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A Bicriteria Optimisation Approach for Waste Management of Carbon Fibre Reinforced Polymers Used in Aerospace Applications: Application to the Case Study of France

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Abstract The increased use of carbon fibre reinforced polymers (CFRP) has raised the environmental concerns on waste disposal and consumption of non-renewable resources as well as economic awareness for the need to recycle CFRP wastes stemming from aircraft. This study develops an optimisation approach of CFRP waste management with the simultaneous objective of minimising cost and global warming potential impacts along the the entire network. Various CFRP waste types are involved with multiple available techniques of fibre/no-fibre recovery techniques. The scenarios that are investigated are based on the current situation in France. The large inventory of the existing sites concerning aerospace CFRP industry is carried out to predict the waste quantity that is likely to be generated in the future. The objective is to develop waste allocation strategies, which are both good for economic and environmental aspects. The results obtained show that the economic interest and the environmental effect are conflicting. Transportation turns out to be an important factor of waste management.

Keywords Carbon fibre reinforced polymers · Waste management · Multiobjective optimization · Recovery · Recycling

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List of symbols

Indices/Sets

$c \in \mathscr{C}$	Market of recovered product
$e \in \mathscr{E}$	No-fibre recovery pathways
$f \in$ {Carbon fibre production, prepreg production, CFRP component production}	Manufacturer type
$i \in \mathscr{I}$	Intermediate product
j	Variant in each aircraft model
$l, l' \in \mathscr{L}$	Location/region
m	Aircraft model
$p \in \mathscr{P}$	Recovered product from fibre recycling technique
$r \in \mathscr{R}$	Fibre recycling technique
$s \in$ {Small, medium, large}	Plant scale
t	Year of the study
$w \in \mathscr{W}$	Waste type

Parameters

a_m	Number of variants in aircraft model m
$CAPD_l$	Maximum dismantling capacity at region l in 1 year (airplanes)
$CAPEL_{el}$	Capacity of no-fibre recovery technique e at region l, (tons/year)
$CAPP_{fs}$	Annual capacity of one plant of type f at scale s in 1 year (tons/plant)
$CAPRL_{rl}$	Recycling capacity of fibre recovery technique r at region l, (tons/year)

CQL_{cp}	Minimum quality of product ***p*** accepted by sector ***c*** (%)
$DISM_l$	Dismantling productivity, (∈ [0 1])
$DIST_{ll'}$	Distance between region ***l*** and region ***l′*** (km)
ECOM	Energy for compression (kWh/ton)
EPR_w	Energy used for pre-treatment of waste ***w*** (kWh/ton)
GWPE	GWP impacts of electricity (tons CO_2 eq./MJ)
$GWPIR_{ri}$	GWP impacts of treatment of intermediate product ***i*** by recycling technique ***r*** (tons CO_2 eq./ton of waste)
$GWPNRAU_{we}$	Avoided GWP impact of no-fibre recovery pathway ***e*** from waste ***w*** (tons CO_2 eq./ton of waste)
$GWPNRU_e$	GWP impacts of treatment by no-fibre recovery pathway ***e*** (tons CO_2 eq./ton of waste)
$GWPP_p$	GWP impacts of conventional production of product ***p*** (tons CO_2 eq./ton)
GWPTRU	GWP impacts of transport (tons CO_2 eq./tkm)
$GWPWR_{rw}$	GWP impacts of treatment of waste ***w*** by fibre recycling technique ***r*** (tons CO_2 eq./ton of waste)
M_{mj}	Operating empty weight of variant ***j*** in aircraft model ***m*** (tons/aircraft)
NOM^l_{fs}	Number of plants of type ***f*** at scale ***s*** in region ***l*** (plants)
n^m_t	Number of aircraft model ***m*** delivered in year ***t*** (aircraft)
pc_m	Proportion of CFRP weight in airframe in model ***m***, (∈[0;1])
PCOM	Cost of compression (€/ton)
PE	Unit cost of electricity (€/kWh)
PIR_{ri}	Cost of treatment of recycling technique ***r*** for intermediate product ***i*** (€/ton)
PNR_{ew}	Cost of no-fibre recovery technique ***e*** for waste ***w*** (€/ton)
PP_p	Price of recovered product ***p*** (€/ton)
$PROD_{fs}$	Productivity of plant type ***f*** at scale ***s*** (∈[0;1])
ps_m	Proportion of airframe weight in operating empty weight in model ***m*** (∈[0;1])
PTR0	Cost of normal transport for recovered product (same for all type product p) (€/ton.km)
PTR_w	Cost of transport for waste ***w*** (€/ton.km)
PWM_{wf}	Generation rate of waste ***w*** from fabrication plant of type ***f*** (%)
PWR_{rw}	Cost of treatment of recycling technique ***r*** for waste ***w*** (€/ton)
$QLPRP_{wp}$	Quality of recovered product ***p*** from waste ***w*** by pretreatment (%)
$QLRPI_{irp}$	Quality of recovered product ***p*** from intermediate ***i*** by recycling technique ***r*** (%)
$QLRPW_{wrp}$	Quality of recovered product ***p*** from waste ***w*** by recycling technique ***r*** (%)
QW_{wl}	Waste quantity ***w*** at region ***l*** (tons/year)
$RECM_l$	Rate of CFRP waste separation from aircraft, (∈[0;1])
$RIRP_{rpi}$	Conversion ratio from intermediate product ***i*** to final product ***p*** by fibre recycling technique ***r*** (%)
RNR_e	Revenue from no-fibre recovery pathway ***e*** (€/ton)
$RWRP_{rpw}$	Conversion ratio from waste ***w*** to final product ***p*** by fibre recycling technique ***r*** (%)
um_t	Average CFRP weight per retired aircraft in year ***t*** (tons)
XDP_{cpl}	Index of existence of sector ***c*** for product ***p*** at region ***l***
XIR_{ir}	Acceptance index of fibre recycling technique ***r*** for intermediate product ***i***, 1 if the technique ***r*** can treat the intermediate product ***i***, 0 otherwise
$XPRP_{wp}$	Index of conversion ***w*** to product ***p*** after pretreatment
XPR_w	Index for waste ***w*** which does not need recycling process after pretreatment step for recovery, 1 if the waste ***w*** does not go to the recycling process for recovery, 0 otherwise
$XTR_{ll'}$	Factor of transport, 1 if two regions (***l*** and ***l'***) are different 0 otherwise
XWI_{wi}	Index of conversion waste ***w*** to intermediate product ***i*** after pretreatment
$XWNR_{we}$	Acceptance index of no-fibre recovery technique ***e*** for waste ***w***, 1 if the technique ***e*** can treat the waste ***w***, 0 otherwise
$XWPR_w$	Index for waste ***w*** which can go to pre-treatment step separately from recycling process, 1 if the separated pretreatment step is opened for the waste ***w***, 0 otherwise
XWR_{wr}	Acceptance index of fibre recycling technique ***r*** for waste ***w***, 1 if the technique ***r*** can treat the waste ***w***, 0 otherwise

Continuous Variables

$FIR_{irll'}$	Flow of intermediate product ***i*** transported from ***l*** to recycling site ***r*** at ***l'***, (tons)

$FPDR_{wrpcll'}$ Flow of product ***p*** recovered from waste ***w*** by direct recycling technique ***r*** at location ***l*** and then distributed to market ***c*** at ***l'***, (tons)

$FPIR_{irpcll'}$ Flow of product ***p*** recovered from ***i*** by recycling technique ***r*** at location ***l*** and then distributed to market ***c*** at ***l'***, (tons)

$FPPR_{wpcll'}$ Flow of product ***p*** obtained from pretreated waste ***w*** at ***l*** directly transported to market ***c*** at ***l'***, (tons)

$FWDR_{wrll'}$ Flow of waste ***w*** from waste source ***l*** transported directly to recycling site ***r*** at ***l'***, (tons)

$FWNR_{well'}$ Flow of waste ***w*** to no-fibre recovery technique ***e*** at region ***l***, (tons)

$FWPR_{wll'}$ Flow of waste ***w*** transported from waste source at ***l*** to pretreatment site at ***l'***, (tons)

Introduction

Air traffic has been expanding at nearly two and half average economic growth rates since 1960 [22]. In the 20 year forecast of Airbus [3], passenger air traffic is expected to continue this tendency with an average annual growth rate of 4.6 %. However, regarding the impacts of energy crisis through its history, this industry is one of the most vulnerable ones to oil price variation. While electricity can be produced from various sources, liquid fuels used for aviation have yet no other economically viable alternatives than from fossil ones for the scale of current consumption. The energy crisis has induced the demand for fuel efficiency as a characteristic of aircraft [6]. Beside this economic reason, the improvement of fuel efficiency can reduce the emission of greenhouse gases from burning of fuels. Indeed, with 16,000 commercial jet aircraft in the world, aviation generates more than 600 million tons of CO_2 per year which is nearly equivalent to all human activities in Africa [22]. The effects of aviation on climate change has been extensively studied by Brasseur et al. [8], Dessens et al. [14], Lee et al. [26], Penner et al. [37], Prather et al. [43], Rothengatter [45], Wuebbles et al. [59].

The aviation industry has made diverse efforts in design and materials in aircraft and different practices in order to reduce airplane fuel consumption since the past three decades. These efforts allow a dramatic reduction in fuel consumption of 70 % in new aircraft compared to those of 40 years ago. By the middle of the century, 40 50 % improvement is projected [29]. One of the strategies for fuel savings is the reduction of aircraft weight by using lighter materials, i.e. aluminium and composite. This latter has exclusively high technique properties such as high strength, relatively low weight and corrosion resistance. Composites have been used originally in military aircraft and have then been adopted progressively in civil airplane from secondary part to primary structure in the latest models of Boeing and Airbus, e.g. B787 with 50 % in composite, A350 with 53 % in composite.

These two models have marked the revolution of carbon fibre reinforced polymer (CFRP) composite utilisation in airframe with CFRP fuselage. Adopted since 1970s, CFRP is increasingly used in structural applications of aircraft to replace more conventional materials (steel, aluminium, alloys…) in order to design lighter products due to their low density and high performance of chemical and physical properties and become the major composite in recent models among the other composites (GFRP, GLARE, Carbon/Caron Composite…). This material is constituted of two main components: carbon fibre and polymer matrix. In aerospace applications, carbon fibre exhibits the high mechanical properties and polymer matrix is principally thermoset.

In contrast to metal, glass, thermoplastics and many other engineering materials for which a solid recycling industry has been established, CFRP and composite materials in general have not yet been properly recycled and landfill still constitutes the main option used. The main difficulty of recycling is related to the heterogeneous nature of the matrix and the reinforcement, especially in the case of thermoset composite [38]. This one cannot be remoulded after curing/hardening process like thermoplastics. At this time, the lack of markets, the high recycling cost associated with the lower quality of the recyclates versus virgin materials constitute major commercialisation barriers for composites recycling [60].

Moreover, carbon fibre production needs high energy in production, approximately 183 286 MJ/kg [52]. This process generates environment and human health impacts due to emissions from the oxidation and carbonization furnaces such as hydrogen cyanide (HCN), ammonia (NH_3), nitrogen oxide (NO_x), volatile organic compounds (VOCS), carbon monoxide (CO) and carbon dioxide (CO_2) [17]. Therefore, instead of being landfilled or burned for energy recovery, carbon fibre can be recycled from composite like CFRP for several interests. First, it is necessary to limit the accumulation of waste that is likely to be generated; second, recycling could be a fibre supply solution in order to meet future demand in different applications [7]. Finally, recycling could be expected as a less-energy-intensive operation with lower environmental impact than the traditional way to produce CFRP, by-passing some production steps.

