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Designing reverse supply networks for carbon fibres: Enabling cross-sectoral circular economy pathways

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ABSTRACT

Carbon fibre reinforced polymer is a widely used material in engineering applications and is expected to be extensively used in the transportation sector due to its light-weight properties. It is a high value, energy intensive material, which is mostly landfilled at its End-of-life, however, it could potentially be recycled and replace virgin material in different sectors. Therefore, considering also the significant amounts of End-of-life aircrafts and automotive expected in the future, it is imperative to identify circular economy pathways for this waste stream. This study investigates the feasibility of a cross-sectoral circular economy pathway of carbon fibre material waste thermal recycling and proposes a four-tier reverse supply chain network for the waste in the aeronautic and automotive sector. A novel MILP optimisation model is developed, in order to optimise the network structure and minimise the costs of the proposed design problem with an end-to-end scope. The model is applied in the geographical context of Europe, for 2023 and 2050. The results indicate that the optimum reverse supply chain network design is relatively centralised with processing facilities in central Europe. The proposed circular economy pathway is economically viable; however, the process is even more attractive when the resin is recycled too.

1. Introduction

Composite materials are commonly used in engineering applications to replace conventional material (Clark et al., 2020), due to their technical properties and long life span (Yang et al., 2012). In specific, carbon fibre reinforced polymer (CFRP) is utilised due to its light weight, high strength - comparable with metal components (Roberts, 2007) -, reduced corrosion and offering the possibility to design single piece parts without the need to produce multiple components (Roberts, 2007). These properties render composites a valuable material for the transportation sector that benefits fuel consumption and carbon footprint (Li et al., 2016).

Currently, CFRP material is widely used in aeronautic applications; the majority of the defence aircrafts consist of 50% of composites (Yang et al., 2012) and it is also used in commercial aircrafts (Roberts, 2007). It is forecasted that in the future it will have an extensive application in the automotive industry too (Li et al., 2016), even though the properties of the material used in the two sectors differ, with the material in aeronautic being more demanding regarding strength (Suzuki and Takahashi, 2005). However, there are still concerns for the CFRP use in automotive due to the high energy consumption and cost of the virgin fibres production (Suzuki and Takahashi, 2005) and it is challenged that CFRPs “are still far too expensive to be used in the chassis or any other high volume application in motor vehicles” (Furst, 2016).

It is estimated that the first generation of aircrafts containing carbon fibres are reaching the end of their service (Marsh, 2008) and a large amount of CFRP waste is expected to be available from aeronautic and automotive industry in the coming years. In general, despite the high value of the material, the End-of-Life (EoL) CFRP for the last decades has been disposed of through landfilling (Karuppannan Gopalraj and Kärki, 2020). In specific, the majority of the EoL aircrafts are stored in deserts or designated aircraft ‘boneyards’ (Yang et al., 2012) with few associations, like Aircraft Fleet Recycling Association (AFRA) supporting environmental pathways for the aircrafts’ disposal. At the same time, the European Union Directive (1999/31/EC) has introduced regulations that forbid the landfilling of large composite parts.

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The aforementioned combination of increase of CFRP demand, the limitations regarding the traditional waste streams along with the regulatory pressure, render crucial the identification of potential reverse supply chain network pathways for carbon reinforced composites. Especially, since studies indicate that the recycled carbon fibres can be competitive compared to virgin (Vo Dong et al., 2018), in specific in the automotive sector (Caltagirone et al., 2021; Meng et al., 2018). In addition, it is supported that the production of virgin carbon fibres is energy-intensive, leading to an expensive material (Pimenta and Pinho, 2011). Therefore, it is critical for regulatory, environmental and economic reasons to identify potential recycling pathways for the CFRP (Li et al., 2016).

Furthermore, it is crucial when considering recycling pathways to respect the technical requirements and properties of the material, which makes it necessary to consider a cross-sectoral approach. This will enable the use of recycled CFRP between sectors in order to take advantage of the different material property requirements, as well as the reduction of the recycled fibres quality, compared to the virgin ones. It is suggested that the use of recycled fibres in another market instead of virgin carbon or glass fibres is possible but depends highly on the recycling technology used (He et al., 2020; Vo Dong et al., 2018).

Therefore, the aim of this work is to propose a reverse supply chain network that will facilitate a cross-sectoral circular economy pathway for CFRP from the automotive and aeronautic sectors and assess its feasibility. The latter is achieved through modelling the whole four-tier reverse supply chain, containing both existing and new actors, and optimising its structure and characteristics in order to minimise the system-wide costs. This work contributes to knowledge by proposing the first reverse supply chain network design optimisation model with an end-to-end scope, specifically for recycling EoL CFRP. The application scope of this work is the 27 country members of the European Union (EU-27) plus United Kingdom (UK); however, the method developed is generic, it can be applied in any geographical context and can include additional sectors. The implications of this work are significant for the carbon fibre users, the waste owners, the third-party waste collectors as well as the regulatory bodies and policy makers.

The rest of the paper is organised as follows. First, in Section 2, background information on existing closed loop and reverse supply chain optimisation models is summarised. The proposed reverse supply chain network along with the developed mathematical model is presented in Section 3. In Section 4, the assumptions considered in this work are discussed. The results from the case study application are discussed in Section 5. Finally, concluding remarks are summarised in Section 6.

2. Literature review

Recently, the traditional linear production model has been challenged as unsustainable due to the significant amount of waste generated (Lahane et al., 2020). Therefore, there is pressure from the customers for more environmentally friendly operations throughout the supply chain (Niinimäki and Hassi, 2011). As a result, companies amend their business models in order to connect the reverse operations to the traditional forward ones, leading to closed-loop supply chains (Erhun et al., 2020). At the same time, research has been focusing on the barriers to shift from the traditional linear supply chain (Neves and Marques, 2022). Another incentive for a closed loop supply chain is the cost reduction (Govindan and Popiuc, 2014), which 'is emerging as an economic strategy rather than a purely environmental strategy' (Yuan et al., 2006).

In the past years, there has been extensive research in identifying ways to enhance the supply chain sustainability (Seuring and Müller, 2008; Tuni et al., 2018). Along these lines, the closed loop and reverse supply chains optimisation has also been widely discussed (Van Engeland et al., 2020).

2.1. Reverse supply chain and closed loop optimisation models

One main difference between reverse and forward supply chain optimisation is the number of suppliers, which in a forward supply chain is small, whereas a reverse supply chain may have numerous collection points (Zikopoulos and Tagaras, 2015). In addition, the product in the latter case is more complex and there are concerns regarding the quality (Zikopoulos and Tagaras, 2015).

In this respect, linear programming models have been developed to optimise the closed loop or reverse supply chain of different products such as electronic and electrical equipment (Islam and Huda, 2018), perishable goods (Amin and Zhang, 2012), fashion products (Kim et al., 2018), generic products (Yavari and Geraeli, 2019) or multi-products (Sheriff et al., 2014). In many cases, uncertainty considerations were incorporated (Salema et al., 2007) with the main focus on the demand uncertainty (Prakash et al., 2020; Soleimani et al., 2016) or the pricing of the recycled product (Ke et al., 2018). The majority of the developed models proposed optimisation of the supply chain in respect of the cost, whereas some authors introduced a profit-oriented optimisation (Kim et al., 2018), or both environmental and economic objectives (Jindal et al., 2017; Yavari and Geraeli, 2019).

2.2. Reverse supply chain and closed loop optimisation models in automotive and aeronautic

Various studies have also investigated the reverse supply chain of EoL vehicles. The barriers of shifting from linear supply to reverse have been investigated, indicating that economic and policy related issues are among the most influential (Kaviani et al., 2020). In the existing literature focus has been placed on specific parts of the reverse supply network of EoL vehicles. The disassembly of automotive is considered an important step for the vehicles reverse supply chain (Yu et al., 2017). For this reason, it has attracted the interest of various researchers. The cost and time efficiency of the process was investigated (Go et al., 2011). In addition, the optimisation of the vehicles' disassembly was attempted with the use of network graphs (Yu et al., 2017). The disassembly of specific car parts was also optimised, such as electric vehicle batteries, with environmental and economic considerations (Alfaro-Algaba and Ramirez, 2020) or the automotive transmission (Mao et al., 2021). In addition, in order to enable car producers to design a recovery network for EoL vehicles in Germany, focus was placed on the dismantlers and collection points (Ahn et al., 2005). Moreover, the optimisation of the collection points employing an uncapacitated facility location problem in Mexico was investigated (Cruz-Rivera and Ertel, 2009), while others proposed models for the optimal car dismantlers location in Poland (Gołębiewski et al., 2013). Finally others introduced a vehicle routing problem for separating and reprocessing plastic of EoL vehicles in Germany (Schultmann et al., 2006).

