the cost and the environmental impact of the recycling methods considered.

Keywords: Recycling / polymer-matrix composites (PMCs) / carbon fiber / End-of-Life (EoL)

1 Introduction

Fiber reinforced composites are currently being extensively used in several industry domains, such as the aviation, the automotive and the wind energy sector, due to their exceptional properties. Nevertheless, one of the biggest challenges posed by these materials is their recycling. It is worth mentioning as an example that by the year 2050, the aviation industry only, will have generated approximately 500 k tones of accumulated CFRP waste resulting from both the production (scrap) and the end-of-life phase of the already-flying aircrafts [1]. For decades, landfill and incineration were the most popular methods for disposing composite waste, with the majority of the waste being buried into landfill sites [2], although during the last years, more dedicated actions have been taken [3]. However, landfills do not only use up huge amounts of land but also cause major health hazards deriving from gases, hazardous air pollutants and odors which can severely affect the environment and public health. Furthermore, they contribute to the greenhouse effect and have been linked to respiratory diseases and cancers [4]. Regarding incineration, despite the fact that some of the composite waste can be recovered as energy to generate electricity, the drawbacks of this method outweigh that advantage by far [5]. Both landfill and incineration, do not involve material

recovery, hence, they cannot be classified as recycling technologies and they are not at all consistent (landfill) or partially consistent (incineration) with the principles of circular economy system (CES). The increased environmental impact of composites which are either landfilled or incinerated urge the development of industrial scale recycling solutions, while the environmental legislation and directive are becoming more and more restrictive [6].

In this context, in the last two decades, alternative composite waste treatment methods are being studied. These involve mechanical processes (mainly grinding) as well as thermal and thermochemical processes (e.g. pyrolysis and solvolysis, respectively) [7–9]. Studies have mainly been focused on recycling CFRP waste due to the high price range of the virgin fibers (1–3 €/kg for virgin glass fibers, 30–60 €/kg for virgin carbon fibers) and the potential to partially retain the mechanical properties of the carbon fiber for reuse in relevant applications [9]. Among, the recycling methods utilized, mechanical recycling has attracted considerable attention as it offers both environmental and economic advantages; namely, neither atmospheric nor water pollutants production during the process, as no chemicals are used, and considerably lower energy demands compared to other recycling methods. Also, there is no need for expensive and high-end technical equipment, and processing of large amounts of waste at higher rates is possible as well [10]. Regarding CFRPs, research has been focused on the subsequent use of the fibrous recycle as filler, or as

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reinforcement for new composites in short-fiber applications such as bulk molding compound (BMC), sheet molding compound (SMC) parts or inclusions in injection molded components as well as for the production of 3D printing filaments [2,11]. Nevertheless, commercial or industrial exploitation seems to remain very limited so far, mainly due to the low quality of the recycled fibers. Thus, this technique has become mostly a pre-recycling process for resizing composite parts into smaller parts before being fed to the actual recycling process [9,12]. Thermal processes, such as conventional pyrolysis and fluidized bed process appear as very promising recycling techniques in terms of the recycled fiber properties achieved. Conventional pyrolysis has already been commercialized in some countries [12] and therefore, can be considered as a well exploited recycling method. The fluidized bed process (FBP) is a pyrolysis variant developed at the University of Nottingham since 2000s and is now functioning at a pilot-scale [13]. FBP involves feeding of the size-reduced recyclates into a silica sand bed, which is fluidized by a hot air stream. Microwave-assisted pyrolysis, where the conventional source of heating is replaced by microwave radiation, has been considered and trialed by several universities and companies during the last few years for the recovering of carbon fibers, achieving mechanical properties similar to these of the virgin ones [7,14,15]; however, so far it has not been successfully commercialized [12]. Thermochemical processes (or solvolysis), have been proved capable of obtaining cleaner recycled fibers of high quality. Among all tested solvents, near- and supercritical water and alcohols are mainly processed as solvolysis media due to their environmentally friendly nature, although such processes are not yet commercialized as significant environmental as well as cost issues (mainly due to significant energy consumptions) must be tackled [11]. Therefore, it is evident from the above that apart from the environmental impact and financial costs of each recycling method, the price as well as reusability of the recycled fibers will dictate the commercialization process, an aspect that remains nowadays the greatest barrier for the majority of the available methods [9].

To assess the environmental and financial impact of waste treatment processes, Life Cycle Assessment (LCA) [16] and Life Cycle Cost (LCC) [17] models have been broadly recognized as decision making tools for efficiently selecting the most suitable waste management process and method. LCA is a standardized, holistic methodology that addresses the environmental aspects and impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [16]. Among the LCA indicators referring to recycling processes of CFRP waste, global warming potential (GWP), i.e. the carbon dioxide equivalent (CO_2eq) based on 100 year greenhouse gas factors from the Intergovernmental Panel on Climate Change (IPCC) 2013 [18], has been identified as being the most crucial one [10]. LCC models are used to compare the total costs of different FRP waste treatment routes; a typical cost model of a FRP recycling process includes capital and operational costs of the facility, as well as material pre-treatments

(dismantling, shredding) costs, and transportation cost to the facility site [19].