CFRP composite recycling is receiving a lot of attention from academics and industries [35] as highlighted by an increasing number of recent publications on the subject. Because of the technical difficulties to separate thermoset matrix from the reinforcement materials [60], the development of recycling technologies has been mainly focused on this type of composite materials. Several recycling technologies have been developed and proposed over the past decades in order to improve the recycling yield and the properties of the recovered fibre involving three main types of techniques, i.e., mechanical (grinding and electrodynamic fragmentation), thermal (pyrolysis, fluidised bed and microwave), and chemical (low temperature pressure and high temperature pressure in supercritical conditions). Beside these three main techniques, other recycling solutions can be found like electrochemical [51] and biotechnological [20]. The recent review of Oliveux et al. [35] is recommended for the current recycling techniques of Fibre Reinforced Polymer (FRP) composite in general including those of CFRP type and other fibre reinforced polymer composites such as GFRP (glass fibre reinforced polymer).

Aerospace sector has to face up with the problem of increasing CFRP waste. Regarding the long lifespan of airplane (20 30 years), the main stream of current CFRP waste may come from manufacturing of recent aircraft, which use high quantity of CFRP material. Otherwise, the flow of end-of-life CFRP waste from retired aircraft will be more important in the next decades when the high CFRP-content aircraft will be dismantled. In aviation, there is no legislation or regulation imposed on aircraft owners or aircraft manufacturers about how to design or deal an aircraft that meets proper and due end-of-life requirements like end-of-life vehicle directive and WEEE (waste electrical and electronic equipment) legislation in Europe [54]. However, recent programs of Boeing and Airbus like AFRA, TARMAC have motivated valorisation and reuse of reclaimed materials including CFRP and other composites in aviation on developing the best practices and processes with concerned stakeholders.

This context motivates the essential of modelling for CFRP waste management in aerospace sector in order to reduce the increasing flow of waste and to regain economic and environmental benefits from recycling. However, this model is complex with multiple possible routes for CFRP waste treatment. Each waste type has different characteristics and needs its own operation conditions. The market of recovered fibre is not still mature as the utilisation of recycled carbon fibres in industry generates some challenges which come from their lower quality than that of virgin carbon fibres [31] and their variability affecting many factors such as length, length distribution, surface quality (adhesion of fibre and matrix), as well as their origin (different grades of fibres are found at composite scraps from different manufacturers) [35]. In aerospace, the closed loop of carbon fibre material is limited because of high requirements in structural components and the degradation of fibre through recycling process. Recycled carbon fibre can be used in the applications in aerospace or other sectors which do not demand high quality in mechanical properties such as interior, automotive, construction etc. which can give more environmental benefits than the disposal solutions, e.g. landfill, incineration.

Considering these challenges, this study aims to develop an optimisation approach of CFRP waste management in aerospace with two objectives, i.e. minimising both cost and global warming potential (GWP) impacts, in order to assess both economic and environmental factors in the entire network. A linear programming model has been developed to determine the optimal material flow of CFRP waste going into different routes under each strategy. This framework is applied in France where the aviation industry is strong with Airbus and important suppliers in global aviation.

This paper is organised as follows. Section 2 presents the general concept of the network and its mathematical model with the associated constraints and objective function. The data and assumptions used in the case of France can be found in detail in Sect. 3. Section 4 presents the results of the network design under different strategies, following first a mono-objective optimisation strategy with economic cost and GWP impacts as separate criteria; second the criteria are associated in a bi-criteria optimisation formulation. This assessment is extended by a sensitivity study relative to the influence of recycling capacity. Finally, conclusions and perspectives are highlighted in Sect. 5 focusing on the extension of the model.

Problem Formulation

System Definition and Assumptions

The waste management model is developed through three main layers: waste types, waste treatment techniques and recovered products. The economic and environmental assessments are evaluated by all the activities concerning these three layers: transportation of waste from source to plant for treatment, waste treatment process and recovered products output from waste treatment (Fig. 1).

The model is formulated here as a static problem in which there is no variation of waste quantity and waste treatment capacity during the considered horizon time. All the wastes produced at the various sources have to follow the treatment system completely and cannot be stored at source. The waste treatment techniques are assumed to be available with a fixed capacity and the problem of deployment is not considered in this study.

According to Potter and Ward [42], waste in the aerospace composites industry can be defined generally as either end-of-life or manufacturing waste. The latter is constituted of different scrap types including woven prepreg, unidirectional prepreg, composite manufacturing part, clean fibre and

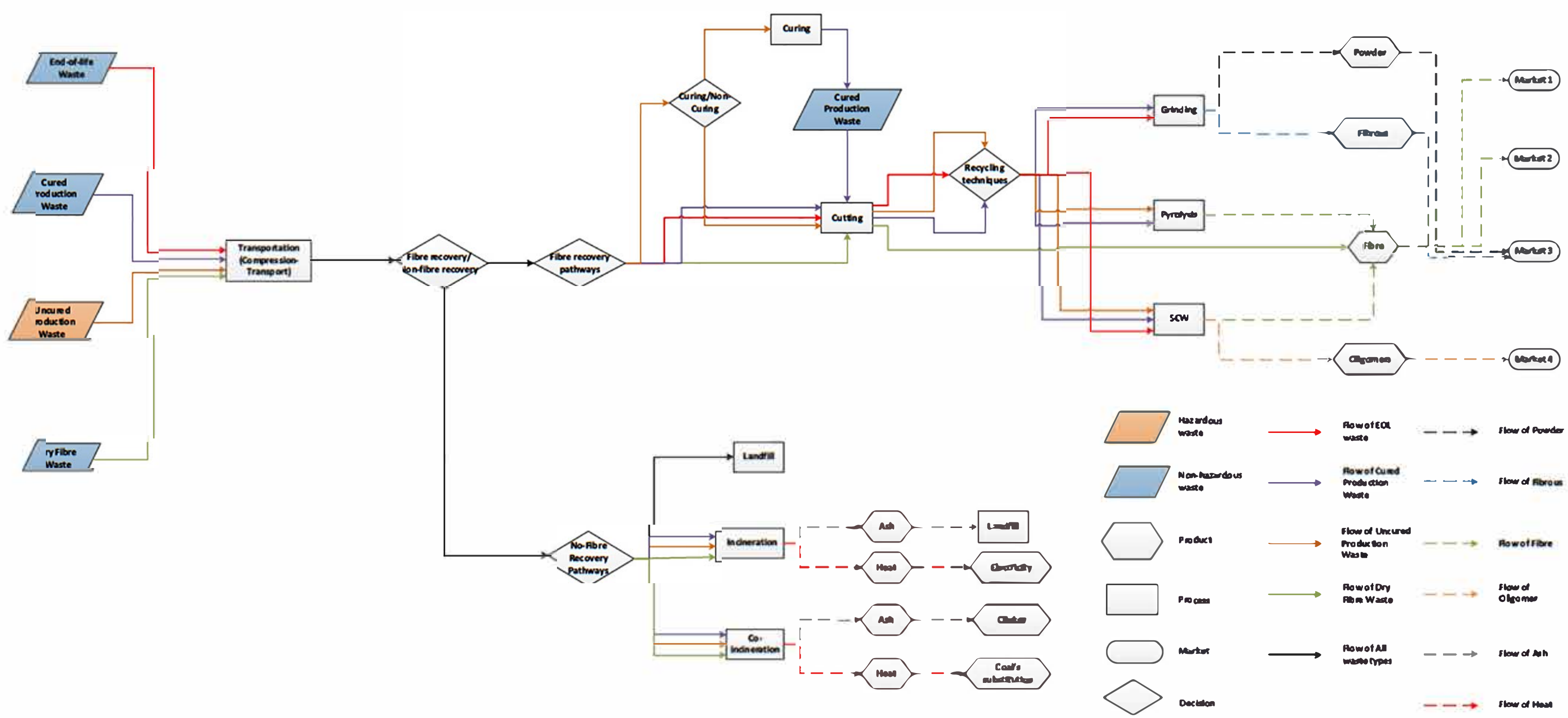


Fig. 1 System of CFRP waste management

fabric selvedge [31]. In this study, the composition of the input waste flow only considers the status of polymeric matrix via its curing level in scrap since the thermosetting polymer is principal resin used in aerospace application. The form of carbon fibre, e.g. fabric, or unidirectional form is not applied to classify the waste type. Based on carbon fibre chain in aerospace industry, the model considers four waste types: dry fibre waste, uncured production waste, cured production waste and cured end-of-life waste.

As carbon fibre is the most value component in CFRP, we focus on how the recycling rate of carbon fibre varies in the system under different scenarios. There are two main routes for waste treatment, i.e., no-fibre recovery and fibre recovery. The techniques considered in the first group are landfill, incineration and co-incineration. Heat or heat/material couple valorisation can be obtained through incineration or co-incineration respectively. Otherwise, fibre recovery pathways allow the recovery of carbon fibre through pre-treatment steps and recycling process. Due to the nature of waste types and technical constraints of recycling process, each waste type has to go into firstly pre-treatment step and then recycling process. Pre-treatment activities encompass shredding and curing. The techniques of recycling process considered are grinding, pyrolysis and recycling using supercritical water. Beside recovery of carbon fibre, by-products can be obtained. The modelling of these techniques is based on literature. Data collection is mainly obtained from a literature analysis based on an experimental approach for CFRP recycling.

Due to its nature, each waste type has its own constraints for the selection of the possible routes (Fig. 1). All waste types are required to go through shredding before going to recycling process. However, dry fibre waste can be recovered only by this step and does not need to go into any further process. The curing activity is applied on uncured waste due to the hazardous classification of this waste for transportation and to the requirements of some processes which cannot operate the uncured waste. Pre-treatment activities are assumed to be available at all recycling plants. All waste types are free to choose either direct recycling way, which means the pre-treatment step and recycling process at the same location or the indirect recycling way by which waste is pre-treated at one location and then transported to other locations for recycling. Considering the presence of flame retardant, end-of-life waste cannot go to the thermal process, i.e. incineration, co-incineration and pyrolysis.

The quality of recovered fibre is also considered in the model and may vary according to the selected process. The retention of tensile strength in comparison with virgin fibre is used to quantify the quality of recycled fibre. This parameter can help to distinguish pyrolysis from supercritical water to separate the recovered fibres from. Although a fibrous fraction can be obtained by grinding, its quality is assumed to be too low for high-value carbon fibre market and can be used in lower value market considering the degradation of fibre and the impurity of matrix in this fraction.

For transportation, the geographic unit of the model is based on a regional grid. The distance between the regions corresponds to the average distance between their two prefectures. The model does not consider the intra-mobility in each region. Although each waste type is generated by specific plants, e.g. end-of-life waste from aircraft dismantling site, uncured waste from prepreg/composite production plants, etc., the collection of all waste type in each region is not considered in the model and all of waste in each region is assumed to be available at the same location, i.e. its prefecture. In the same way, the transportation of waste from source to treatment plant and the distribution of the recovered product to market at the same region are not considered in the model.

There is no storage of waste at source and all the waste generated at each region has to be treated completely through either no-fibre recycling or fibre recycling pathways until there is no waste left in the static model. Two quantitative constraints are formulated at upstream: conservation of waste quantity allocated according to different techniques and to the capacity of waste treatment plants. As the aerospace industry has not been clearly regulated for the waste problem yet, there is no constraint on the recycling rate in the model. This variable factor is kept track of in order to study carbon fibre recyclability in the system in function of different criteria.