Other authors have attempted to model and optimise the whole reverse supply chain. Vehicle EoL batteries have attracted great attention and the various strategies of handling them after the end of their service life has been investigated (Gu et al., 2021; Wang et al., 2020). On the other hand, authors developed a fuzzy optimisation (Phuc et al., 2017) to address the complexity of the supply chain. The reverse supply chain of reusable CFRP frames was optimised for car sharing vehicles with two EoL streams, either remanufacturing or recycling (Rentizelas and Trivyza, 2022). Other authors, focused only on the car parts of a conventional vehicles with considerations of both recycling and landfilling of the parts (Özceylan et al., 2017). Similar attempts were made specifically for reverse supply networks in China (Xiao et al., 2019) and Turkey (Yildizbaşi et al., 2018).

However, despite the great interest on the fate of vehicles after the end of their service life, no studies focusing on the CFRP from the EoL vehicles, which is a challenging waste flow, were found.

For the aeronautic sector, Vo Dong et al. (2019) introduced a bi-objective optimisation model for the design of an aeronautic CFRP waste management supply chain in France, including various waste treatment pathways, both fibre recovering and non-fibre recovering, such as pyrolysis and landfilling, respectively. In addition, different end products were considered, depending on the treatment process and, consequently, the recycled fibre properties. However, the reverse supply chain proposed in the aforementioned work did not consider a cross-sectorial approach or included the outbound link to the recycled fibre customers.

The existing literature indicated the benefits of the circular economy as well as the challenges of CFRP recycling. CFRP waste will be critical specifically for the automotive and aeronautic sector due to the significantly increased volumes forecasted in the future. A variety of reverse supply chain optimisation models have been introduced and applied on different products; however, there is a gap on reverse supply chain network optimisation models for recycling the CFRP waste adopting cross-sectoral approaches in general, as well as specifically in the automotive and aeronautic sectors.

3. Reverse supply chain network design problem for CFRP waste recycling

In this section, a cross-sectoral reverse supply chain network is proposed for the CFRP waste recycling from the automotive and aeronautic sectors. The mathematical model developed for the network optimisation is presented along with the main assumptions considered.

3.1. Network definition

The proposed four-tier reverse supply chain network structure is presented in Fig. 1. The waste supply streams of the system are: the automotive sector with the EoL cars, the aeronautic with EoL aircrafts and the production waste from the aircraft composite parts manufacturers. The processing stages are the thermal treatment of the composite parts with pyrolysis, where the outputs are recycled fibres and recovered resin, the latter of which is sold and considered as a revenue of the system. The recycled fibres are then transported to a chemical facility (compounder) and are transformed into pellets, which are sent to the end users, assumed to be the 1st Tier car part manufacturers, as they are currently using the material in this form in their manufacturing processes.

The reverse supply chain network consists of the following entities (nodes) linked with transportation links (arcs):

- Authorised disassembly centres (Tier 4): facilities permitted to take back and depollute the EoL vehicles.
- Aircraft boneyards (Tier 4): EoL aircraft collection points.
- Aircraft composite part manufacturers (Tier 4): more than 15% of the CFRP waste on the aeronautic sector originates from the production waste (Lefeuvre et al., 2017). The amount of carbon composites from production waste was allocated as an approximation to the market segment of each company on the wing, fuselage and empennage production and the carbon composite proportion on these parts, since these parts contain the majority of carbon fibres.
- Thermal processing facilities (Tier 3): Waste CFRP material is processed to recover the carbon fibres. Pyrolysis is selected as the technology for the CFRP fibres recycling due to the high retention of mechanical properties and the potential recovery of resin (Pimenta and Pinho, 2011), as well as it is considered among the most promising recycling technologies for industry scale applications (Pakdel et al., 2021). In addition, it is indicated that with pyrolysis the recovery of carbon fibres requires only 5–10% of the energy required to produce virgin fibres (Wood, 2010). More technical information regarding the recycling of CFRP with pyrolysis can be found in Naqvi et al. (2018).
- Compounders (Tier 2): The recycled carbon fibres (rCF) retrieved from the pyrolysis are sent to large-scale chemical facilities, in order to create pellets that can be used for injection moulding in automotive. This is a standard process for virgin thermoplastic material (Schultmann et al., 2006).
- 1st Tier composite car part manufacturers: These existing automotive suppliers constitute the final tier of the reverse supply chain network and are the point at which the rCF are re-introduced into the forward automotive supply chain. Carbon fibres are currently considered too expensive for the automotive sector according to experts. Therefore, a cross-sectoral approach is adopted in this work by proposing to

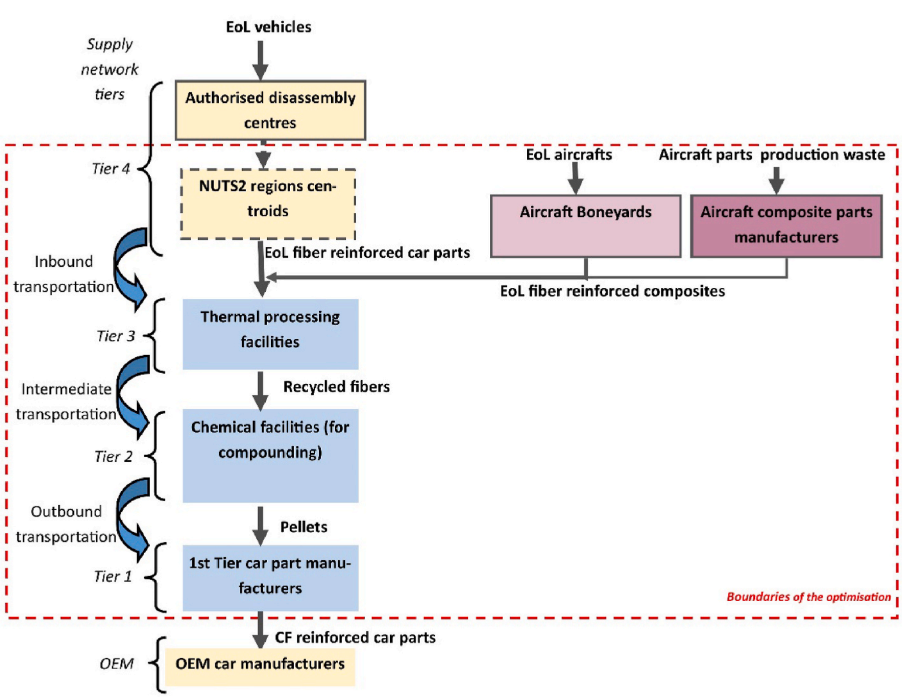

Fig. 1. Proposed reverse supply chain structure.

replace the glass fibres or the expensive virgin carbon fibres in car part manufacturing with recycled carbon fibres.

3.2. Mathematical model formulation

The model formulation is based on the aforementioned four-tier reverse supply chain network. The adopted notations are presented in Appendix A.

The objective of the model is to minimise the annual total cost of the reverse supply chain network while satisfying the constraints. All the stages from retrieving the waste to delivering the recycled product to the end user are explicitly modelled. Even though the objective function is the cost, the carbon emissions from each supply chain tier are analytically estimated. Carbon emissions are considered in the objective function with a carbon tax price; however, in the case study application this value is assumed equal to zero, to reflect the current reality. The time frame of the optimisation model is one year.