Focusing on CFRP-related works, recent LCA studies have highlighted the environmental benefits of implementing recycling processes that involve fiber recovery (e.g. pyrolysis and solvolysis), over landfilling and incineration [20–24]. In a relevant LCA study, Meng [25] has shown the environmental and cost benefits of adapting the fluidized bed process (FBP) instead of conventional pyrolysis and chemical recycling. Recently, Kumar [26] characterized chemical recycling as the most environmentally favorable recycling technique in contrast to other recycling methods (mechanical grinding and pyrolysis). However, the studies combining LCA and LCC models to assess both environmental and economic impacts of CFRP waste treatments remain very limited. Li [19] combined LCA and LCC methods to assess both environmental and financial impacts of CFRP recycling through grinding and compared them with conventional waste treatments (landfill and incineration). The results demonstrated that the potential environmental benefits of mechanical grinding are impaired by the severe reduction of the mechanical properties of the recycled fibers. In a more detailed combined LCA and LCC study, Vo Dong [27] studied the potential economic and environmental benefits of CFRP waste treatment, i.e. grinding, pyrolysis, microwave and supercritical water; it was concluded that there was a conflict between economic and environmental impacts, as none of the considered recycling techniques was found able to reduce both recycling costs and environmental impacts simultaneously. Finally, Tapper [28] highlighted the importance of including a technology aspect/dimension into a life-cycle study apart from an economic and environmental assessment, reinforcing the importance of a global life-cycle approach.

A recent study conducted by Delvere [29] has implemented a Multi Criteria Decision (MCD) tool to evaluate and compare different CFRP waste recycling techniques. The MCD analysis takes into account economic, environmental, social, and technological performance aspects and prioritizes the environmental criteria over the rest criteria considered. The afore-mentioned study leads to the arguable conclusion that mechanical recycling is the most sustainable recycling FRP method, although the authors question whether the results are representative of the current development level of CFRP recycling; therefore, they highlighted the need for other potential sustainability criteria in order to conduct more effective comparisons among different recycling methods. Despite the afore-mentioned efforts, a concept or tool for a holistic assessment of the implementation potential of FRP waste treatment processes, based on the simultaneous consideration of economic and environmental aspects as well as the reusability potential of the retrieved recycled fibers, does not currently exist.

To this end, an End-of-Life (EoL) Index is introduced to serve as a decision support tool for choosing the optimal recycling process among a number of alternative recycling processes. For the choice of the optimal recycling process, the aspects of quality of the recycled fibers as well as cost and environmental impact of the recycling methods under

consideration are accounted for. Quality is interpreted as the reusability potential of the recycled fibers and the importance weights of the above aspects on selecting the optimal process are determined by the engineer as initial input for implementing the Index.

2 Methodology

2.1 Definition of the index

The EoL Index introduced herein is an adaptation of the Index proposed in [30]; the latter was identified as a decision-making tool to aid engineers select an appropriate manufacturing technique for certain components as well as define the optimal process parameters for the implementation of each technique. The selected process parameters reflect a trade-off between quality, cost and environmental footprint of the existing component. Index P is derived from:

$$P = K_Q \cdot Q - K_C \cdot C - K_E \cdot E \quad (1)$$

where Q is the selected quality feature of the material, C is the cost of the selected process and E is the environmental footprint of each process. K_Q , K_C , K_E in equation (1) are dimensionless weight factors that depend on the application and the design restrictions considered, and reflect the importance of each term for the overall value of the Index.

The EoL Index proposed herein aims to provide a decision making tool for the selection of the appropriate recycling method of CFRP waste, by adapting the above features, i.e. Quality, Cost, and Environment to the requirements of the current study. Quality is associated with the reusability potential of the recycled fibers, deriving from each recycling method considered, while Cost and Environment are associated with the financial and environmental impact of each technique, respectively. To calculate the C, E Terms of the Index, LCA-related data has been utilized from literature studies (cited in the subsequent Sections) implementing principles and models described in relevant specifications (e.g. [16]). The weight factors of the Index are defined using a Multi Criteria Decision (MCD) making methodology. As a result, a quantified Index is derived for each of the recycling methods considered and a ranking among them is done. It should be noted that landfill and incineration cannot be classified as recycling methods as there are no fibers recovered through these methods; therefore, they were not further considered for the present analysis.