The economic criterion taken into account includes all the costs of the entire system, i.e., transportation, waste treatment, products distribution activities. The environmental impact is based on GWP impacts and is evaluated through both impacts from the activities of the whole system and the avoided impacts gained by the replacement of conventional products by the recovered products, which are assumed to have the same nature. An equivalent amount of the recovered product replaces the virgin product.

Position of the Proposed Model

The majority of current works about CFRP waste are related to the recycling process itself and do not embed the whole recycling chain. Along with the use of composite materials in various applications like aerospace, automotive and leisure activities, studies on life cycle assessment of composite in general and CFRP in particular have received a lot of attention to study the environmental benefits of composite utilisation that can be gained compared to the conventional materials [12, 49, 52, 53, 56, 57]. However, these studies focused mostly on production and utilisation phases of such materials. The phase of waste treatment is poorly studied and limited on one technique, e.g. recycling by microwave [12, 52] or recovery energy by incineration [57].

The analysis of the works dedicated to the CFRP waste management shows that the scope is limited by the lack of data and the heterogeneous sources used since composite recycling is still not mature and is currently on the phase of process development for some processes with heterogeneous technology readiness levels (TRL) for the identified recycling processes [46].

Hedlund-Åström [19] applied life cycle cost (LCC) and life cycle assessment (LCA) in order to study waste treatment routes of CFRP and other composites. The curing level of matrix in CFRP waste is considered in this study with two types of waste: uncured and cured CFRP. The cost-benefit analysis and the environmental load unit are assessed through the scenarios of three waste treatment pathways, i.e. incineration for energy recovery, mechanical recycling for material recovery and fluidised bed for material/energy recovery, applied in each waste type.

Witik et al. [58] developed a quantitative model for the determination of equivalent quantities of virgin carbon fibre and virgin glass fibre, which are replaced by recovered carbon fibre to achieve mechanical performance equivalent to virgin material in a short fibre composite beam, i.e. sheet moulding compound (SMC). This study assessed environmental impacts (climate change, resources, ecosystem quality and human health) of three waste treatment options: landfilling, energy recovery with incineration and carbon fibre recovery with pyrolysis.

Li et al. [27] carried out the study on LCC and environmental assessment (GWP, energy use, final disposal waste) for end-of-life CFRP in the automotive sector with three options (landfilling, incineration and mechanical recycling) within regulations of UK and EU. In this hypothetic case, between the two conventional disposal techniques (landfill, incineration), landfill tax can be viewed as a useful tool to shift CFRP waste from landfill to incineration because of the low GWP impacts and energy use in landfilling. Benefits of recycling depend on displacement factors of virgin carbon fibre by recycled fibre and on the recycling rate in order to balance the energy-intensive recycling process.

The decision support frameworks developed in waste management study waste allocation and compare the existing waste management options to guide decision-makers in the selection of the best available and applicable option(s) [33]. The current waste management models can be categorized into three main categories: cost benefit analysis, life cycle analysis and use of a multicriteria technique. The principal applications of waste management modelling are planning of municipal solid waste management (MSWM) in order to optimise plant locations, collection network under various criteria such as environmental impacts (e.g. global warming, human health risks, resource depletion, ecosystem damage), associated economic costs and benefits and regional characteristics (e.g. waste generation rate, political and social factors) [48]. The increasing interest on materials recovery (environmental consciousness, legislation, security of raw materials…) has motivated the integration of waste management in reverse supply chain for efficient materials management, especially for industrial waste, e.g. electronic waste (e.g. [2, 34]), battery (e.g. [23]) end-of-life vehicles (e.g. [10]).

Instead of analysing individually each waste treatment pathway, the proposed study focuses on the economic and environmental assessment of the entire system in which diverse CFRP waste type inputs are involved with multiple available techniques of fibre/no-fibre recovery techniques. Waste distributions can be varied under different strategies in this flexible model of CFRP waste management. Furthermore, the consideration of the market presence for recovered products allows the control of outputs.

Mathematical Model

The CFRP waste management system in this study is formulated as a single-period linear problem which predicts the distribution of wastes in multiple pathways of waste treatment techniques under two objectives: minimisation of the cost and minimisation of the GWP impacts. Four types of constraints are included in this model, i.e. mass conservation, treatment capacities, non-negative flows, and acceptability characteristics of techniques.

Constraints

Waste Quantity Conservation All the wastes generated at source $\boldsymbol{l}$ cannot be stored at source and have to be treated completely through either no-fibre recovery or fibre recovery pathways. There are two options for the secondary routes: pretreatment step and recycling process are separated for flow $\mathrm{FWPR}_{\mathrm{wll'}}$; direct recycling in which pretreatement can be integrated in function of the adaptability of process $\boldsymbol{r}$ with waste $\boldsymbol{w}$. Therefore, each output flow of each waste type $\boldsymbol{w}$ at source $\boldsymbol{l}$ has to be equal to the waste quantity of that waste type at the same location (1).

$$\sum_{e\in\mathscr{E}}\sum_{l'\in\mathscr{L}} FWNR_{well'} + \sum_{l'\in\mathscr{L}} FWPR_{wll'} + \sum_{r\in\mathscr{R}}\sum_{l'\in\mathscr{L}} FWDR_{wrll'} = QW_{wl}, \quad \forall w\in\mathscr{W}, \quad \forall l\in\mathscr{L} \tag{1}$$

Capacity Constraints The waste treatment capacity at each plant is applied for all waste inputs. The total waste streams which go into No-Fibre recovery techniques are under constraints (2). The flow of waste that pre-treated separately is lower than the capacity of pre-treatment which is equal to the total of capacity of all recycling techniques at the same location (3). All stream inputs of each recycling plant are inferior to its capacity (4).

$$\sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}} FWNR_{well'} \leq CAPEL_{el'}, \quad \forall e \in \mathscr{E}, \quad \forall l' \in \mathscr{L} \tag{2}$$

$$\sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}} FWPR_{wll'} \leq \sum_{r\in\mathscr{R}} CAPRL_{rl'}, \quad \forall l' \in \mathscr{L} \tag{3}$$

$$\sum_{i\in\mathscr{I}}\sum_{l\in\mathscr{L}} FIR_{irll'} + \sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}} FWDR_{wrll'} \leq CAPRL_{rl'}, \quad \forall r \in \mathscr{R}, \quad \forall l' \in \mathscr{L} \tag{4}$$

Non Negativity Constraints All streams of waste, intermediate product and recovered final product cannot take negative values according to constraints (5) (11).

$$FWNR_{well'} \geq 0, \quad \forall w \in \mathscr{W}, \quad \forall e \in \mathscr{E}, \quad \forall l, l' \in \mathscr{L} \tag{5}$$

$$FWPR_{wll'} \geq 0, \quad \forall w \in \mathscr{W}, \quad \forall l, l' \in \mathscr{L} \tag{6}$$

$$FWDR_{wrll'} \geq 0, \quad \forall w \in \mathscr{W}, \quad \forall r \in \mathscr{R}, \quad \forall l, l' \in \mathscr{L} \tag{7}$$

$$FIR_{irll'} \geq 0, \quad \forall i \in \mathscr{I}, \quad \forall r \in \mathscr{R}, \quad \forall l, l' \in \mathscr{L} \tag{8}$$

$$FPPR_{wpcll'} \geq 0, \quad \forall w \in \mathscr{W}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{9}$$

$$FPDR_{wrpcll'} \geq 0, \quad \forall w \in \mathscr{W}, \quad \forall r \in \mathscr{R}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{10}$$

$$FPIR_{irpcll'} \geq 0, \quad \forall i \in \mathscr{I}, \quad \forall r \in \mathscr{R}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{11}$$

Acceptability Constraints According to their type, the wastes can be accepted or not in a waste treatment pathways due to the difficulty of treatment. The waste streams to each route are restricted by the constraints (12) (14). The adaptability of intermediate products after pretreatment step in recycling technique is under constraint (15).

The constraints (16) (18) show the acceptability of recovered product streams in the corresponding market. Besides the types of recovered products, each market requires a minimum quality of products so that they can be accepted by that market. These constraints are expressed in (19) (21).

$$\sum_{l'\in L} FWNR_{well'} \leq XWNR_{we} * QW_{wl}, \quad \forall w \in \mathscr{W}, \quad \forall e \in E, \quad \forall l \in \mathscr{L} \tag{12}$$

$$\sum_{l'\in L} FWDR_{wrll'} \leq QW_{wl} * XWR_{wr}, \quad \forall w \in \mathscr{W}, \quad \forall r \in R, \quad \forall l \in \mathscr{L} \tag{13}$$

$$FWPR_{wrll'} \leq XWPR_{w} * QW_{wl}, \quad \forall w \in \mathscr{W}, \quad \forall r \in \mathscr{R}, \quad \forall l, l' \in \mathscr{L} \tag{14}$$

$$\sum_{l'\in\mathscr{L}} FIR_{irll'} \leq QWIR_{il} * XIR_{ir}, \quad \forall i \in \mathscr{I}, \quad \forall r \in R, \quad \forall l \in \mathscr{L}$$

with

$$QWIR_{il} = \sum_{w\in W}\left[\sum_{l'} FWPR_{wl'l} * (1 - XPR_{w})\right] * XWI_{wi}, \quad \forall i \in \mathscr{I}, \quad \forall l \in \mathscr{L} \tag{15}$$

$$\sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}} FPPR_{wpcll'} \leq XDP_{cpl'} * M, \quad \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \quad \forall l' \in \mathscr{L}$$

with

$$\sum_{c\in\mathscr{C}}\sum_{l'\in\mathscr{L}} FPPR_{wpcll'} = \left.\sum_{l''} FWPR_{wl''l} * XPR_{w}\right) * XPRP_{wp}, \quad \forall w \in \mathscr{W}, \quad \forall p \in \mathscr{P}, \quad \forall l \in \mathscr{L} \tag{16}$$

$$\sum_{w\in W}\sum_{r\in R}\sum_{l\in L} FPDR_{wrpcll'} \leq XDP_{cpl'} * M, \quad \forall c \in \mathscr{C}, \quad \forall p \in \mathscr{P}, \quad \forall l' \in \mathscr{L}$$

with

$$\sum_{c\in C}\sum_{l'\in L} FPDR_{wrpcll'} = \sum_{l''\in L} FWDR_{wrl''l} * RWRP_{rpw}/100, \quad \forall w \in \mathscr{W}, \quad \forall r \in \mathscr{R}, \quad \forall p \in P, \quad \forall l \in \mathscr{L} \tag{17}$$

$$\sum_{i\in I}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}} FPIR_{irpcll'} \leq XDP_{cpl'} * M, \quad \forall c \in \mathscr{C}, \quad \forall p \in \mathscr{P}, \quad \forall l' \in \mathscr{L}$$

with

$$\sum_{c\in\mathscr{C}}\sum_{l'\in\mathscr{L}} FPIR_{irpcll'} = \sum_{l''\in\mathscr{L}} FIR_{wrl''l} * RIRP_{rpi}/100, \quad \forall i \in \mathscr{I}, \quad \forall r \in \mathscr{R}, \quad \forall p \in \mathscr{P}, \quad \forall l \in \mathscr{L} \tag{18}$$

$$FPDR_{wrpcll'} * QLRPW_{wrp} \geq FPDR_{wrpcll'} * CQL_{cp}/100 \quad \forall w \in \mathscr{W}, \quad \forall r \in \mathscr{R}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{19}$$

$$FPIR_{irpcll'} * QLRPI_{irp}/100 \geq FPIR_{irpcll'} * CQL_{cp}/100$$
$$\forall i \in \mathscr{I}, \quad \forall r \in \mathscr{R}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{20}$$

$$FPPR_{wpcll'} * QLPRP_{wp} \geq FPPR_{wpcll'} * CQL_{cp}/100, \quad \forall w \in \mathscr{W}, \quad \forall p \in \mathscr{P}, \quad \forall c \in \mathscr{C}, \quad \forall l, l' \in \mathscr{L} \tag{21}$$

M is a big number that is used to impose the qualitative constraints in the mathematical model. In this case, it is applied to the restrictions of markets for recovered products.