In the objective function (Eq. (1)), the following decision variables are used:

- The waste material flow x(f,l) from the waste supplier f ∈ F, to the first stage processing facility l ∈ L (pyrolysis facilities).
- The recycled material flow z(l,m) from processing facility l ∈ L to second stage processing facility m ∈ M (compounders).
- The material flow t(m,c) from the second stage processing facility m ∈ M to the customer c ∈ C.
- Finally, the binary variable y(l,s) concerns the existence of a pyrolysis processing facility of size s ∈ S at the location l ∈ L. The size of the pyrolysis facilities s is selected among a predefined set of sizes S.

The objective function (Eq. (1)) of the mathematical model is the annual cost of the reverse supply chain network. The annual cost corresponds to the sum of the inbound transportation cost *(Ctin)*, the storage cost (*Cst*), the variable operating cost (Cov_1^p), the maintenance cost *(Cm)*, the fixed *(Cof)* operational costs, the annualised investment cost *(Ci/an)*. In addition, other costs such as the investment and fuel cost for the forklift machinery employed in the facility are accounted in *(Cmi)* and *(Cmf)*, respectively. Other transportation costs, such as for the material flow from the first stage to the second processing stage *(Ctint)* and the outbound transportation cost *(Ctout)* are considered. The objective function includes also the variable costs from the second stage processing facility (Cov_2^{co}), and the cost of carbon emissions with a carbon tax cost of *co2t* from the emissions derived by the various stages of the reverse supply chain ($CO2fu_{o2}$, $CO2fu_t$, $CO2el$, $CO2el_2$). Finally, the revenues from not disposing the CFRP waste *(Rdisp)* and from selling the recycled resins *(Rup)* are included in (Eq. (1)). The aforementioned costs are described in Eqs. 2–19.

$$Min\ F = Ctin + Cst + Cov_1^p + Cm + Cof + \frac{C_i}{an} + Cmi + Cmf + Ctint + Cov_2^{co} + Ctout + co2t\,(CO2fu_{o2} + CO2fu_t + CO2el + CO2el_2) - Rdisp - Rup \tag{1}$$

The transportation costs from the waste supplier to the first stage processing facility (Eq. (2)), from the first stage to the second stage processing (Eq. (11)) and from the second stage to the end customer (Eq. (13)) depend on the amount of material transported, the distance between the nodes and the transportation cost factor, which is affected by the material density. The costs of the first stage processing facility (pyrolysis) include the storage cost (Eq. (3)), the machinery investment (Eq. (4)) and fuel cost (Eq. (5)), which depend on the capacity of the optimal selected facilities. On the other hand, the facility maintenance cost (Eq. (6)) is calculated as a fixed percentage of the facility investment cost (Eq. (7)). The variable operating (Eq. (9)) costs of the first stage processing facility consist of the tool wear, electricity consumption and required additives costs and depend on the waste material processed, whereas the fixed costs consist of the personnel cost and the machinery as well as facility insurance costs and are a function of the facility capacity (Eq. (10)).

$$Ctin = \sum_{f=1}^{F}\sum_{l=1}^{L}(tcin + tcinf)conv_1\left(dfl_{f,l} + d1_f\right)x_{f,l}, \quad f = 1..F,\ l = 1..L \tag{2}$$

$$Cst = \sum_{st=1}^{ST}\sum_{l=1}^{L}\sum_{s=1}^{S} cst_{st}Cap_s y_{l,s}, \quad st = 1..ST,\ l = 1..L,\ s = 1..S \tag{3}$$

$$Cmi = cmi\sum_{s=1}^{S}Cap_s\sum_{l=1}^{L}y_{l,s}, \quad s = 1..S,\ l = 1..L \tag{4}$$

$$Cmf = cmf\sum_{l=1}^{L}cdf_l\sum_{s=1}^{S}Cap_s y_{l,s}, \quad l = 1..L,\ s = 1..S \tag{5}$$

$$Cm = \sum_{s=1}^{S}cm_s ci_s\sum_{l=1}^{L}y_{l,s}, \quad s = 1..S,\ l = 1..L \tag{6}$$

$$Ci = \sum_{s=1}^{S}ci_s\sum_{l=1}^{L}y_{l,s}, \quad s = 1..S,\ l = 1..L \tag{7}$$

$$an = \frac{1 - \frac{1}{(1+df)^Y}}{df}, \tag{8}$$

$$Cov_1^p = \sum_{l=1}^{L}\left[(ctp + cep\ ce_l + cap)\sum_{f=1}^{F}x_{f,l}conv_1\right], \quad l = 1..L,\ f = 1..F \tag{9}$$

$$Cof = cols\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L}y_{l,s}\right) + cmins\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L}y_{l,s}\right) + \sum_{s=1}^{S}\left(cins_s\sum_{l=1}^{L}y_{l,s}\right),\ s = 1..S,\ l = 1..L \tag{10}$$

$$Ctint = \sum_{m=1}^{M}\sum_{l=1}^{L}(tcint + tcintf)dlm_{l,m}z_{l,m}, \quad m = 1..M,\ l = 1..L \tag{11}$$

For the second stage processing, which is performed in existing compounding facilities, only the variable operating costs are included in (Eq. (12)), since no new investment will be required. These costs account for the variable tool wear cost for recycled fibre compounding, the chemical additives and electricity consumption cost.

$$Cov_2^{co} = (ctc + cac)\sum_{m=1}^{M}cec\ ce_m\sum_{l=1}^{L}z_{l,m}, \quad m = 1..M,\ l = 1..L \tag{12}$$

$$Ctout = (tcout + tcoutf)\sum_{c=1}^{C}\sum_{m=1}^{M}dmc_{m,c}t_{m,c}, \quad m = 1..M,\ c = 1..C \tag{13}$$

The model also calculates the direct carbon emissions from each process: due to electricity consumption (Eq. (14)) or fuel consumption (Eq. (16)) during the pyrolysis, due to electricity consumption for the compounding (Eq. (15)) and the emissions from all stages of transportation (Eq. (17)), which depend on the carbon emission factor for diesel and electricity per country. Finally, the system revenues from not disposing the CFRP waste (Eq. (18)) as well as from selling the recycled resin (Eq. (19)) depend on the waste material flow.

$$CO2el = \mathrm{cep}\sum_{l=1}^{L}co2ee_l\sum_{s=1}^{S}Cap_s y_{l,s}\Big/10^6,\ l = 1..L,\ s = 1..S \tag{14}$$

$$CO2el_2 = \mathrm{cec}\sum_{m=1}^{M}co2ee_m\sum_{l=1}^{L}z_{l,m}\Big/10^6,\ m = 1..M,\ l = 1..L \tag{15}$$

$$CO2fu_{o1} = efd\ cmf \sum_{l=1}^{L}\sum_{s=1}^{S} Cap_s\, y_{l,s} \Big/ 10^6,\ l = 1..L, s = 1..S \quad (16)$$

$$CO2\mathrm{fu}_t = fct\frac{efd}{10^6}\left[\sum_{l=1}^{L}\sum_{f=1}^{F}\left(dfl_{f,l} + \mathrm{d1_f}\right)x_{f,l} + \sum_{l=1}^{L}\sum_{m=1}^{M} dlm_{l,m} z_{l,m}\right], \quad (17)$$

$$l = 1..L, f = 1..F,\ m = 1..M$$

$$Rdisp = \sum_{f=1}^{F} cdisp_f \sum_{l=1}^{L} x_{f,l}, \quad \mathrm{f = 1..F,\ \ l = 1..L} \quad (18)$$

$$Rup = \mathrm{up}\ \ conv_1 \mathrm{convup} \sum_{f=1}^{F}\sum_{l=1}^{L} x_{f,l}, \quad \mathrm{f = 1..F,\ \ l = 1..L} \quad (19)$$

subject to:

$$sup_f \geq \sum_{l=1}^{L} x_{f,l}, \quad f = 1 \ldots F \quad (20)$$

$$sup_f = \sum_{l=1}^{L} x_{f,l}, \quad f = 1 \ldots F \quad (21)$$

$$\sum_{m=1}^{M} z_{l,m} = \sum_{f=1}^{F} x_{f,l} \prod_{ps=1}^{2} conv_{ps}, \quad l = 1 \ldots L \quad (22)$$