2.1.1 Quality term (Q) definition

In a circular economy, the achievement of a closed-loop recycling (CLR) approach is the primary target across the recycling industries [30–32]. According to this approach, the valuable fibers from composite wastes, such as the carbon fibers, must be reclaimed, remanufactured, and reused into a new composite. When focusing on the retrievable monetary value of composites, carbon fibers are

targeted for reuse due to their great value which can approach a purchase price of 60€ per kg [9]. On the other hand, matrix recycling has received up to now very little attention due to the difficulties which are associated with recycling a thermosetting material and their very low price as compared to the fibers; for example, epoxy resins are in the range of 4–18 €/per kg [33]. Therefore the resin products have been mainly considered as energy source or as chemical feedstock [7].

The value as well as the reusability potential of recycled fibers strongly depend on their quality. Hence, in the present study, the quality term Q , which is required for the implementation of the EoL Index, was linked to the reusability potential of the recycled fibers and expressed through an appropriate quantity. It is known that most recycling processes usually lead to a degradation of the fiber mechanical properties, either major or minor. The severity of property degradation depends on the recycling process involved. Yet, in order to achieve producing a composite material possessing the same mechanical properties as the one containing a certain volume fraction of virgin fibers (vCF), a higher volume fraction of recycled fibers (rCF) would be needed [25]. Hence, the fiber volume fraction (f) of the rCF composite that balances the mechanical properties reduction due to the use of the recycled fibers, relative to the virgin ones (rcf/vcf) offers a suitable quantity to link the mechanical properties of the rCF reinforced material with its reusability potential and was exploited to define the quality term Q of equation (1). It should be stated in this point that quality of the composite containing the recycled fibers does not depend only on the tensile properties of the fibers; bending properties, recycled fiber length as well as the surface properties and the adhesion capability of the fiber to the new matrix are of great importance and may affect the mechanical performance of the new composite. However, due to lack of literature data needed for the comparison of the considered recycling techniques, the afore-mentioned quality aspects could not be included in the proposed Index, and that can obviously underestimate or sub estimate the fiber reusability potential for each recycling method. Nonetheless, goal of the proposed Index is to provide an empirical tool which can be modified to include more detailed information based on the ongoing or future research associated with the capabilities of the considered recycling methods of composites.

For the present study, the mechanical properties considered for the calculation of the above ratio are the tensile elastic modulus and strength of the material containing the rCF . For applications such as aircraft structures, this choice is well justified as the allowable design does not exceed the linear elastic region of the corresponding stress-strain curve which, in addition, remains almost linear up to failure.

The Q_R term, based on the reusability of the recycled fibers, assumes that both mechanical properties are considered equally important and therefore, it can be defined as the sum of the Q_{R1} sub term and Q_{R2} sub term,

Table 1. Tensile Properties, Primary Energy Demand (PED), and Global Warming Potential (GWP) of CFRP Waste recycling techniques.

	Tensile Properties reduction (compared to vCF)		PED (MJ/kg CFRP)	GWP (kg CO ₂ eq./kg CFRP)
	Elastic modulus reduction (%)	Tensile strength reduction (%)		
vCF (PAN based)	—	—	704 [35]	31 [35]
Pyrolysis rCF	−12 [36]	−4 [7]	37.36 [25]	2.88 [25]
FBP rCF	Retained [12,37]	−18 [38]	9.98 [25]	1.54 [25]
Microwave pyrolysis rCF	−13 [14]	−1 [15]	10 [14,27]	0.53 [27]
Solvolytic with SC rCF	Retained [39]	−2 [40]	19.2 [41]	0.87 [27]

referring to the elastic modulus or the tensile strength, correspondingly. Therefore, the modified holistic EoL Index P can be introduced as:

$$P = K_{Q_R} \cdot Q_R - K_C \cdot C - K_E \cdot E \quad (2)$$

where

− $Q_R = Q_{R1} + Q_{R2}$ is the sum of the fiber volume fraction ratios (vCF/rCF)_{R1} + (vCF/rCF)_{R2};
 − C is the cost of the selected recycling process determined as: $C = \frac{C_{\text{process}}}{C_{\text{reference}}}$;
 − E is the environmental footprint of the selected recycling process determined as: $E = \frac{E_{\text{process}}}{E_{\text{reference}}}$;
 − K_{Q_R} , K_C , K_E are dimensionless weight factors.

To calculate the above Index, two different processes were taken as reference and consequently, two different values were calculated for each of the quantities involved in the Index. Firstly, the virgin carbon fiber process has been taken as reference; that will allow for a direct assessment of the benefits or drawbacks of using recycled fibers derived from different recycling methods considered. Hereafter, the above analysis will be referred to as “Comparison Case 1”. The second process taken as reference has been the one leading to recycled fibers offering the highest tensile properties; that will allow a better evaluation and a direct comparison between the different CFRP waste recycling techniques, accounting more clearly for their cost and environmental impact. Hereafter, the afore-mentioned analysis will be referred to as “Comparison Case 2”. In equation (2) the term Q_R can be understood as a ‘bonus’ for the total value of the recycling technology under consideration, compared to the Cost (C) and (E) terms which are both understood as ‘penalties’ to its value.