Objective Functions

The bi-criteria optimisation approach in the model is carried out through all activities in the system boundary (Fig. 1) from transportation, waste treatment process to distribution of recovered product with two indicators, i.e. the economic cost and the GWP impacts. The objective functions are the minimisation of the cost and the minimisation of the GWP impacts. These objectives functions consist of variable costs (22 27) and variable GWP impacts (28 34) that depend on flows of wastes and products in the network. The input data are collected from literature in general and evaluated from Simapro v7.3 with ReCiPe Midpoint (H) v.1.06 assessment method for unit GWP impacts.

Cost Minimisation

$$\text{Cost} \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}\left[\begin{array}{r}(FWNR_{well'} + FWPR_{wll'} + FWDR_{wrll'}) * PTR_w + \\ +(FIR_{irll'} * PTR0)\end{array}\right] * DIST_{ll'} + \tag{22}$$

(Transport cost)

$$+ \sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWNR_{well'} * PNR_{ew}\Bigg) + \tag{23}$$

(Cost of No-Fibre recovery pathways)

$$+ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}(FWNR_{well'} + FWPR_{wll'} + FWDR_{wrll'} + FIR_{irll'}) * XTR_{ll'} * PCOM) + \tag{24}$$

(Compression cost)

$$+ \sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWPR_{wll'} * EPR_w * PE\Bigg) + \tag{25}$$

(Pretreatment cost)

$$+ \sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWDR_{wrll'} * PWR_{rw} + \sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FIR_{irll'} * PIR_{ri}\Bigg) + \tag{26}$$

(Cost of recycling process)

$$+ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}(FPPR_{wpcll'} + FPDR_{wrpcll'} + FPIR_{irpcll'}) * DIST_{ll'} * PTR0) \tag{27}$$

(Cost of distribution of recovered product)

Minimisation of the GWP Impacts The GWP is expressed as follows:

$$\text{GWP} = \sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWNR_{well'} * GWPNRU_e\Bigg) + \tag{28}$$

(No-fibre recovery activities impacts)

$$+ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}\left(\begin{array}{r}FWNR_{well'} + FWPR_{wll'} + \\ FWDR_{wrll'} + FIR_{irll'}\end{array}\right) * (DIST_{ll'} * GWPTRU)) + \tag{29}$$

(Transport impacts)

$$+ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}(FWNR_{well'} + FWPR_{wll'} + FWDR_{wrll'} + FIR_{irll'}) * XTR_{ll'} * ECOM * 3.6 * GWPE) + \tag{30}$$

(Compression impacts)

$$+ \sum_{w\in\mathscr{W}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWPR_{wll'} * EPR_w * 3.6 * GWPE\Bigg) + \tag{31}$$

(Pretreatment activity impacts)

$$+ \sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWDR_{wrll'} * GWPWR_{rw} + \sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FIR_{irll'} * GWPIR_{ri}\Bigg) + \tag{32}$$

(Recycling activity impacts)

$$+ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}(FPPR_{wpcll'} + FPDR_{wrpcll'} + FPIR_{irpcll'}) * DIST_{ll'} * GWPTRU) \tag{33}$$

(Distribution impacts)

$$-\left[\begin{array}{l}\sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}} FWNR_{well'} * GWPNRAU_{we}+\\ \sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l\in\mathscr{L}}\sum_{l'\in\mathscr{L}}\left(FPPR_{wpcll'}+FPDR_{wrpcll'}+FPIR_{irpcll'}\right) * GWPP_p\end{array}\right] \tag{34}$$

(Avoided impacts from recovered products of No-Fibre recovery and Fibre recovery pathways).

Coupling Multi-Objective Optimisation with MCDM Strategy

The CFRP waste management is modelled as a linear problem with a deterministic approach fixing the waste quantity input of system. Two objective functions are considered in the model, i.e. minimising the cost and minimising the GWP impacts either separately or simultaneously. In this study, from a multiobjective point of view, the lexicographic method and the ε-constraint method have been combined to build the so-called the Pareto front which represents in the objective function space the non-dominated vectors of Pareto optimal solutions (so-called non-inferior, admissible or efficient solutions) which cannot be improved in one objective function without declining the performance in at least one of the remaining objectives [55].

Both lexicographic and ε-constraints are categorised as a priori preference methods, in which multiobjective optimisation is transformed into a single objective optimisation problem by optimising one objective function after the other (lexicographic), or by optimising one objective by transforming all other objectives function into inequality constraints (ε-constraints). As two distinct lexicographic optimisations with distinct sequences of objective functions do not produce the same solution [11], the solutions of the lexicographic method in this bi-criteria optimisation problem correspond to two extremities of Pareto front. Between the two extreme solutions, the other alternatives in Pareto front are obtained by ε-constraints method. The GWP impact function is minimised while the cost is limited under successive intervals till the lowest cost.

The multiobjective optimisation step is then followed by the use of a multiple criteria decision making (MCDM) procedure that consists in finding the best alternative among a set of feasible alternatives. Among the many approaches of MCDM, a variant of the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method [44], called M-TOPSIS has been selected to rank the Pareto optimal solutions. TOPSIS is based upon the concept that the chosen alternative should have the shortest distance from the Positive Ideal Solution (PIS) (the lowest GWP impacts and the lowest cost in the studied case) and the furthest from the Negative Ideal Solution (NIS). The final ranking is obtained by means of the closeness index [44].

TOPSIS has been selected mainly for four the following reasons: TOPSIS logic is rational and understandable, the computation process is straightforward, the selection of the best alternatives for each criterion is carried out by a simple mathematical form, and the importance of weights is incorporated into the comparison procedures. In this study, the two criteria are considered to have the same importance weight; there is no preference of one criterion over the other. M-TOPSIS is therefore the appropriate decision aid method to rank the alternatives in Pareto front and determine the compromise solution for the two objectives. It must be yet emphasized that MCDM techniques are not the panacea for all decision problems and the TOPSIS methods present certain drawbacks such as the phenomenon known as rank reversal [44].

Case Study

The case study refers to the situation of France in 2016 for carbon fibre wastes from aerospace industry. The horizon time of this study is 1 year. The data input and the assumptions for the modelling of the case study, i.e. waste quantity, waste treatment pathways, transport, will be detailed in this section.

Waste Types

Apart from dry fibre scrap, the other waste types considered in the model are constituted of both carbon fibre and polymeric matrix. In the aerospace sector, CFRP are assumed to have 65 wt% of carbon fibre, and 35 wt% of thermoset matrix in average. The additives are considered to be negligible.

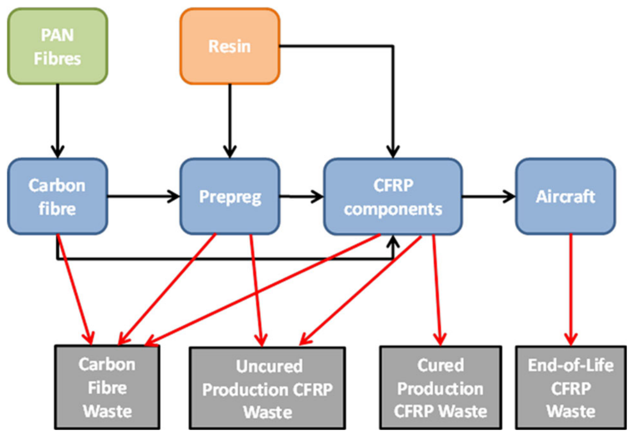


Fig. 2 Waste generation in Aerospace carbon fibre chain

Carbon fibre in all waste types considered in this model is PAN (Polyacrycolonitrile)-based, which due to high carbon yield, competitive process cost and superior physical properties, has been dominating the global market with 90 %, the remaining 10 % are made from rayon or pitch (Zoltek). This type of carbon fibre is therefore employed extensively in aerospace and industrial field and sporting/recreational goods (The Japan Carbon Fiber Manufacturers Association).

Through carbon fibre chain in aerospace (Fig. 2), only wastes containing carbon fibre are considered in the boundary of system, i.e. dry fibre, uncured production CFRP, cured production CFRP and end-of-life CFRP, the other wastes such as PAN fibre and resin are excluded. Based on input output relations of each step in carbon fibre chain, we determine the potential carbon fibre wastes of the system (Fig. 2). Dry fibre comes from production of carbon fibre as production scrap, from production of prepreg and finished composite component as raw material scrap. Uncured production waste is generated during manufacturing prepreg as production scrap and finished composite component as raw material scrap. Cured production waste is produced from fabrication of finished CFRP component and end-of-life CFRP waste comes from retired aircraft after dismantling.

End-of-Life Waste from Aircraft Dismantling

End-of-life (EoL) CFRP waste is extracted from CFRP components of retired airplanes through their dismantling. In France, two sites are identified at Tarbes and Châteauroux, with a respective dismantling capacity estimated at 50 and 30 airplanes per year at full capacity. The rate of CFRP separation is assumed to reach 95 %. There is no consideration of reuse for CFRP waste, right after dismantling.

The rate of generation of CFRP waste per aircraft at a dismantling site is assumed to be equal to the average of all aircraft retired in 2006. Due to the variety in aircraft types and their CFRP content, the average weight of CFRP per aircraft at their retirement age [see expression (35)] is used to estimate the quantity of end-of-life waste according to expression (36).

Even if the retirement time of an aircraft depends on several factors such as the number of pressurisation and depressurisation cycles, greater efficiency, financial reasons, an average 25-year life span of aircraft (t_r) is generally considered. The aircraft weight depends on its load, e.g. operating empty weight, maximum take-off weight. However, the weight of airframe structure is not well described by aircraft manufacturers. This parameter is therefore based on the operating empty weight with an index of proportion of airframe structure in this weight (ps_m). The operating empty weight, which includes structure, systems, engines, equipment, non-usable fuel, crew, is the nearest well-documented weight to the airframe structure weight. The index ps_m is assumed to be 0.9 for all aircraft types. Considering the light variation between the different variants in each aircraft model, the operating empty weight considered is the average of all the variants.