$$\sum_{l=1}^{L} conv_3\ z_{l,m} = \sum_{c=1}^{C} \mathrm{t_{m,c}}, \quad m = 1..M \quad (23)$$

$$dem_c = \sum_{m=1}^{M} t_{m,c}, \quad c = 1..C \quad (24)$$

$$dem_c \geq \sum_{m=1}^{M} t_{m,c}, \quad c = 1..C \quad (25)$$

$$\sum_{s=1}^{S} y_{l,s} \leq 1, \quad l = 1..L \quad (26)$$

$$conv_1 \sum_{f=1}^{F} x_{f,l} \leq \sum_{s=1}^{S} Cap_s y_{l,s}, \quad l = 1..L \quad (27)$$

$$z_{l,m} \geq 0, \quad l = 1..L,\ m = 1..M \quad (28)$$

$$t_{m,c} \geq 0, \quad m = 1..M,\ c = 1..C \quad (29)$$

$$x_{f,l} \geq 0, \quad l = 1..L, f = 1..F \quad (30)$$

$$y_{l,s} = 0\ or\ 1, \quad l = 1..L,\ s = 1..S \quad (31)$$

Constraints to ensure the mass balances on each node of the reverse supply chain are imposed. The reverse supply chain is modelled either as demand driven when the available waste is greater than the supply to the facilities or as supply driven when the demand is higher. Therefore, the mass balance between the CFRP waste available at the EoL vehicles dismantling facilities, the CFRP aircraft manufacturer and aircraft boneyards provided to the pyrolysis facilities for the first stage processing is modelled for a supply driven model in (Eq. (20)), whereas for a demand driven in (Eq. (21)). A constraint is imposed to ensure that the amount of recycled fibres obtained by the pyrolysis processing is equal to the amount of product that is supplied to the second stage facility for compounding (Eq. (22)). Eq. (23) models the mass balance ensuring that the material produced in the compounding facilities equals the material supplied to the customers. When the supply is greater than demand, all the demand is satisfied for each end customer, with Eq. (24) ensuring that the material transported to the end customers is equal to their demand. Whereas, when the demand is greater than the supply, not all demand is covered (Eq. (25)). Other constraints are modelled to ensure that only one capacity exists for each pyrolysis facility (Eq. (26)) and that the capacity for each location is sufficient to process all the waste (Eq. (27)). Constraints to ensure that all the material flows are non-negative are modelled in (Eqs. (28)–(30)). Finally, the variable for the location and capacity of the first stage processing facilities is modelled as binary in (Eq. (31)).

4. Supply chain network of CFRP waste in Europe

The developed model is applied to the context of Europe (EU-27 and UK) and the following assumptions are made for the supply chain network entities:

- Authorised disassembly centres (Tier 4): Currently there are approximately 12,900 facilities in Europe, where vehicles are disassembled into parts and sent to the appropriate facilities to be treated. Due to their high number, it is assumed that the EoL CFRP from the automotive sector is allocated to the Nomenclature of Territorial Units for Statistics 2 (NUTS2) regions centroids in Europe (see Fig. 2). To determine the distribution of the authorised treatment facilities in European countries Belgium, Czech Republic and the UK were examined in more detail. For this purpose, the individual coordinates of the facilities per country were identified and the results show that the authorised treatment facilities are relatively homogenously distributed across these countries. This assumption of homogenous geographical distribution was applied to all EU-27 and UK countries. In addition, a 1st stage distance from the authorised disassembly centres to the NUTS2 region centroids is assumed as the average distance of facilities from their respective NUTS2 regions

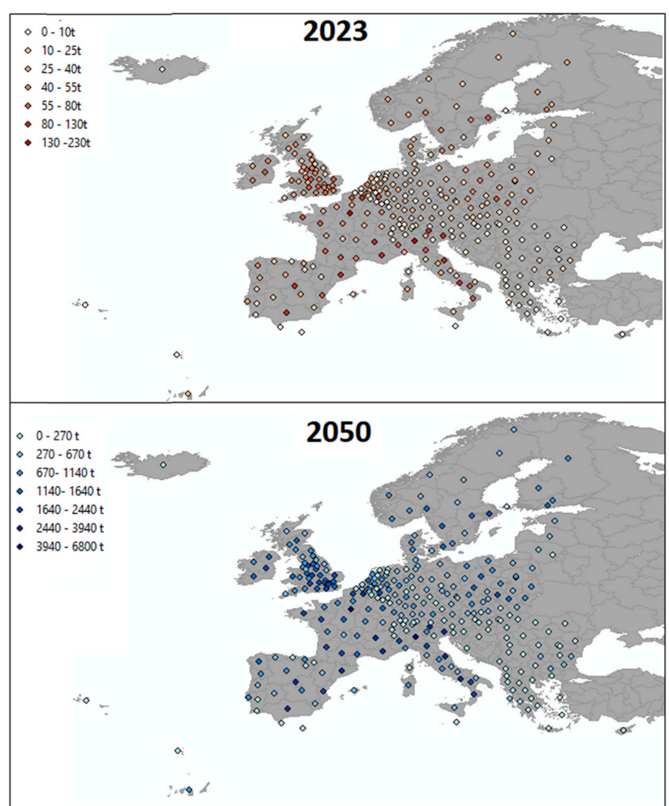

Fig. 2. CFRP waste from automotive sector.

centroids of Belgium, Czech Republic and the UK where analytical data were available.

- Aircraft boneyards (Tier 4): Four such locations are identified in Europe (Fig. 3). The amount of carbon fibre composites from the EoL aircrafts is assumed equally allocated to the authorised boneyards due to data unavailability. It should be noted that the current practice does not restrict the EoL aircrafts of European operators to stay within Europe, and currently many end up in boneyards around the world. However, a key assumption has been made in this work that all EoL aircrafts used by European operators would need to be processed within Europe in the future, something that adheres with the underlying 'proximity' and 'polluter pays' principles of the EU legislation on Waste Management.
- Aircraft composite part manufacturers (Tier 4): The main aircraft CFRP parts manufacturers were identified in Europe and can be found in Fig. 3.
- Thermal processing facilities (Tier 3): These facilities need to be created, as they don't currently exist. The potential location of the facilities is assumed on the NUTS2 centroids and the capacity as well as the economies of scale are considered according to industrial data. It is assumed that the pyrolysis facilities operate 4680 h per year, thus the maintenance and downtime is considered.

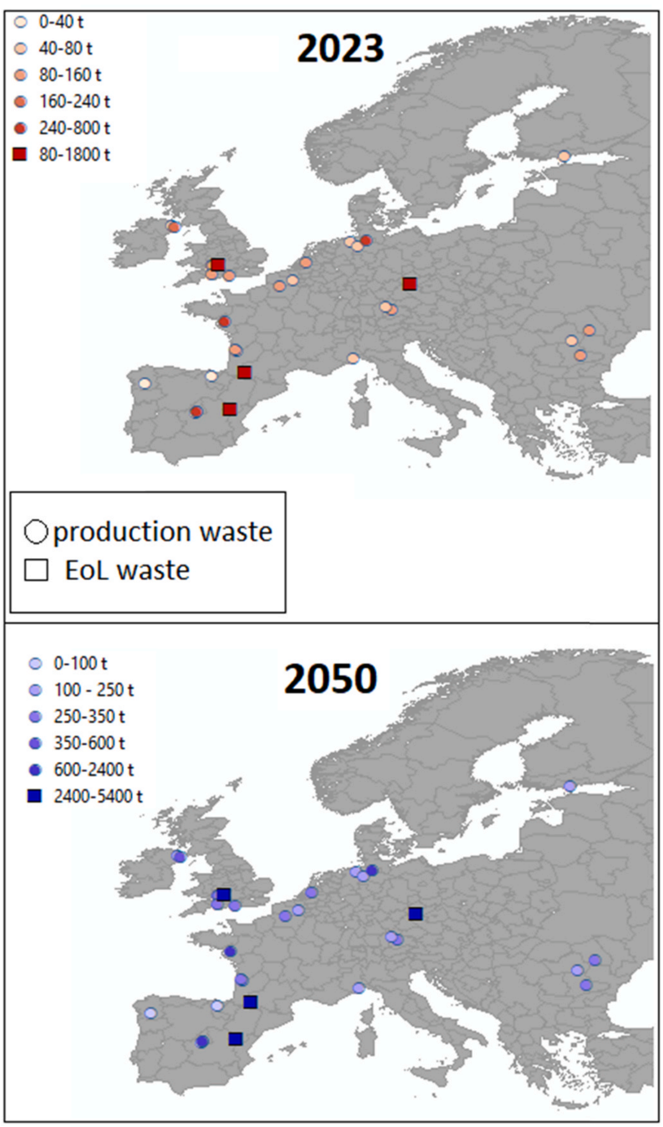

Fig. 3. CFRP waste from aeronautic sector.