For the calculation of the Q_{R1} and Q_{R2} subterms, the rule of mixtures (ROM) was implemented. In order to implement the ROM, it has been assumed that the recycled fibers have been fully aligned prior to their inclusion in the new matrix; that is a logical assumption as the alignment of recycled fibers has been proved feasible and comprises a prerequisite for their implementation in high grade applications [34]. Moreover, it has been assumed that the recycled chopped fibers aspect ratios (length to diameter) are great enough so that the new composite

performance is not affected by their short length; that is also a realistic hypothesis/assumption based on the progress of the ongoing research which focuses on the retainment of the initial fiber length after the composites recycling [7]. The calculation has been based on data obtained from the literature and technical datasheets (see Tab. 1), referring to the degraded mechanical properties of carbon fibers resulting from a number of CFRP waste recycling processes. Then, the fiber volume fraction of the rCF composite that leads to an equivalent elastic modulus or an equivalent strength to the vCF composite was calculated.

Thus, assuming a composite comprised of unidirectional carbon fibers and a uniform stress distribution, ROM was applied for the estimation of the longitudinal elastic modulus:

$$E_C = f E_f + (1 - f) E_m \quad (3)$$

where

− E_c is the elastic modulus of the composite;
 − $f = \frac{V_f}{V_f + V_m}$ is the fiber volume fraction;
 − V_f is the volume fraction of the fibers into the composite;
 − V_m is the volume fraction of the matrix into the composite;
 − E_f is the elastic modulus of the fiber;
 − E_m is the elastic modulus of the matrix.

Correspondingly, the rule of mixture for the estimation of longitudinal tensile strength, assuming a unidirectional fiber composite and a uniform stress distribution, takes the following form:

$$\sigma_c = f \sigma_f + (1 - f) \sigma_m \quad (4)$$

where

− σ_c is the tensile strength of the composite;
 − $f = \frac{V_f}{V_f + V_m}$ is the fiber volume fraction;
 − σ_f is the tensile strength of the fiber;
 − σ_m is the tensile strength of the matrix.

From the above calculations, the Q_{R1} and Q_{R2} subterms were expressed as the fiber volume ratios vCF/rCF , referring to either the equivalent elastic modulus or strength, and their sum ($Q_{R1} + Q_{R2}$) was applied as the quality term Q_R of the proposed Index P (Eq. (2)). Table 1

Table 2. Selected cost drivers of the present study.

	vCF (PAN-based) production	Conventional pyrolysis	FBP	Microwave pyrolysis	Solvolytic with SC
Capital Investment (€) C_1	53 833 375 [44]	1 450 000 [27]	3 929 234 [43]	2 550 000 [27]	6 430 000 [27]
Operation Input Cost (€/kg) C_2	22.293	1.183	0.316	0.317	0.608
Labor cost (€/h) C_3	N/A	130.4	130.4	130.4	130.4
Dismantling (€/kg) C_4	N/A	1.51	1.51	1.51	1.51
Transportation (€/t-km) C_5	N/A	0.048	0.048	0.048	0.048
Shredding (€/kg) C_6	N/A	0.035	0.035	0.035	0.035
Administration (€/h) C_7	N/A	117.36	117.36	117.36	117.36

contains relevant data from the literature concerning available or potential waste CFRP recycling techniques, and the included data will assist in the implementation of the proposed Index.

2.1.2 Cost term (C) definition

A cost model of CFRP recycling, usually includes capital and operational costs associated with the recycling facility construction and operation, the waste CFRP pre-treatment (dismantling and shredding) cost, and cost of transportation to the recycling site [19]. In a detailed study, Vo Dong [27] implemented classical methodologies for early estimates as reported in [42] in order to determine the contribution of variable costs, fixed capital costs and capital depreciation, associated with waste CFRP treatment techniques. However, he stated the difficulties in retrieving information concerning the capacity and the location of the recycling facilities, as well as the lack of data regarding the investment costs of less common waste treatment processes such as microwave pyrolysis and solvolysis.