The CFRP content in structure of each aircraft model has been evaluated from literature review. This case study is applied for the commercial jets from McDonnell Douglas/Boeing and Airbus, which have CFRP content, the other aircraft from these manufacturers, which have no CFRP are not considered. Due to the lack of data, the assumptions are applied for the aircraft models, for which only the general information on composite proportion with yet no detail on CFRP content: the first models which adopt CFRP in secondary structure and the recent models which use CFRP in primary structure have respectively 50 and 85 wt% of CFRP in the total composite content. Data concerning aircraft models, i.e. operating empty weight, proportion of CFRP, and the number of deliveries can be found in online Appendices 1 and 2 respectively.

$$um_t = \frac{\sum_m \left[n_{t\ t_r}^m * \left(\frac{\sum_j M_{mj}}{a_m} * ps_m * pc_m \right) \right]}{\sum_m n_{t\ t_r}^m} \qquad (35)$$

$$QW_{w=EOL}^l = um_{t0} * CAPD_l * DISM_l * RECM_l \qquad (36)$$

Manufacturing Waste

The quantity of each type of production waste is calculated by the following formula (37):

$$QW^{l}_{w \in \mathscr{W} \setminus \{EOL\}} = \sum_{f} \sum_{s} CAPP_{fs} * NOM^{l}_{fs} * PROD_{fs} * \frac{PWM^{f}_{w \in \mathscr{W} \setminus \{EOL\}}}{100} \quad (37)$$

To our knowledge, no data concerning either waste quantity or waste production rate in the upstream steps of CFRP production, i.e. fibre and prepreg manufacturing are available. The wastes generated from these activities are assumed to represent 1 % of the products and 0.5 % of the raw materials of the output capacity of each plant. CFRP waste from manufacturing is assumed to be composed of 66 % prepreg, 18 % cured parts, 13 % trimmings, 2 % finished parts, and 1 % bonded honeycomb (Department of Defence 2002). In our model, these values are simplified and distributed to the three studied waste types: 66 % uncured, 27.5 % cured, and 6.5 % dry fibre on considering 50 50 distribution of cured CFRP and dry fibre in trimming waste and combining cured parts, finished parts, bonded honeycomb and trimmings (50 %). In aerospace, the average manufacturing waste generated is estimated of 14 % of raw materials input of process [42]. Based on this value, the proportion of all wastes generated from CFRP production is therefore calculated at 16.28 % of products output of process. The generation rates of each waste type compared to product output are summarized in Table 1.

Only the big manufacturers of carbon fibre report the capacity of their plants. Similar data for fibre conditioning (fabric production), prepreg production, and finished aerospace CFRP component plants are not available. For this purpose, the plants in aerospace CFRP production chain (carbon fibre, prepreg, finished CFRP production) have been categorised into three classes of scale in function of supplier status for jets manufacturers i.e., prototype suppliers, outsourcing raw materials suppliers, subsidiaries. The assumed capacity of each class is proposed in Table 2 The number of plant types in each region in this study is presented in detail in online Appendix 3. As carbon fibre manufacturing involves expensive processes, the manufacturing cost exclusively depends on a stable demand of markets. The current global carbon fibre production is evaluated at 68 % of its maximum capacity in 2016 according to the report of the project [1]. This yield has been applied for all steps in CFRP production chain in this study.

Snapshot of Waste Sources in France

Following the aforementioned methods, the quantity waste estimated in each region of France can be visualized in Fig. 3.

Waste Treatment Pathways

A classical material flow analysis (MFA) methodology [9] for determining the flow of materials and energy for all types of wastes based on cured production waste in all pathways has been developed. For the sake of illustration, the case of cured production waste is presented in Fig. 4. For the other wastes, the following assumptions have been used:

- The MFA of all wastes in no-fibre recovery pathways (i.e. landfill, incineration, co-incineration) is the same.
- Dry Fibre waste is assumed to be shredded and does not need specific recycling technique for recovery. Its recycling yield is assumed to be 100 %.
- Because of uncured matrix, the uncured production waste has to be cured before going to grinding. Pyrolysis and supercritical water (SCW) process are assumed to accept this waste type.
- The MFA of cured and uncured in pyrolysis and SCW is assumed to be the same.
- Due to the possible presence of retardant flame additives in end-of-life waste, this waste type cannot go into the thermal techniques (i.e. incineration, co-incineration, and pyrolysis).
- In grinding and SCW, the necessary auxiliaries for end-of-life waste treatment are 2.8 times of the cured production waste with the same quantity of waste on considering its difficult recovery due to multiple layers. This assumption is generalised from the work on SCW experiments between cured production sample and aircraft piece of Knight [24].
- Beside, the costs of transport and treatment of no-fibre pathways of the uncured production waste are 1.5 times of the cured production waste because of the handling precaution for this hazardous waste.

Table 1 Generation rate of waste of production plant PWM_{wf} (%)

PWM_{wf} (%)	Dry carbon fibre waste	Prepreg (uncured production CFRP waste)	Cured production CFRP waste
Carbon fibre production (fibre/fabric)	1	0	0
Prepreg production	0.5	1	0
CFRP production	1.06	10.74	4.48

Table 2 Annual capacity of production plants $CAPP_{fs}$ (tons/plant)

$CAPP_{fs}$ (tons/plant)	Plant scale (s)		
	Small	Medium	Large
Carbon fibre production	1500	5000	9000
Prepreg production	500	1000	1500
CFRP components production/aircraft manufacturer	50	250	500

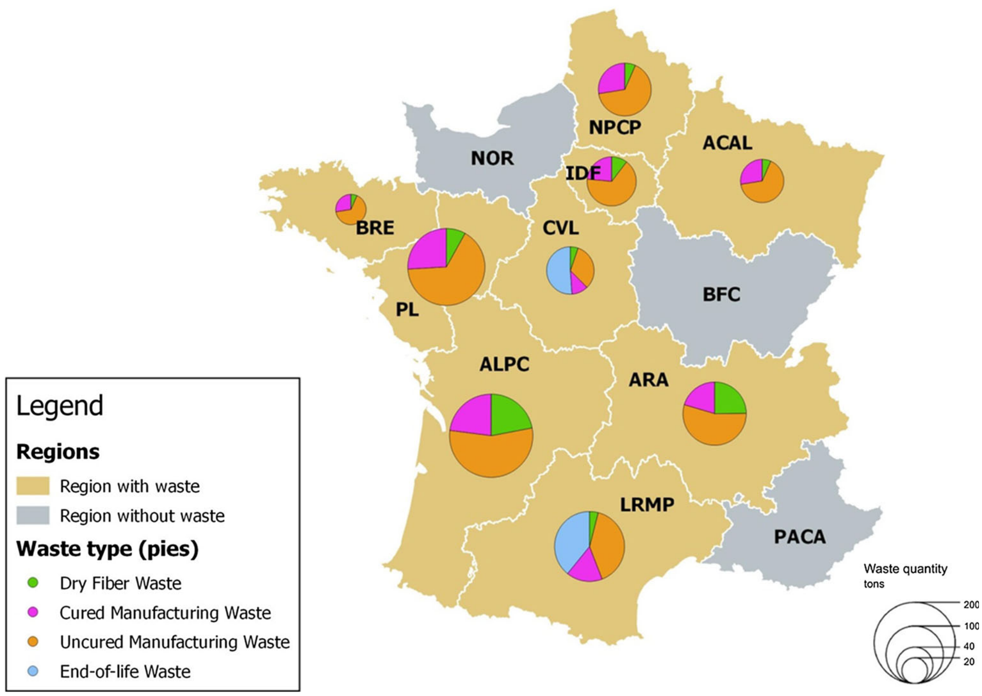


Fig. 3 Snapshot of waste quantity in France

Landfill

Landfill can be defined as a specific underground storage of waste when there is no available recycling technique for this kind of waste. In this study, landfilling is considered as a disposal pathway, not as a kind of storage. Therefore, once landfilled, the potential recovered products from waste are lost.

No specific process for composite landfilling is defined in Simapro v.7.3 databases, e.g. Ecoinvent 2.2. The landfilling of plastics mixture in sanitary landfill process, which is the closest option to composite landfilling solutions regarding the similar organic chemical nature of polymeric composite and plastics, has been adopted in order to evaluate GWP impacts of waste landfilling. The impacts from losing the recyclable fibre in wastes through landfilling are considered in order to avoid neglecting the lost potential. These impacts are evaluated with a negative GWP value of production for the equivalent quantity of virgin carbon fibre as the quantity of carbon fibre presented in landfilled waste. According to a report in 2012 by Fischer et al. [15] for EEA, the general landfill charge in France in 2015 is estimated of 95 €/tonne.

Incineration

Incineration is a thermal process, which allows recovering energy in heat resulting of waste combustion. The heat can be used directly or converted into electricity. In this scenario, the process is assumed to be auto-thermal; the heat and the ash by-product released from the process are estimated 32 MJ/kg of waste and 8 wt% of input waste respectively as in the work of Witik et al. [58]; the emission of combustion is based on the work of Hedlund-Åström [19]. The heat is then converted to electricity with an efficiency of 35 % [5] The ash by-product is landfilled as an inert waste. The cost of general waste incineration (including incineration activity and ash landfilling) is about

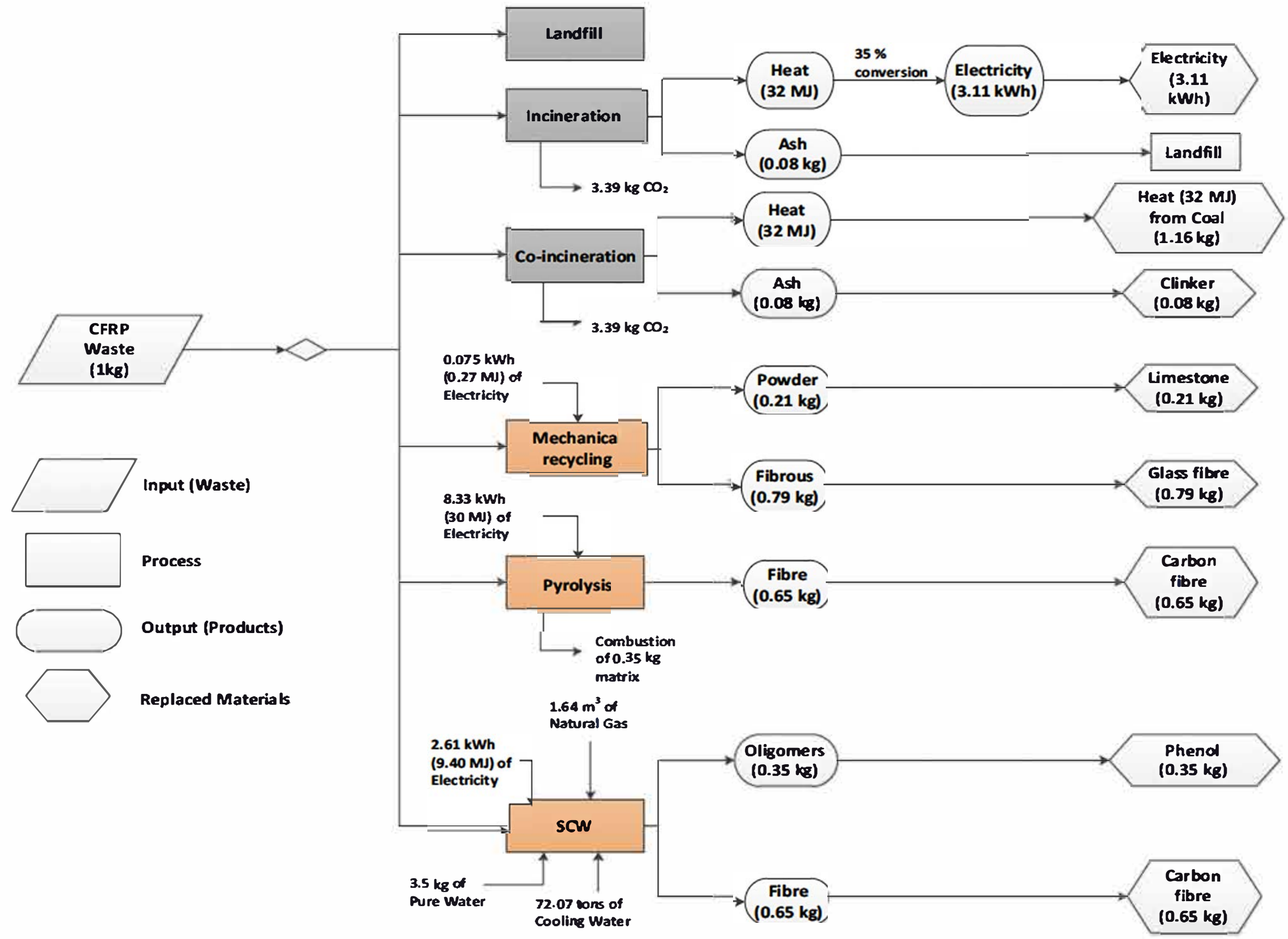


Fig. 4 Material flows of cured production waste in the studied system [19, 21, 24, 36, 52, 58]

92 €/tonne in France in 2015 according to Fischer et al. [15].