- Compounders (Tier 2): The location of existing compounders in Europe is considered (Fig. 4), and it is assumed that they already have high available capacity, therefore extra capacity is not required (Schultmann et al., 2006).
- 1st Tier composite car part manufacturers: The main existing 1st Tier composite car part manufactures in Europe that use Carbon fibres are considered in this work (Fig. 5); however, due to lack of data on actual demand, the recycled CFRP is assumed equally distributed among the manufacturers identified.

4.1. CFRP forecast from automotive sector

In this section, the amount of CF waste until 2050 is forecasted. First, the CFRP amount used in Europe until 2020 was estimated according to the global amount of carbon fibres used in automotive reported in Composites Market Report (Witten et al., 2018) and the European share in the global car market (ACEA, 2019). Then, the amount of CFRP until 2050 is forecasted (see Fig. 6) by employing the exponential forecast that was identified as the one with the best accuracy (MAPE:0.84, MAD:34.54, MSD:1628.21). To forecast the amount of CFRP from EoL cars a 7-year average car life was assumed.

To allocate the EoL CFRP to individual countries, the data with the amount of EoL cars (number and tonnes) per European country from 2006 till 2017 were considered according to Eurostat (2019) and a forecast was developed for the increase of EoL cars per country until 2050. The trend of EoL cars increase was assumed linear based on historical data. Finally, the CFRP from EoL cars is allocated geographically to NUTS2 level in each European country (Fig. 2) by considering the number of inhabitants per region according to Eurostat (2020).

According to Fig. 1, the demand side of the proposed network is the CFRP 1st Tier car part manufacturers. For this purpose, the amount of CFRP derived from the forecast of Fig. 6 is also used as the demand of recycled CFRP, assuming that recycled CFRP can fully replace virgin CFRP.

4.2. CFRP forecast from aeronautic sector

The amount of carbon composites from the EoL aircrafts and production waste in Europe for 2023 and 2050 is derived from existing studies (Lefeuvre et al., 2017) and is presented in Fig. 7.

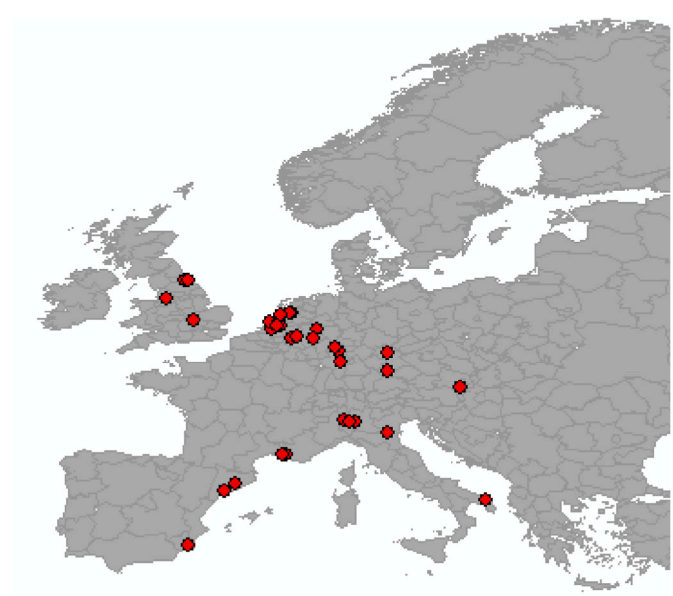

Fig. 4. Map with compounders location considered in the application for both 2023 and 2050.

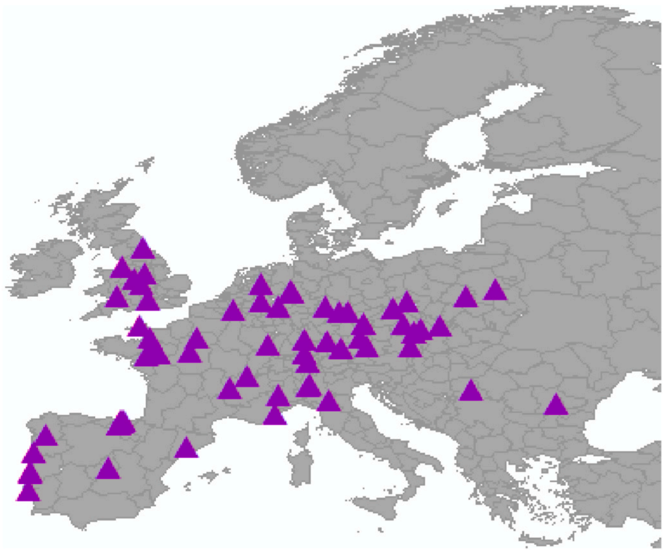

Fig. 5. 1st Tier composite car part manufacturers location for both 2023 and 2050.

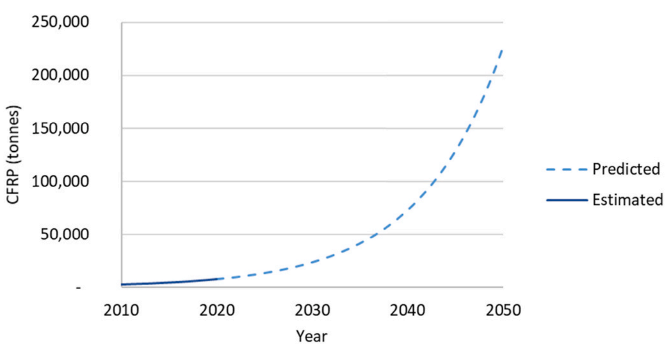

Fig. 6. Forecast of CFRP demand in Europe in the automotive sector.

5. Results and discussion

The reverse supply chain network optimisation model was applied to the case study of EU-27 and UK, using the input parameters presented in Appendix B (Tables B1-B3). The results are discussed in this section. The model has been implemented in GAMS, version 27.2 and was solved using LINDO solver, on an Intel(R) Core™8 i7-2600 CPU at 3.40 GHz operating system.

5.1. Optimal reverse supply chain network design

The model was applied for 2023 and 2050, to understand the evolution of the optimal supply chain network structure over time. The material supply and demand amounts are reported in Table 3. It is assumed that in 2050 landfilling is banned, therefore the only alternative to dispose the waste is to send it in the cement kiln, which is the current alternative with a gate fee of 155€/t.

For 2050, two scenarios are considered: the medium scale (2050MS) and the large scale (2050LS). The 2050MS scenario considers the existing capacities for pyrolysis facilities when defining the available capacity range. Therefore, it represents the optimal supply chain network design considering the current technological status. On the other hand, for the 2050LS scenario, larger capacities for the facilities were considered that do not currently exist, thus investigating the potential benefits that could come with technology development and scaling up.

The optimal location and the capacity of the facilities, along with the utilisation of their capacity, are presented in Table 1 for the two scenarios. It is evident that the proposed network is semi-decentralised, especially in the case of 2050MS with 4 facilities proposed, where most facilities have the maximum capacity size allowed. It is worth noting that the 2050LS scenario is centralised with one very high capacity facility, which processes 90% of the waste, and two much smaller. Therefore, this indicates that the trade-off between the economies of scale and the transportation costs leans towards the economies of scale at the pyrolysis facility.

For 2023 the waste material quantities are very low, therefore two small facilities are proposed, whereas in 2050 the material quantity is increased significantly; as a result, in 2050 the facilities capacity and number increases. The utilisation of the capacity is quite high, with lowest 80%. Unused capacity is due to the selection of facilities from predetermined capacities. The optimal facilities for 2050MS indicate that

Table 1
Optimal pyrolysis facilities characteristics.