With regard to previous works and relevant literature data [19,27,42], the costs selected for the calculation of the Index proposed in the current study and the respective values are summarized in Table 2. Operation costs were calculated by multiplying the cost of kWh (0.114€ [30]) with the Primary Energy Demand (PED) of each process (obtained from Tab. 1). The labor cost was considered equal to 32.6 €/h [30] and assumed 4 operating personnel [27,42]. Prior to the recycling process, CFRP components usually must be manually dismantled from the vehicle or part. Dismantling has been found to have a considerable contribution to the total recycling costs, with an estimated cost of approximately 1.51 € per kg CFRP [19]; it is noticeable that another study has empirically estimated this cost at 0.37–0.73 €/kg [43]. CFRP waste is typically size-reduced before the main treatment by shredding, milling, crushing or other similar mechanical processes, with the cost considered equal to 0.035 €/kg CFRP [27]. Transportation costs which represent less than 1% of total costs of the recycling processes were considered equal to 0.048 (€/t-km) [19]. Finally, administration costs were calculated as being 90% of the operating labor cost, according to [43]. Labor, dismantling, transportation,

shredding, and administration cost were considered to be identical for all recycling processes; although the above is a too simplistic assumption, lack of commercialization and lack of data from relevant research, do not provide the option to include such variations in the Index, for a more complete and realistic assessment of each recycling method available.

2.1.3 Environmental term (E) definition

LCA studies have emerged from the comparison of various FRP recycling methods. However, it is very challenging to identify the indicators that are most relevant for decision making in the composite waste recycling sector as there is a lack of indicator selection methods and relevant criteria [45]. Among all the LCA indicators, global warming potential (GWP), human toxicity, and acidification, have been identified as the most essential for the assessment of the environmental impact of composites recycling [8,46], with the GWP being the most relevant environmental impact indicator for the assessment of greenhouse gas emissions [46]. However, the EoL activities and processes employed, potentially consume resources and release emissions that contribute, apart from the ones mentioned above, to a wide range of other important environmental impacts such as eutrophication, ozone depletion, toxicity on the ecosystems, and resources depletion [20,24,47]; although the GWP impact has been found to be magnitudes larger compared to other impact indicators. In this context, the GWP indicator was utilized as the most relevant environmental Term E for the present Index. The GWP for each recycling process considered herein, was derived from relevant LCA studies from the literature, and the respective values are shown in Table 1.

2.1.4 Multi criteria decision – analytic hierarchy process (AHP)

K_{QR} , K_C , and K_E in equation (2) stand for dimensionless weight factors which are application-dependent and reflect the significance of each term of the Index as well as their contribution to the calculated Index value. In order to reduce subjectivity on the weight factors definition, a Multi Criteria Decision (MCD) tool has been implemented.

Table 3. The fundamental scale.

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment moderately favor one criterion over another
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another
7	Very strong importance	A criterion is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

Among the several MCD making methods available [48], the AHP methodology is well established; it has been applied for different study fields such as the wind turbine and the building sector [27,49,50], for the evaluation of particular processes and the assignment of a specific importance to the selected criteria.

In brief, AHP is based on the principle of paired comparisons. The paired comparisons are used to compare the alternatives with respect to the various criteria defined and to estimate the criteria weights, on a scale of 1 to 9 (Tab. 3) [51]. One (1) means that the criteria are of equal importance, i.e. they contribute equally to the objective. Nine (9) means that a selected criterion is extremely more important compared to another criterion, i.e. the evidence favoring one criterion over another is of the highest possible order of affirmation. In this context, three different but interdependent criteria are chosen, i.e. Reusability, Cost, and Environmental Impact, to compare the waste CFRP recycling methods considered in the current study, via the AHP process. The AHP analysis was conducted using the ‘SuperDecisions’ software [52].

3 Results and discussion

3.1 Quality analysis (reusability potential)

For the sake of simplification, the application of the rule of mixtures (ROM) for the present analysis assumes that the CFRP component considered is a unidirectional composite comprising of aligned and continuous fibers, either virgin or recycled ones; to implement the proposed Index, a typical aerospace epoxy-based material with a 65% carbon fiber volume fraction was considered as the functional unit of the analysis [53]. The Q_R Term which is defined as the fiber volume ratio vCF/rCF was calculated for “Comparison

Case 1” and “Comparison Case 2”, as described in Section 2. The resulting Q_R Term of the Index is the sum of the two sub terms Q_{R1} and Q_{R2} (referring to elastic modulus and tensile strength, correspondingly). The results are summarized in (Tabs. 4 and 5). It should be noted that the tensile properties of the recycled fibers through mechanical recycling cannot be easily measured mainly due to the fact that the chopped fibers are covered with resin, and the performance of the fibrous fragment is mainly judged by integrating it into the new resin which makes it difficult to compare it directly to the recyclates of other recycling methods [9]. Furthermore, mechanical recycling results in fibers whose mechanical properties cannot compete with these of the virgin long fibers due to low quality. That comprises a major issue for the viability of this recycling process, as the recycled carbon fibers obtained through grinding do not seem to have the potential to be implemented in applications where high performance fibers are required (e.g. the aviation sector) and close the life-cycle loop of CFRP as a consequence. For the above reasons, mechanical grinding has been excluded from the present analysis.