Co-Incineration

As incineration and co-incineration are both based on combustion of waste, we assume that there is no change in the quantity of heat and ash produced in co-incineration compared with incineration technique. However, co-incineration allows material recovery in addition to energy recovery. Indeed, in co-incineration technique, waste is used as a substituted fuel involved in clinker fabrication where coal is normally used as fuel and the products of waste combustion, i.e. heat and ash, are completely valorised in co-incineration. Heat released from combustion of waste can substitute the same amount of heat from coal combustion in furnace and ash is mixed with the raw materials of clinker in its manufacturing. According to Halliwell [18], the cost of treatment of co-incineration of composite waste charged by the cement industry is around 1 € per kg.

Grinding

The principle of this technique is to separate fibres from matrix by a grinding process. After mechanical process and sieving, the obtained products are a mixture of matrix and fibre. They are separated into different fractions in function of the proportion and the length of fibre [25, 36].

From Palmer et al. [36], two products are assumed to be recovered from the composite waste, i.e., a powder product (29 wt%), which is rich in matrix and used as filler, and a fibrous fraction (71 wt%), which is rich in fibre. The process energy of this technique is estimated at 0.27 MJ/kg by Hedlund-Åström [19] which is in agreement with the value proposed in Howarth et al. [21] in a test with industrial equipment.

Pyrolysis

Pyrolysis is a thermal recycling process of FRP that decomposes the matrix at around 400 750 °C [35] depending on the thermal properties of resin in order to recover fibres. The main characteristic of this process is the thermal decomposition in an inert environment or in a controlled atmosphere with a low proportion of oxygen to avoid the oxidation of fibres. A rapid gasification might be needed after the main process step to clean the fibres from char of resin decomposition [13, 32] The gas fraction produced from the decomposition of matrix can be condensed to be reused as a fuel or burned to recover heat.

In this study, the pyrolysis is modelled as a combustion process of the matrix (35 wt% of CFRP waste) for assessment of environmental impacts. No energy recovery from thermal decomposition of matrix has been assumed. The total energy used in pyrolysis has been estimated at about 30 MJ/kg composite [58].

Supercritical Water (SCW)

In supercritical condition (temperature above 374 °C and pressure superior to 221 bar), "the properties of water change considerably: the hydrogen bonds disappear and water becomes similar to a moderately polar solvent; oxygen and all hydrocarbons becomes completely miscible with water; mass transfer occurs almost instantaneously; and solubility of inorganic salts drops to ppm range" [28]. Due to these properties, the polymer matrix is decomposed into different oligomers and the carbon fibre is recovered in supercritical water. Other supercritical solvents such as acetone, methanol, ethanol and propanol are also used for CFRP recycling because of their lower critical temperature and pressure compared to water [41].

This technique has been industrialised for hazardous waste treatment since 1980s [30]. For composite application, although it has received a lot of attention from academics and industry [35], supercritical water for CFRP waste is still at pilot scale. Only scarce information is available for this process. From Knight [24], for 1 kg of CFRP (35 wt% matrix) waste, the process requires 2.61 kWh of electricity, 1.64 m^3 of natural gas, 3.5 kg of pure water for solvent and 72.07 tonnes of cooling water. CFRP waste is assumed to lead to 100 % recovery yield of carbon fibre and matrix (in the form of oligomers).

Distribution of Waste Treatment Echelon

The non-fibre recovery techniques are assumed to be available in all regions with a capacity at each region exceeding to the total wastes in the system. Currently, fibre recovery techniques have a limited presence in France with only three sites: (1) Bretagne (BRE), (2) Auvergne-Rhône-Alpes (ARA) and Pays de la Loire (PL). BRE site has a capacity of over 1000 tons of chopped carbon fibre for the grinding technique (Procotex). In another source [31], this site is reported to involve pyrolysis. Therefore, in this model, a capacity of 1000 tons of waste input with 50 % in grinding and 50 % in pyrolysis is assumed. The ARA site uses grinding technique with a 3000 ton-capacity [18]. This site also works with other composites in reality, but we assume that its full capacity is available for carbon fibre waste in this study. SCW at pilot scale applied for carbon fibre recycling is found in the site in PL region [35] and is assumed to have a capacity of 200 ton-input per year. The location and the capacity of waste treatment techniques are summarised in Table 3.

Transport Echelon

In order to simplify the system, the CFRP waste management in this study uses the road mode of transport. All wastes have to be compressed at source before being transported to other regions for treatment. If the waste is treated at the origin region, the compression step is not necessary.

The lorry of 16 32 tonnes certified EURO5 is used to transport all wastes and recovered products in this model. The evaluation of GWP impacts from this activity is based on this type of vehicle. The transport price is a variable cost depending on waste/recovered products quantity and distance. This cost is estimated at 0.14 €/(ton.km) [47] for all normal goods including non-hazardous wastes and recovered products. Considering the specific configuration for uncured waste which is classified as a hazardous waste, its transport cost is assumed to be 1.5 times than the standard cost.

Table 3 Location and capacity of waste treatment techniques

Waste treatment techniques Non fibre recovery techniques (landfill, incineration, co incineration)	Availability All regions	Capacity (tonnes/year) Unlimited
Grinding	BRE	500
	ARA	3000
Pyrolysis	BRE	500
Supercritical water (SCW)	PL	200

Quality of Recovered Products and Markets

The products recovered from the fibre recovery pathways have diverse qualities depending on the process. Moreover, the requirement of each market is different from the type of product and quality of products. In this study, the ratio of quality of recovered products over standard conventional products replaced by the equivalent recovered products, are used to represent the quality of products output and the so-called acceptability index of market. This assumed index is the minimum quality that recovered products must have to go into the corresponding market. There is no weight compensation to satisfy the quality requirement of replaced materials in market.

The retention of tensile strength in comparison with virgin fibre is used to quantify the quality of recycled fibre. Its values are the average of the best qualities of recycled fibre from the experiments of Akonda et al. [4], Greco et al. [16], Meyer et al. [32], Pimenta and Pinho [39], Piñero-Hernanz et al. [40], Stoeffler et al. [50]. The dry fibre is considered to conserve its quality after shredding. The other recovered products are assumed to have 100 % of quality of the replaced materials. The quality of all recovered products from the Fibre Recovery Pathways and the characterisation of markets are resumed in online Appendix 4.

Results and Discussions

Pareto Optimal Solutions

The Pareto front (Fig. 5) is constituted of 11 alternatives. Alternatives 1 and 11 refer to cost minimisation and GWP minimisation respectively. The convex form of Pareto front indicates that the two objective functions are conflicting, resulting from the effect of the avoided impacts included in the GWP function though both the cost and the GWP impacts of process activities (without the avoided impacts) have linear relationship with materials flows.

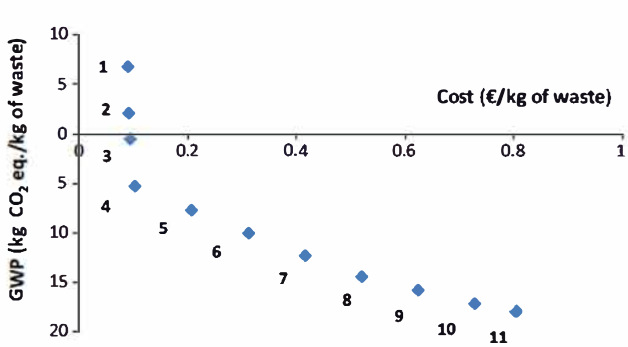


Fig. 5 Pareto front of the case study

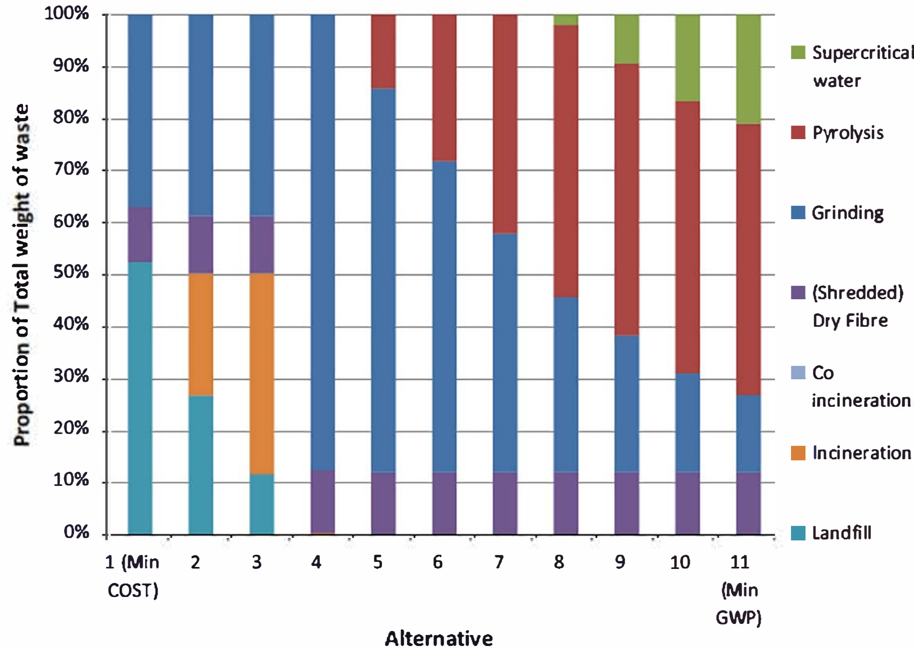
Figure 6 shows the evolution of waste treatment techniques used through the alternatives of Pareto front. Minimising the GWP impacts promotes the recovery pathways in general and the techniques with high value recovered products. From alternatives 1 11, the utilisation of landfill is reduced and replaced by incineration (2 3); this latter is also substituted more and more by grinding which loses gradually its part then favouring pyrolysis and SCW in the alternatives 5 11. This evolution corresponds to an increase in the avoided impacts released from incineration to grinding then to pyrolysis and SCW.

Instead of losing recoverable materials in landfill, waste can be valorised to electricity in incineration. The avoided impacts from substitution of energy produced in France are too low to compensate all impacts from the emissions of process. Although co-incineration is modelled with a similar process as for incineration, the reuse of its outputs in clinker production covers all GWP impacts from the process. However, due to its high cost, co-incineration which has negative GWP impacts cannot win over the other techniques. With the high values of recovered products, all fibre-recovery techniques have negative GWP impacts. The conventional production of carbon fibre emits very high GWP impacts. The avoided impacts from the replacement of carbon fibre in pyrolysis and SCW are much more important than limestone-glass fibre from grinding. Besides, as matrix is also valorised as a by-product in SCW, and this technique offers the lowest GWP impacts.