	Facilities location	Capacity (t/year)	Capacity Utilisation
2023	Austria	2000	100%
	Netherlands	5000	87%
2050MS	Switzerland	40,000	100%
	France	40,000	100%
	Netherlands	40,000	100%
	Sweden	20,000	80%
2050LS	Switzerland	125,000	100%
	Norway	10,000	83%
	Sweden	5000	80%

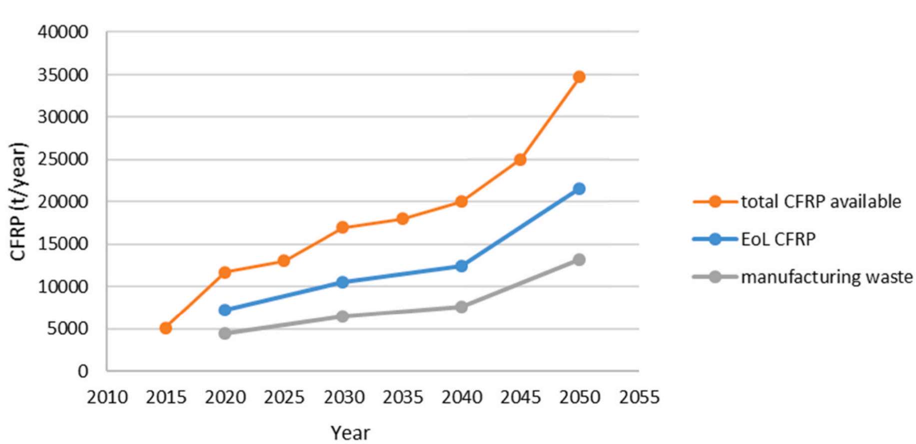

Fig. 7. CFRP waste material from aeronautic sector adapted by Lefeuvre et al. (2017).

the facility in Netherlands should remain but increase in size by 700%, whereas the small one in Austria is no longer proposed as optimal and other large facilities are identified spread across Europe. Comparing the two 2050 scenarios, it is evident that the facility in Switzerland is optimal in both cases and especially on the 2050LS case it has more than three times higher capacity. The facility in Sweden is decreased in size on the 2050LS scenario and the other facilities are replaced by a smaller one in Norway.

In Fig. 8, the supply side (inbound flow) of the optimal network for the material to be thermally treated is presented. The bubble size indicates the amount of material available on each NUTS2 centroid. It is evident that the facilities are located in the central part of Europe and they draw material from countries around the facilities for both 2023 and 2050.

In Fig. 9, the intermediate flow from the pyrolysis facilities to the compounders is presented. It is evident that the facilities location is in most cases in close proximity to the compounders' location. In 2023 more than one facilities provide recycled fibres to the same compounder; whereas, in 2050 each compounder receives material only from one facility. This indicates a proposed differentiation in the supply network structure over time.

The optimal outbound flow of the pellets from the compounders to the 1st Tier car part manufacturers is displayed in Fig. 10. It can be concluded from Figs. 8–10 that the model favours the location of the facilities that are closer to the compounders, compared to material suppliers or end customers.

5.2. Economic assessment

The circular economy system proposed has three potential revenue streams: revenues from avoided disposal costs for EoL CFRP parts; selling the recycled UP resin; and selling the recycled CF. In Fig. 11, the total economic yield per tonne of end product for the optimal reverse supply chain networks is presented, before considering revenues from selling the recycled carbon fibre material. In the figure the cost analysis considers in all cases the savings from avoiding disposing the EoL CFRP parts, but only solid bars consider also the revenues of selling the recycled resin. This is because most existing pyrolysis technological options do not manage to capture the resins as a recycled by-product, but the potential has been reported by pilot-scale applications, and hence it was interesting to investigate its impact in the system economic performance. It is evident that the revenues from selling the resin are quite high, approximately 300€ per tonne of end product, therefore the total system revenue on the latter case is almost 4 times higher. It is also apparent that the avoided disposal costs, which are one revenue stream for the circular economy system, are only a small fraction of the system costs. Therefore, it is highlighted that the inclusion of the resin recycling and the associated revenues has a great impact on the final cost of the fibres recycled, significantly improving the economics of the system.

In Table 2 the breakeven price of recycled carbon fibres (outputs of the first processing stage), the final product (compound) and per unit of waste material input for the different scenarios investigated is presented. These are the prices the material would need to achieve in the market so that the whole reverse supply network system is viable, and will have to face the competition with the virgin fibres/compound. Comparing these values with an approximate market price between 10 and 35 € kg^{-1} for virgin carbon fibres, the recycled fibre material could be an attractive alternative. The process is much more competitive, when the resin revenues are included, although the breakeven price is still attractive compared to virgin material even without resin recycling. It is observed that the breakeven price in 2023 is much higher compared to 2050; this is because the material quantities are significantly increased in 2050, while the processing cost is not proportionally increased due to economies of scale. As a result, the most competitive price is provided on 2050LS while considering the revenues from the recycled resin. It should also be noted that scenarios 2050MS and 2050LS lead to a very similar breakeven price, which means that economies of scale beyond the current technological level are not so important for the viability of this circular economy system. This can be explained by the fact that any economies of scale obtained in scenario 2050LS compared to 2050MS, are counterbalanced by increased

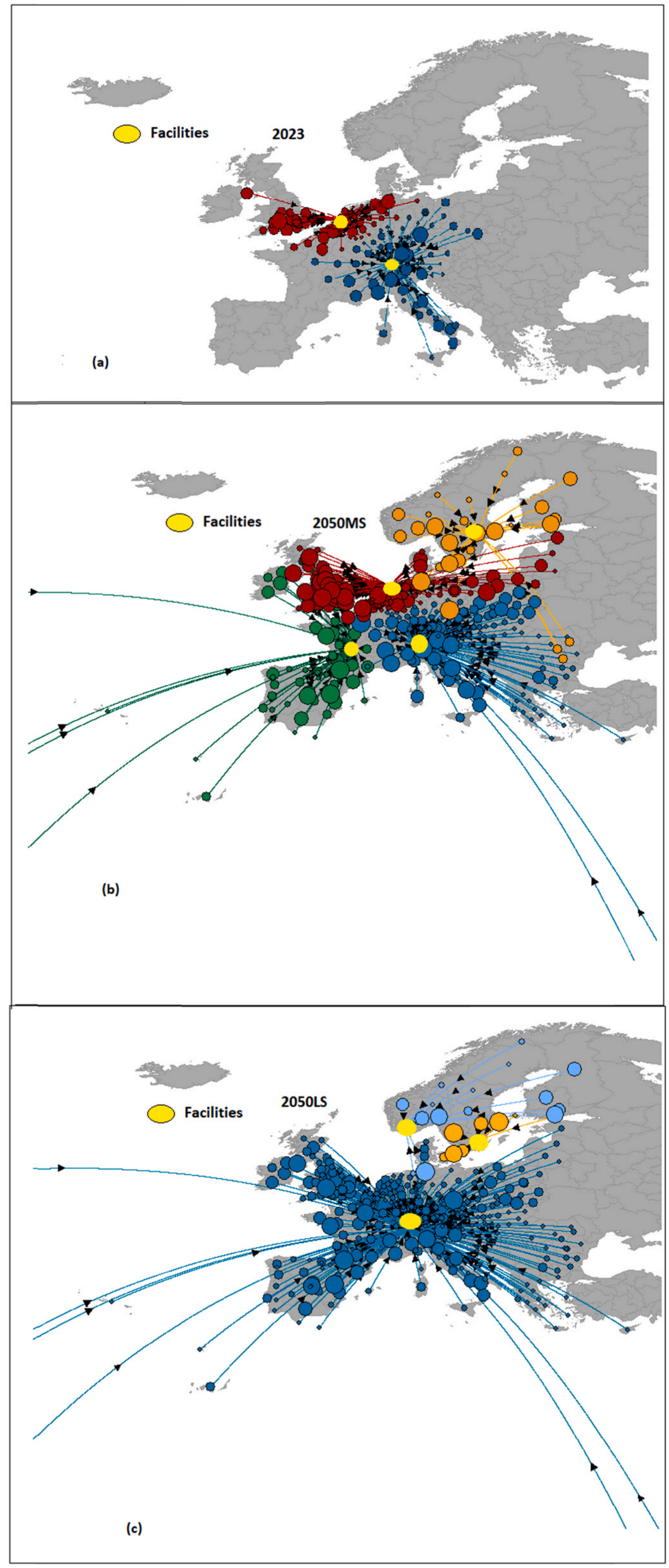

Fig. 8. Supply network flows (from the waste suppliers to the pyrolysis facilities): a)2023, b)2050MS, c) 2050LS