The Q_R Term can be understood as a fiber replacement indicator. For example, $Q_{R1} = 0.882$ for the conventional pyrolysis process, means that 1 kg fibers rCF recycled through pyrolysis can replace 0.882 kg virgin fibers vCF . Obviously an upper limit to the volume fraction of the recycled fibers used in the remanufactured material must be determined, which depends on the fiber sizing, the application, the post processing of the recycled fibers (e.g. alignment), the remanufacturing method implemented, etc.; however, this is not a subject of study of this research work. The reusability term values utilized for the EoL Index calculation (Eq. (4)) are shown and compared in Figure 1. It should be noted that the Index Term values (and consequently the EoL Index P) are dimensionless as

Table 4. Reusability Terms calculation of the Index based on the equivalent elastic modulus.

Modulus-based Reusability						
	Fiber modulus (GPa)	Epoxy resin modulus (GPa)	Modulus reduction (%)	(Equivalent) fiber volume ratio (%)	Q_{R1} (fiber volume ratio vCF/rCF)	Q_{R1} (fiber volume ratio rsolvCF/rCF)
vCF	438 [54]	2.7 [55]	—	65	—	—
Pyrolysis rCF	385	2.7 [55]	−12 [36]	74	0.882	0.882
FBP rCF	438	2.7 [55]	retained [12,37]	65	1	1
Microwave Pyrolysis rCF	381	2.7 [55]	−13 [14]	75	0.870	0.870
Solvolysis with SC water rCF	438	2.7 [55]	retained [39]	65	1	1

Table 5. Reusability Terms calculation of the Index based on the equivalent tensile strength.

Strength-based Reusability						
	Fiber tensile strength (MPa)	Epoxy resin tensile strength (MPa)	Tensile Strength reduction (%)	(Equivalent) fiber volume ratio (%)	Q_{R2} (fiber volume ratio vCF/rCF)	Q_{R2} (fiber volume ratio rsolvCF/rCF)
vCF	4757 [54]	60 [55]	—	65	—	—
Pyrolysis rCF	4567	60 [55]	−4 [7]	68	0.956	0.971
FBP rCF	3900	60 [55]	−18 [38]	80	0.956	0.825
Microwave Pyrolysis rCF	4709	60 [55]	−1 [15]	66	0.984	1
Solvolysis with SC water rCF	4662	60 [55]	−2 [40]	66	0.984	1

Fig. 1. Reusability Terms of the EoL Index for (a) “Comparison Case 1” and (b) “Comparison Case 2”.

Fig. 2. Cost Terms of the EoL Index for (a) “Comparison Case 1” and (b) “Comparison Case 2”.

Fig. 3. Environmental Impact Terms of the EoL Index for (a) “Comparison Case 1” and (b) “Comparison Case 2”.

they are expressed as ratios with regard to the reference process considered. The results state that for both “Comparison Cases” considered as described in Section 2.1.1, Solvolysis with super critical water (SCW) shows the best performance as far as reusability of the fibers is concerned, followed by Microwave Pyrolysis, Conventional Pyrolysis, and FBP where the latter three demonstrate similar values.

3.2 Life cycle cost analysis

Based on Table 2, the Cost Terms for each recycling method considered were calculated. Regarding the first analysis “Comparison Case 1”, the Costs that are common for all methods (including the virgin fiber production) and could be compared, were considered, i.e. C_1 , and C_2 (see Tab. 2), while for the second analysis “Comparison Case 2”, all Costs were taken into account (C_1 – C_7). The Cost Term of the Index P (Eq. (2)) is defined as the sum of the ratios C_i/C_{ref} for each one of the Costs of Table 2. The Cost Terms applied to the Index, are depicted and compared in Figure 2. The results show that the costs of all recycling

methods considered herein, are almost negligible when compared to the virgin fiber production method (Comparison Case 1); that is reflected to the low Cost Term values of each recycling method (Fig. 2a) and is owed to large capital investment and great energy demand of the virgin fiber production compared to the recycling methods considered. However, when a more direct comparison is made among the considered recycling techniques (“Comparison Case 2”), Conventional Pyrolysis and Solvolysis with SC water appear to be the two most cost-intensive techniques compared to FBP and Microwave Pyrolysis.

3.3 Environmental impact analysis

Based on the GWP values obtained from Table 1, the Environmental Terms of the Index P were calculated for both Comparison Cases (“Comparison Case 1” and “Comparison Case 2”), and the corresponding values are shown in Figure 3. The low scores of the Environmental Impact Term for all recycling processes represent the low environmental impact of the recycling processes considered, compared to the environmental impact of virgin

Fig. 4. The AHP Network.

Table 6. AHP decision making matrix.

	Quality	Cost	Environment	Weight factor
Quality/Reusability	1	6	4	≈67%
Cost	0.17	1	0.17	≈7%
Environment	0.25	6	1	≈26%

carbon fibers (“Comparison Case 1”). When comparing the different recycling techniques, with reference to the solvolysis with SC water process (“Comparison Case 2”), the method presenting the highest environmental impact is by far, Conventional Pyrolysis.