The Non-Fibre recovery pathways have an advantage in accessibility for waste treatment. They are assumed to be available at all regions with unlimited capacity. The Fibre recovery techniques are currently located in some regions and are limited in capacity. However, this advantage of the Non-Fibre recovery techniques has a low economic interest in the system. With the slight increase of unit cost per 1 kg of waste (0.0025 €/kg) in alternative 1 which has more than 50 % of waste in No-Fibre recovery technique (i.e. landfill), the GWP impacts of the system become negative in alternative 4 which recovers 99.6 % of waste with the reinforcement of grinding dominance. This technique has the lowest operation cost in Fibre recovery pathways. Furthermore, all wastes can be operated with grinding. SCW can treat all wastes but suffers from a high operation cost. In this case study, the use of a simple recycling technique like grinding, leads to 2.7 % increase in the minimum cost with avoiding the loss of 52.5 % of wastes in landfill. Grinding is therefore helpful to increase the recycling yield under the cost minimisation strategy. However, this technique suffers from a low value added of its recovered products on the market.

The capacity also influences on the distribution of techniques of Fibre recovery techniques. The total capacity

Fig. 6 Distribution of waste treatment techniques in Pareto optimal solutions



of grinding is higher than the total waste quantity. However, pyrolysis and SCW have limited capacities. Although SCW has the lowest GWP impacts, this technique cannot yet dominate in the alternative 11 due to its capacity limitation. This alternative is also highlighted by by the saturation of capacity for pyrolysis and SCW plants.

In this case study, all the recovered products are directly reused on the recycling plant sites for all the solutions found by the optimisation strategy. There is no distribution of products from plant to market because all markets present at the region of recycling plants. Without the limited demand constraints, the markets have no impacts on decision of waste distribution in upstream. This latter depends therefore on the characterisation of the waste treatment techniques.

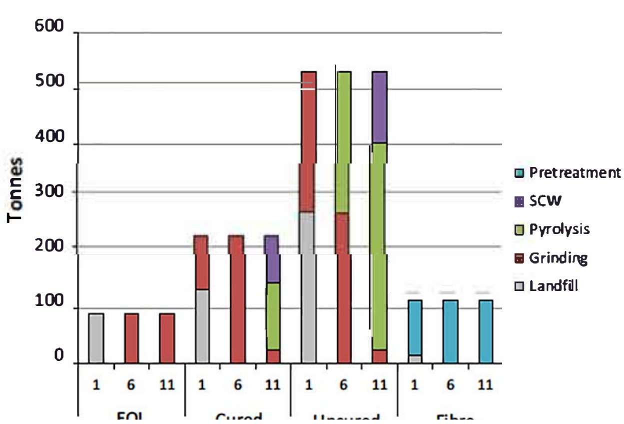


Fig. 7 Distribution of waste type in waste treatement pathways

The alternatives are ranked into this following order by the decision aid method M-TOPSIS with two objectives, i.e. cost minimisation and GWP minimisation: 6 > 7 > 5 > 8 > 4 > 9 > 10 > 3 > 11 > 2 > 1. The M-TOPSIS solution found is alternative 6.

Network Configurations from Bi-Criteria Optimisation

Figure 7 shows the waste distribution for each pathway corresponding to alternatives 1 (i.e. cost minimisation), 6 (i.e. M-TOPSIS choice), and 11 (i.e. GWP minimisation).

For cost minimisation (alternative 1), the model favours the two lowest cost techniques, i.e., landfill and grinding that can treat all kinds of waste. Although grinding exhibits the lowest cost among all the considered techniques with a total installed capacity superior to the global waste quantity, it is only located in two regions. The transport cost is main reason for switching to landfill. Landfilling turns out to the most competitive option compared to the other options apart from "in situ" grinding. Due to the diverse distribution of wastes, over 50 % of total wastes are landfilled on site to minimise cost while all the wastes located in the regions where grinding is present are recovered. Although dry fibre waste can be recovered by whatever the Fibre-recovery techniques by shredding, 12.7 % of this waste is lost in landfill due to the high distance from waste source to recycling plant. The SCW plant (only present in PL region) is used for curing the uncured waste generated "in situ" to reduce the transportation cost, and for shredding the dry fibre waste on site or coming from neighbouring regions (Fig. 8a).

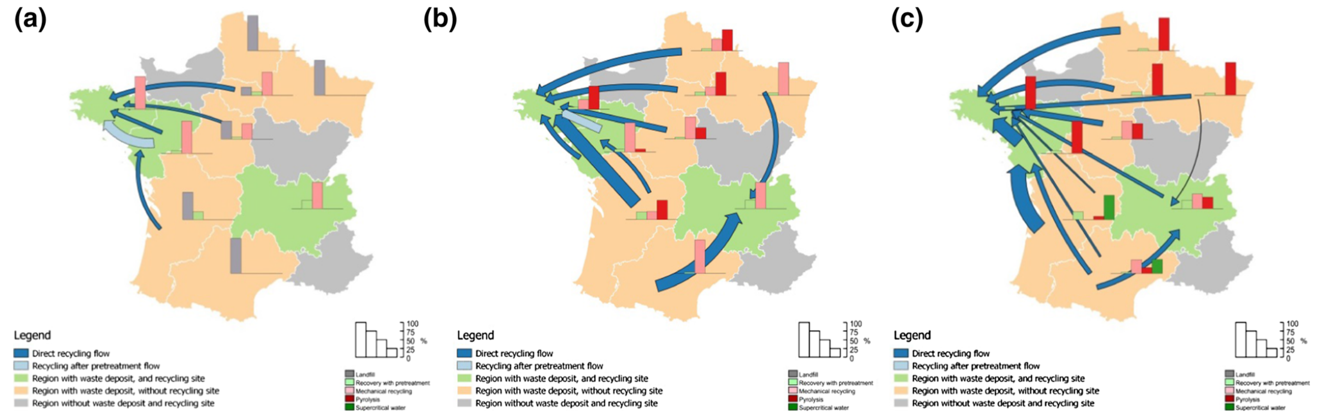


Fig. 8 Waste flows and waste distribution in each region of, **a** alternative 1, **b** alternative 6, **c** alternative 11

However, in order to minimise GWP impacts, the configuration of network found by the optimisation strategy is balanced by the GWP impacts from operation activities, the avoided GWP impacts from recovered products and the capacity of techniques. Since the impacts of the recovered products from fibre-recovery pathways are much more important than both the impacts of activities and the impacts from no-fibre recovery pathways, the first options are favoured so as to avoid the maximum GWP as possible. This explains why this situation leads to a saturation of both pyrolysis and SCW plants. But the total capacity of these two plants cannot take into account all the wastes apart from dry fibre which does not depend on recycling capacity but on pretreatment capacity at recycling plant. Grinding is mainly used for EOL waste treatment. Besides grinding, this waste can be recovered by only SCW (pyrolysis is not allowed). In each process, the treatment of EOL waste needs more auxiliaries input than of the other wastes. This waste also contributes to the lowest part in the total wastes quantity in the system. Therefore, EOL grinding allows saving capacity of pyrolysis and SCW for cured and uncured production wastes on reducing the GWP impacts produced from EOL treatment. As the GWP criterion does not consider the difference in transport between non-hazardous waste and hazardous waste transport like the cost. The uncured waste is directly transported to recycling plant without pre-treatment at source before transportation in alternative 11 (Fig. 8c).

Alternative 6 is the top-ranked solution obtained by M-TOPSIS. As mentioned before, there is slightly small gap in cost between the cheapest No-Fibre recovery technique, i.e. landfill and the cheapest Fibre recovery technique, i.e. grinding; however, the difference in GWP impacts between the two pathways is very high due to the value of recovered products. Although all wastes go to fibre-recovery pathways like the alternative 11, there are fewer flows of waste transported to recycling sites in the alternative 6. The wastes which are not at the regions of recycling plant are transported to the closest region. However, SCW is not applied in this alternative due to the high operational cost of SCW compared to grinding and pyrolysis. The avoided GWP impacts from the reuse of oligomers as phenol are not high enough to balance the GWP impacts and the high cost from recycling operation so that SCW can compete with pyrolysis. In this context, curing the uncured waste at SCW plant (PL region) before grinding this waste at BRE region is needed to reduce the transportation cost in alternative 6 as the network in alternative 1 with a lower quantity of uncured waste. This SCW is also used for shredding the dry fibre on site or from the neighbouring regions (Fig. 8b).

In this case study considered, all the markets exist at the regions where recycling is implemented. Therefore, all the recovered products generated from the recycling plants depend on upstream. Yet, the distribution of products can help developing potential markets where the accumulation of products is generated, so that the upstream waste management can be developed in order to solve the treatment of all wastes on the one hand and the valorisation of recovered products from waste on the other hand.

The snapshots of the amount of recovered products from fibre-recovery pathways are shown in Fig. 9 for (a) alternative 1, (b) alternative 6, and (c) alternative 11. It can be seen that the distribution of recovered products, which results from upstream waste distribution varies with the strategy of the system. The fibre market is not well developed in alternative 1 because of a high contribution of landfilling, whereas pyrolysis and SCW are strongly involved in alternative 11 with strong fibre market. The markets for products of grinding, i.e. powder and fibrous fractions are well represented in alternatives 1 and 6, but poorly contribute in alternative 11. Beside fibre market, the use of SCW needs the existence of market for its by-product, i.e., oligomers.

Extension of Recycling Capacity

Not surprisingly, the results obtained show the importance of recycling capacity in waste distribution, e.g. the

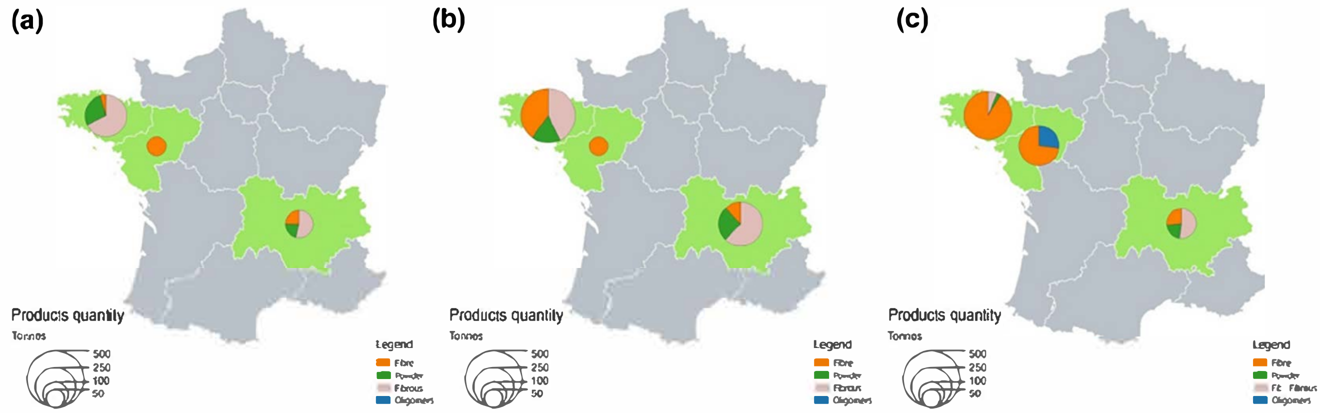


Fig. 9 Snapshot of recovered products from fibre recovery pathways of, a alternative 1, b alternative 6, c alternative 11

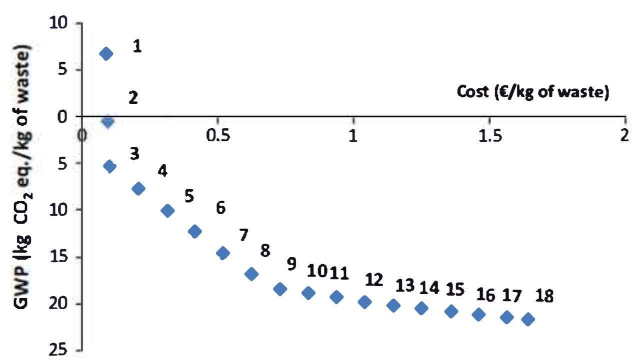


Fig. 10 Pareto front of the case extended recycling capacity

saturation of pyrolysis and SCW in the solution for GWP impacts minimisation. In this section, the recycling capacity constraint is relaxed by the extension of recycling capacity in order to determine the necessary capacity of each plant, i.e. so that the total waste amount of the system can be treated.