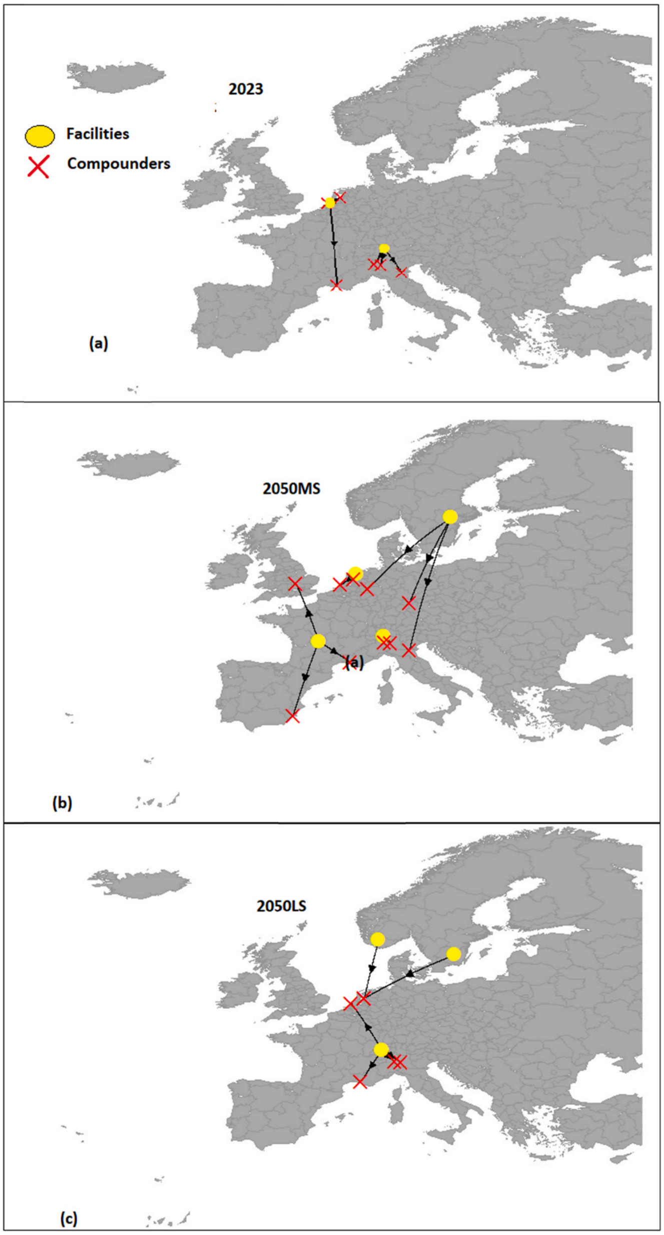

Fig. 9. Intermediate flows network (from pyrolysis to the compounding facilities): a)2023, b)2050MS, c) 2050LS

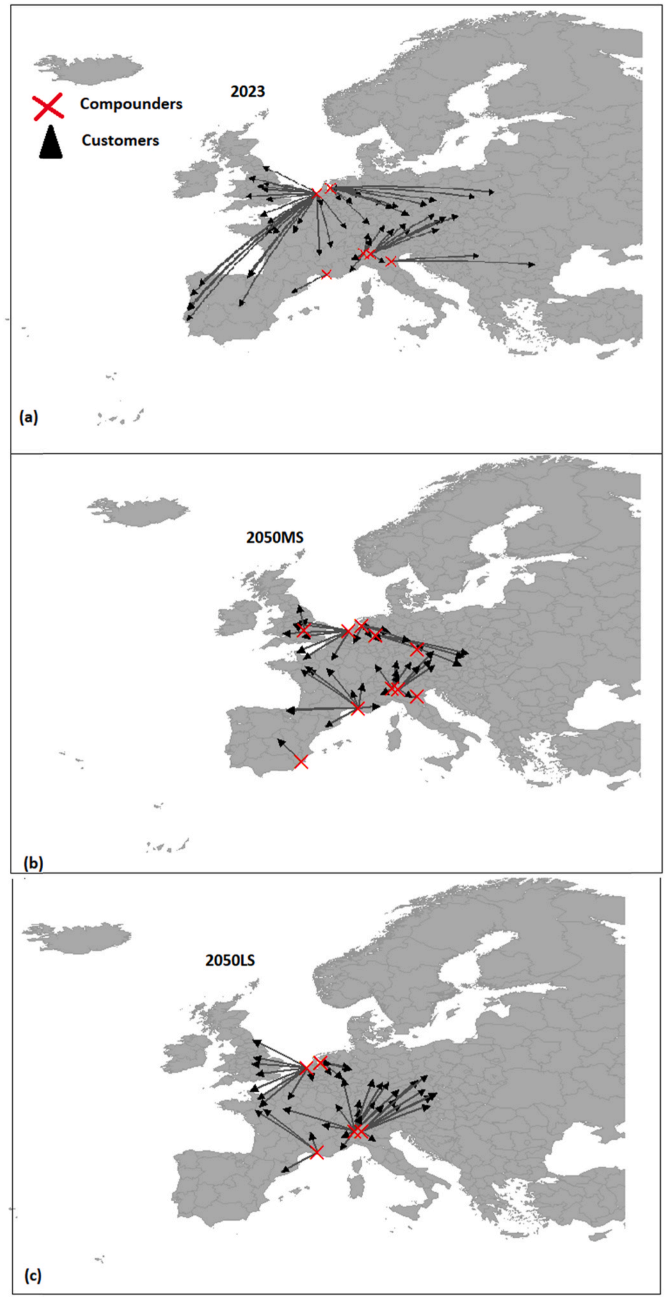

Fig. 10. Demand network flows (from the compounding facilities to the customers): a)2023, b)2050MS, c) 2050LS

transportation costs, as seen in Fig. 12, where the economic breakdown of each stage per tonne of end product for 2023 and 2050 is presented.

It is evident that for the pyrolysis processing stage the most significant cost is the investment along with the fixed costs, which include the labour and insurance costs. The investment and fixed costs are affected by the economies of scale, unlike the electricity and additives use. Finally, the total pyrolysis cost per tonne of end product is lower for the 2050LS case, due to the significant benefit from the economies of scale.

Regarding the compounding it is identified that the greatest cost is due to the additives used in the process, compared to the electricity consumption, resulting from the high price of the chemicals required to produce the pellets. The compounding stage is the most expensive stage in the supply chain for all scenarios.

Finally, the total transportation cost appears to be influenced by the network structure: the more decentralised networks exhibit lower transportation costs, as in the case of the 2050MS scenario compared to the 2050LS one, although the amount of material transported is equal in both cases.