3.4 Implementation of the EoL index

3.4.1 Definition of the weight factors

To calculate the EoL Index and compare the different recycling methods, the dimensionless weight factors were calculated, using the AHP method. The AHP network is shown in Figure 4. Quality, which in the present study was defined as Reusability, was strongly prioritized over Environmental Impact and Cost as the commercial viability of recycled fibers is directly related to their quality of the retrieved fibers [8,9,20]. Obviously, in addition to Quality, Environmental Impact and Cost of recycling need to be accounted for.

For deriving the weight factors in equation (2) through the AHP process described in Section 2.5, the importance intensities for the paired criteria comparisons were defined and the resulting weight factors were calculated (Tab. 6). Quality (or Reusability) was considered to be ‘moderately to strongly more important’ than Environment; thus, the respective paired Importance Intensity between them was assigned to 4. Accordingly, Quality was considered to be ‘strongly to very strongly more important’ compared to Cost, with the assigned paired Intensity being 6. Finally, Environment was also considered to be ‘strongly to very strongly more important’ than Cost, and the respective paired Intensity was set equal to 6. The resulting Weight

Factors which were used for the EoL Index calculation clearly reflect the prioritization of fiber Quality (or Reusability) over Environmental Impact and Cost.

3.4.2 EoL index calculation

Based on the weight factors obtained from Table 6, the EoL Index P takes the final form:

$$P = 0.67 \cdot Q_R - 0.07 \cdot C - 0.26 \cdot E \quad (5)$$

where

- Q_R is the fiber volume ratio $r_{ref}CF/rCF$;
- C is the cost of the recycling process: $C = \frac{C_{process}}{C_{reference}}$;
- E is the environmental footprint of the recycling process: $E = \frac{E_{process}}{E_{reference}}$.

The EoL Index values and the ranking among the recycling methods are presented in Figure 5. The Index P values have been calculated either by considering the virgin carbon fiber production as reference (“Comparison Case 1”) either the Solvolysis with SC water process (“Comparison Case 2”), as being the process which leads to fibers of the highest quality compared to other processes.

Regarding “Comparison Case 1”, Solvolysis with SC water ranks in first place, followed in turn by Microwave Pyrolysis, FBP and Conventional Pyrolysis. Penalties deriving from the Environmental Impact and Cost are considerably small for all processes considered in that case, highlighting the great environmental impact and cost of virgin carbon fiber production and the need for sustainable recycling processes of CFRP waste, in order to reduce the need for virgin carbon fibers.

Fig. 5. EoL Index (P) ranking among the CFRP recycling methods for (a) “Comparison Case 1” and (b) “Comparison Case 2”.

Table 7. AHP Decision Making Matrix-Parametric Analysis 1.

	Quality	Cost	Environment	Weight factor
Quality/Reusability	1	6	1	≈46%
Cost	0.17	1	0.17	≈8%
Environment	1	6	1	≈46%

Table 8. AHP Decision Making Matrix-Parametric Analysis 2.

	Quality	Cost	Environment	Weight factor
Quality/Reusability	1	1	0.17	≈13%
Cost	1	1	0.17	≈13%
Environment	6	6	1	≈75%

Table 9. AHP Decision Making Matrix-Parametric Analysis 3.

	Quality	Cost	Environment	Weight factor
Quality/Reusability	1	1	1	≈33%
Cost	1	1	1	≈33%
Environment	1	1	1	≈33%

Concerning “Comparison Case 2”, Microwave Pyrolysis ranks in the first place followed by Solvolysis with SC water in turn. That is justified by the fact that these two recycling techniques lead to fibers of high quality, exhibiting simultaneously, the lowest environmental impact compared to Conventional Pyrolysis and FBP. The FBP process follows, and Conventional Pyrolysis ranks as the process with the lowest by far score which is owed mainly to the significant environmental impact and secondarily to the cost of this method. This is a noticeable observation, as Conventional Pyrolysis is currently the most commercialized techniques compared to other recycling methods; that signifies the need to further exploit alternative recycling methods or improve the current ones.

3.4.3 Sensitivity of the analysis

It should be noted that the study results are sensitive to the importance definition in deriving the weight factors of the Index. Their definition is subjective and reflects the priorities of the engineer and the specific application. Therefore, considering that the current analysis is affected by the researcher’s subjectivity, three additional analyses were conducted by varying the criteria weights of Quality/Reusability, Cost, and Environment, in order to understand the impacts of uncertainty and variability in these parameters. In this context, the relevant weight factors were determined as shown in Tables 7–9. For the first parametric analysis (Tab. 7), Quality/Reusability and

Fig. 6. EoL Index (P) ranking among the CFRP recycling methods for (a) “Comparison Case 1” and (b) “Comparison Case 2” – Parametric Analysis 1.