The same formulation as the one used for the base case study with ε-constraint method and lexicographic technique, is involved: in this case, the Pareto front (Fig. 10) is constituted of 18 alternatives (numbered from 1 to 18 with decreasing GWP impact). Alternatives 1 and 18 are the solutions of lexicographic technique with priority of cost minimisation and GWP minimisation respectively. Figure 11 shows the waste distributions for the solutions of the Pareto front. Alternative 7 is the M-TOPSIS solution for the bi-criteria optimisation problem in the case of the extension of recycling capacity.

The evolution of waste distribution exhibits the same trend for the solution of cost minimisation and of GWP minimisation respectively as in the base case study. The low cost option with low value of recovered products is substituted by the higher cost option with higher value of recovered products. The effect of extension of recycling capacity can be clearly seen by the total dominance of SCW in the system for GWP minimisation. In the base case study, the system is trapped by the limitation of capacity for both pyrolysis and SCW. The GWP impacts are reduced of 20 % while the cost is doubled in the case of extension of recycling capacity in comparison with the

Fig. 11 Distribution of waste treatment techniques in Pareto optimal solutions of the case extended recycling capacity

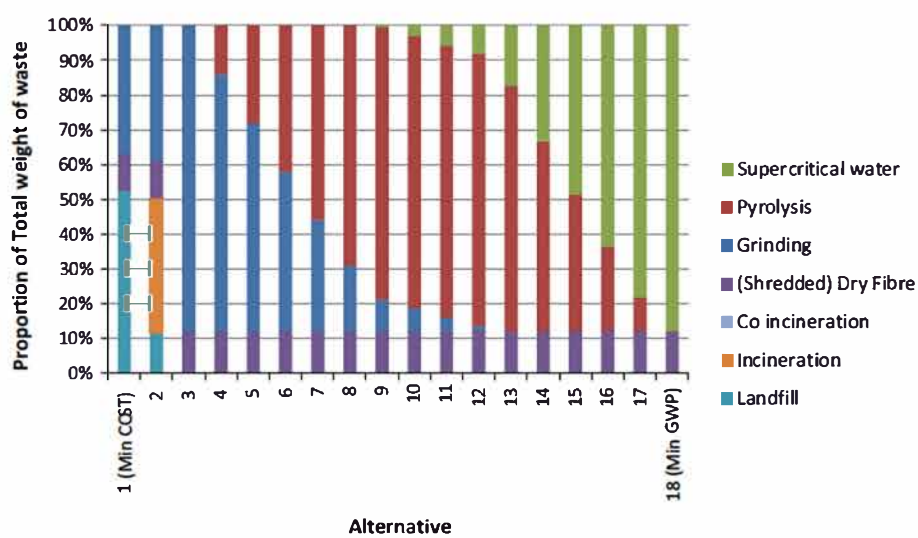


Table 4 Waste distribution of fibre recovery pathways in each region (the number of the alternative is in bold characters)

Amount of waste (Ton)	Pre treatment			Grinding			Pyrolysis			SCW		
	1	7	18	1	7	18	1	7	18	1	7	18
BRE	13	18	18	264	38	0	0	522	0	0	0	0
PL	176	59	59	0	0	0	0	0	0	0	0	841
ARA	30	39	39	90	281	0	0	0	0	0	0	0

base case for the same strategy of GWP minimisation. This situation can be explained by the high operation cost, and by-product recovery of SCW. The impacts of SCW can be confirmed by the deviation of the slope from alternatives 4 9 which do not use SCW to alternatives 10 18 which include SCW in the system. The capacity of grinding in this base case study is high enough to treat all waste input flows in order to achieve the lowest cost in the system. The configuration for cost minimisation strategy with capacity extension is therefore the same as the base case study.

The total waste flows input in recycling plant for alternatives 1, 7 and 18 are shown in Table 4. The wastes volume in pre-treatment of all recycling plant is not changed between the alternatives 7 and 18 because of the optimal distribution of dry fibre waste and no pre-treatment for uncured waste before transportation to recycling site. However, under the objective of cost minimisation (alternative 1), pre-treatment part of PL plant has to treat additionally the uncured waste of the region for curing before grinding this waste at BRE in order to reduce the transportation cost. In this alternative, only grinding plants operate, mainly in BRE and for a small quantity of ARA. However, in alternative 7, the waste flows to ARA are tripled, and a small quantity of waste goes into grinding in BRE; more than half of total wastes are treated by pyrolysis in BRE. Otherwise, all wastes apart from dry fibre are recovered by SCW in PL in alternative 18. This plant has to recycle over 800 tons of wastes though there is no waste treated by SCW technique in the alternatives 1 and 7. With the 3 centres of recycling in BRE, PL and ARA regions, a high concentration of recycling activities in BRE and PL is observed due to the high quantity of wastes around these regions and the multiple recycling techniques in BRE and PL. Grinding in ARA region may be interesting in a solution in which both economic and environmental criteria are taken into account like alternative 7 or in the case with a solid market position for recovered products of grinding around this region.

Conclusion

The increasing use of CFRP in aerospace leads to diverse and high quantity of wastes that will continue to grow in the future. Although the production of carbon fibre is expensive and polluting, the majority of wastes go to disposal routes like landfill or incineration for economic reason. However, with the progress in studies of recycling processes, carbon fibre recycling techniques have become new options for CFRP waste treatment with the conventional disposal paths. It is thus important to develop an optimised network for CFRP waste management dealing with the range of waste types and waste treatment techniques.

In this work, a linear model based on mathematical programming for aerospace CFRP waste management from upstream source to treatment and to downstream market is developed. A bi-criteria optimisation approach is proposed based on simultaneous cost and GWP impact minimisation. Cost evaluation includes all activities in the network, i.e. waste collection, pre-treatment, recycling process, product distribution. Beside the impacts from activities, the value of recovered products is taken into account in GWP impacts via the avoided impacts. The model is applied to a case study for determining the distribution of wastes in the aerospace carbon fibre chain in France.

The results of the case study show the conflicting aspect between cost and GWP impacts. The decrease in GWP impacts can lead to an increase in the cost in the system. The waste distribution among the different treatment options depends on waste type, treatment technique (input, output, capacity, and operation conditions), and transport. The fibre-recovery pathways are favoured for minimising GWP impacts to obtain higher avoided impacts than those obtained with the no-fibre recovery pathways. Furthermore, these options do not have an economic advantage with the current cost in comparison with the operation cost of fibre-recovery pathways. However, due to the centralisation of recycling plants, the wastes in the regions that are far from recycling plants are landfilled instead of being recovered by grinding technique, though grinding cost is lower than landfill fees in this case study in order to minimise the cost of system. An additional pre-treatment capacity besides recycling capacity is an essential strategy to save recycling capacity from recovery of dry fibre scrap for other wastes and to reduce the transportation cost of uncured waste by curing on site before transportation to other techniques. The combination of different techniques allows obtaining the compromise values of cost and GWP impacts in the system. Moreover, in system downstream, with the lack of quantitative data of markets for recovered products, this model allows flexible control under the qualitative data of markets presence in order to determine volume of products revalorised by recycling routes and to then develop potential markets where the accumulation of products is generated.

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Appendix 1– CFRP composition of aircraft types delivered in 1996

Aircraft Model	Series (Airliners.net)	Delivery Period	Operating Empty Weight (tonnes)	%wt Composite	%wt CFRP
A300	A300B2-200; A300B4-200; A300-600, A300-600R; A300-600F	1974-2007	87.47	4.5 (Cinquin, 2002)	2.25* (50% of total composites)
A310	A310-200; A310-300	1983-1998	80.67	8 (Cinquin, 2002)	4* (50% of total composites)
A320	A320-200	1988-present	42.2	13 (Liu, 2013)	9 (Liu, 2013)
MD80	MD81; MD87; MD88	1980-1999	34.65	1 (Cinquin, 2002)	0.5* (50% of total composites)
MD11	MD11; MD11F; MD11C; MD11CF	1990-2001	124.41	4.5 (Cinquin, 2002)	2.25 (50% of total composites)
B737 (Original & Classic)	B737-100; B737-200; B737-300; B737-400; B737-500	1967-present	30.55	2 (National Programme on Technology Enhanced Learning)	1* (50% of total composites)
B747	B747-100; B747-100SR; B747-200; B747-300; B747-400; B747SP	1969-present	170.44	1.75 (Cinquin, 2002)	0.875* (50% of total composites)
B757	B757-200; B757-300;	1982-2005	61.22	3 (National Programme on Technology Enhanced Learning)	1.5* (50% of total composites)
B767	B767-200; B767-200ER; B767-300; B767-300ER; B767-400	1982-present	89.13	3.5 (Cinquin, 2002)	1.75* (50% of total composites)

*: assumption

Appendix 2 – Aircraft deliveries of each model in 1996

Aircraft Model	Deliveries in 1996 (aircraft)
A300 (Airbus)	25
A310 (Airbus)	19
A320 (Airbus)	119
MD80 (Boeing)	140
MD11 (Boeing)	31
B737 (Original & Classic) (Boeing)	215
B747 (Boeing)	64
B757 (Boeing)	80
B767 (Boeing)	62
Total (aircraft)	755

Appendix 3 – Inventories of waste production plants

	Scale	NPCP	NOR	BRE	ACAL	IDF	PL	CVL	BFC	ALPC	ARA	LRMP	PACA
Finished CFRP production	Small	0	0	0	0	1	0	0	0	1	1	1	0
	Medium	1	0	1	0	2	2	1	0	4	3	3	0
	Large	1	0	0	1	0	2	0	0	1	0	0	0
Prepreg Production	Small	0	0	0	0	0	0	1	0	0	0	0	0
	Medium	0	0	0	0	1	1	0	0	0	1	0	0
	Large	0	0	0	0	0	0	0	0	0	0	0	0
Carbon fibre Production	Small	0	0	0	0	0	0	0	0	0	2	0	0
	Medium	0	0	0	0	0	0	0	0	1	0	0	0
	Large	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 4 – Quality of recovered products from Fibre-recovery pathways and the quality requirement of markets

Waste	Recovered product	Replaced material	Quality of recovered product (%)				Market 1 (NPCP, BRE, ACAL, IDF, PL, CVL, ALPC, ARA, LRMP)	Market 2 (NPCP, NOR, BRE, ACAL, IDF, BFC, ALPC, ARA)	Market 3 (All regions)	Market 4 (All regions)
			Shredding	Grinding	Pyrolysis	SCW	Min. quality (%)	Min. quality (%)	Min. quality (%)	Min. quality (%)
Dry fibre	Fibre	Carbon fibre	100	x	x	x	90	80	x	x
CFRP waste (EOL, uncured and cured production)	Powder	Limestone	x	100	x	x	x	x	100	x
	Fibrous	Glass fibre	x	100	x	x	x	x	100	x
	Fibre	Carbon fibre	x	x	89	93	90	80	x	x
	Oligomers	Phenol	x	x	x	100	x	x	x	100

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