Fig. 7. EoL Index (P) ranking among the CFRP recycling methods for (a) “Comparison Case 1” and (b) “Comparison Case 2” – Parametric Analysis 2.

Fig. 8. EoL Index (P) ranking among the CFRP recycling methods for (a) “Comparison Case 1” and (b) “Comparison Case 2” – Parametric Analysis 3.

Environment Impact were considered as being equally important and both strongly prioritized over the Cost Impact. Regarding the second parametric analysis, all three parameters were considered as being equally important (Tab. 8). Concerning the third analysis, Environment was considered to be strongly prioritized over Quality and Cost, while the latter two are considered as being equally important (see Tab. 9). The corresponding EoL Index comparisons are depicted in Figures 6–8. In all parametric analyses considered, the advantage of using recycled carbon fibers over virgin ones is highlighted when the virgin fiber process is taken as reference (“Comparison Case 1”). When a more direct comparison between the considered recycling methods is made (“Comparison Case 2”), Microwave Pyrolysis ranks, for all three analyses considered, as the recycling method with the highest score followed by Solvolysis and FBP; that was anticipated as Microwave Pyrolysis presents the best Environmental and Cost performance as well as a Reusability performance almost equal to that of Solvolysis with SC water. Solvolysis with SC water ranks in the second place, although the FBP seems to be closing the gap with the two highest-ranked methods when all three parameters, i.e. Quality/Reusability, Cost and Environment, are considered as being equally important (Fig. 8). Conventional Pyrolysis presents the worst performance by far for all analyses considered, compared with the alternative recycling methods. The negative Index values of the recycling methods observed for all three parametric analyses are owed to the highest penalty values of the Environment and Cost Terms deriving from the higher importance weights considered for these two Terms of the Index calculation (see Eq. (2)).

4 Conclusions

Currently, landfill and incineration are considered the most popular methods for disposing FRP waste, being the methods adopted by conventional waste disposal industries. However, accounting for factors such as climate change, more and more restrictive legislation and directives, and a sustainable alternative and circular economy, waste disposal industries have recently shifted to methods capable of achieving complete fiber recovery. Commercial suppliers often look to the aerospace industry as a source of production scrap and end-of-life materials to be used as recyclates, and confidence in the recycled fiber quality increases. However, displacement of virgin fiber completely is not currently a short-term objective, especially in aerospace where there are high strength and stiffness requirements.

In this study, a novel EoL Index referring to waste CFRP treatment is introduced to serve as a decision support tool for choosing the optimal recycling process among a number of alternative recycling processes. For the choice of the optimal recycling process, the aspects of quality of the recycled fibers as well as cost and environmental impact of the recycling methods under consideration are accounted for. Quality is interpreted as the reusability potential of the recycled fibers and the importance weights of the above aspects on selecting the

optimal process are determined by the engineer as initial input for implementing the Index. LCA data and the cited mechanical properties were retrieved from the most relevant and recent literature. However, data variations among studies (e.g. costs and energy consumption), arising from differences in operating conditions and assumptions for the chosen technology have not been taken into account. Aim of the Index is to offer an estimated balanced score which represents a trade-off between the reusability potential of the recycled fibers, the environmental impact and cost of available and potential CFRP waste recycling methods. To reduce subjectivity on the weight factors definition of the proposed Index, an AHP methodology tool has been implemented. The results clearly state the urgent need for replacing virgin carbon fibers with recycled ones, due to significant environmental impact and cost gains. When the Reusability potential of the recycled fibers is prioritized over the Environmental and Cost performance, the ranking among the different recycling methods considered, presents a clear advantage of Microwave Pyrolysis and Solvolysis with SC water over FBP and Conventional Pyrolysis; the latter method show by far the worst score compared with the alternative methods. Finally, variation of the weight factor values of the AHP process, did not affect the final ranking among the different recycling methods considered, although it affected the difference gaps between the considered recycling methods.

The proposed EoL Index aims to serve as an empirical decision support tool, directed to engineers or recyclers, for choosing a suitable FRP recycling process. FRP, and especially CFRP recycling, constitutes a critical issue for the sustainable utilization of lightweight composite materials in the fields of transportation, construction, etc. Thus, the implementation of the proposed Index can be exploited in most composite sectors where Quality, Environmental Impact, and Cost, are of concern.

Implications and influences

In the present work a linear relationship for determining an End-of-Life (EoL) Index is introduced to serve as a decision support tool, directed to either engineers or recyclers, for choosing the optimal recycling process among a number of alternative recycling processes. Such a tool could be of use for the assessment of the implementation potential of FRP waste treatment processes, based on the simultaneous consideration of economic and environmental aspects as well as the reusability potential of the retrieved recycled fibres.

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