5.3. Environmental assessment

Despite the fact that the proposed circular economy system is inherently sustainable compared to the business as usual case, it is interesting to provide an understanding of the carbon footprint of the proposed system. For this purpose, the direct carbon emissions per tonne of end product for the reverse supply chain of the thermally treated fibres have been calculated and are presented in Fig. 13. The emissions from electricity consumption for the compounding and the pyrolysis constitute the greatest part of the emissions. It is observed that the pyrolysis emissions for 2023 are much higher than the 2050 cases, almost double per tonne of end product. This is due to the fact that the country-level carbon emissions per kWh differ. For example, Sweden, Norway,

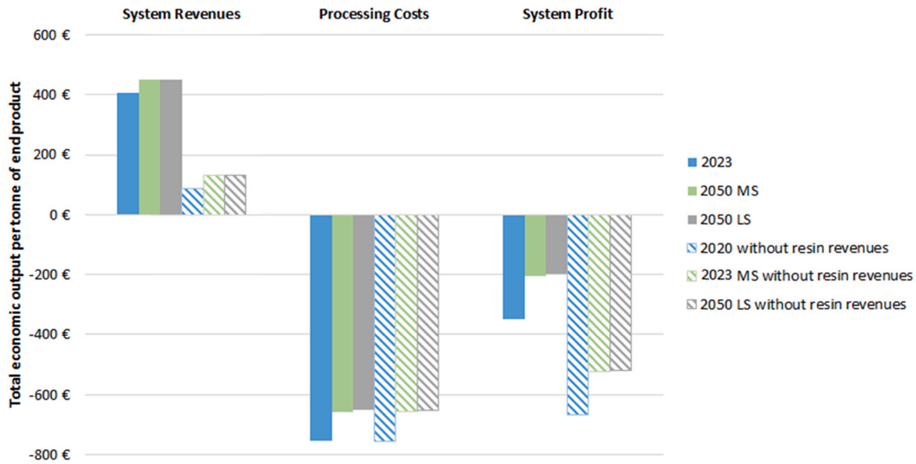

Fig. 11. Total economic output per tonne of end product with and without resin revenues (before recycled fibre sales revenue).

Table 2
Breakeven price for the scenarios.

Scenarios	Price (€/kg of recycled fibres)	Price (€/kg of compound)	Price (€/kg of input waste material)
2023	1.054	0.348	0.171
2023 (without resin revenues)	2.024	0.668	0.329
2050MS	0.621	0.205	0.240
2050MS (without resin revenues)	1.590	0.525	0.614
2050LS	0.601	0.199	0.232
2050LS (without resin revenues)	1.571	0.518	0.606

Table 3
Supply and demand material flows.

	2023	2050
Waste material available from automotive (t/yr)	3415	102,092
Waste material available from aeronautic (t/yr)	11,860	35,046
Total waste material available (t/yr)	15,278	137,138
Total demand of material from automotive sector (t/yr)	7515	225,988
	Supply> Demand	Demand>Supply
	Demand driven model	Supply driven model

France and Switzerland (selected for locating the pyrolysis facilities in 2050) have a lower carbon emissions coefficient compared to Austria and Netherlands (selected for locating the facilities in 2023).

The carbon emissions from pyrolysis constitute more than 50% of the total emissions, whereas the compounding around 40%. As a result, electricity is the energy form that is responsible for 94% of the emissions of all reverse supply chains, with only approximately 6% due to diesel, most of it used for transportation activities. It should be noted that the country electricity emissions factors adopted for the 2050 scenario were the same as in 2023, due to lack of available information on how the decarbonisation of electricity generation will evolve in each European country. Therefore, the values for 2050 are subject to significant reduction if aggressive decarbonisation targets are adopted and achieved.

5.4. Sensitivity analysis

Finally, the sensitivity analysis of the most uncertain parameters is performed against the total system cost; including the technologies capital cost, the electricity and diesel fuel price. In addition, the density of the transported material and the cost of the additives used for the compounding are included in the analysis due to the uncertainty of the assumptions made. The impact of these parameters is investigated on the total system costs before considering any revenue streams. The findings from the sensitivity analysis can be found in Fig. 14.

It is identified that in all cases the compounding additives cost is the most impactful parameter followed by the pyrolysis technology capital cost and the electricity price. In addition, for 2050 the diesel fuel cost also has a high influence on the total cost, due to the higher transportation distances. In 2023 it is observed that the technology capital cost has higher impact on the total cost compared to 2050, because in 2050 the capital cost benefits from the economies of scale. This is also evident from the analysis on the pyrolysis costs, where the technology cost changes by 20% have an impact of more than 8% change of the total cost for this processing stage in 2023; this is not so intense in 2050 due to the economies of scale whereas the other costs increase proportional. On the other hand, the uncertainty on the density of the material transported is more impactful than the fuel price for the transportation cost.

5.5. Insights and implications

The results presented lead to several implications for practitioners and policy-makers. Firstly, the trade-off between transportation costs and economies of scale at the processing facilities lean more towards the latter for the 2050 case, when CFRP volumes are significantly increased. Still, any facility size larger than the currently established leads to minimal benefits, due to the significant increase of transportation cost. All supply chain networks identified require EoL material catchment areas spanning multiple countries; this indicates that to reduce the recycled product cost, any barriers from moving the EoL CFRP parts across country borders should be removed. Improving the transported material density was found to reduce the overall costs, but its impact is not critical.

The optimal networks entail a four-tier supply chain, consisting of multiple existing and new players, indicating a complex network; hence, effective coordination will be crucial for its success. Furthermore, it was identified that the increased volumes of EoL material available in the future will lead to significant reduction in the breakeven selling price of the recycled product, improving the proposed system's viability. The importance of identifying multi-product recycling solutions should also be emphasised, since recycling the UP resin additionally to the CF was

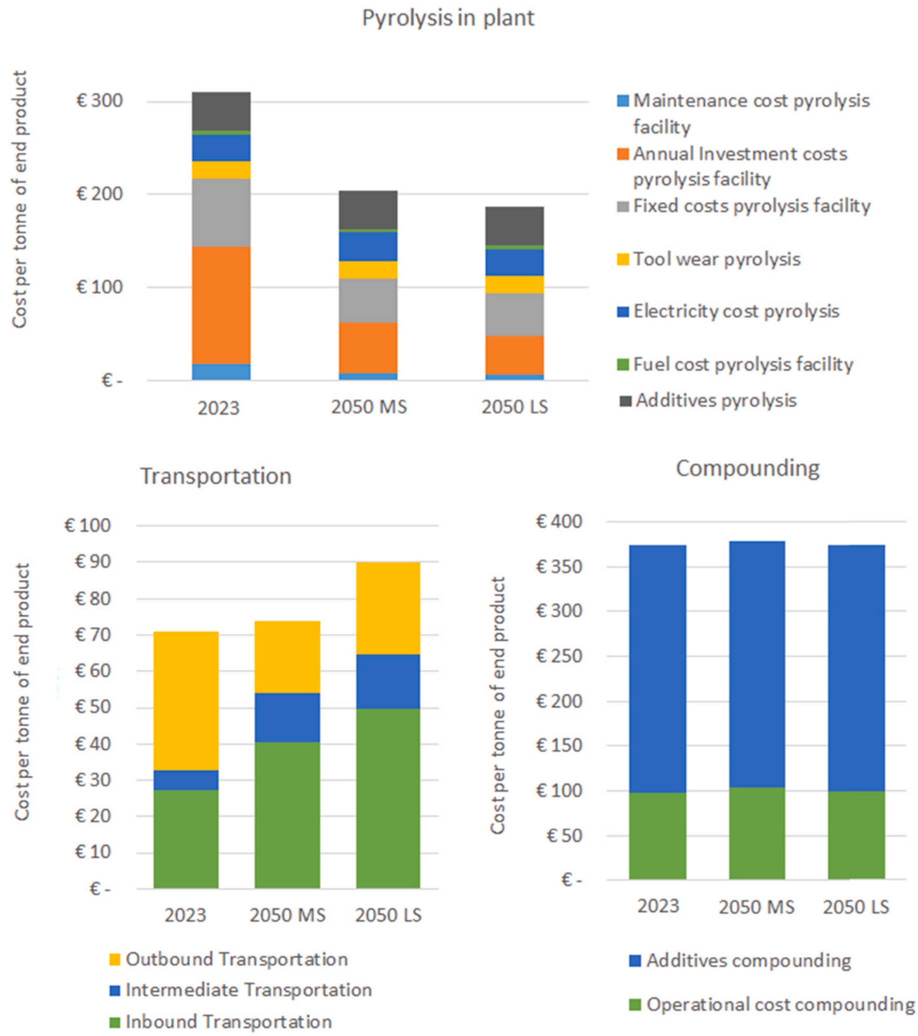

Fig. 12. Economic breakdown per tonne of end product at each stage.

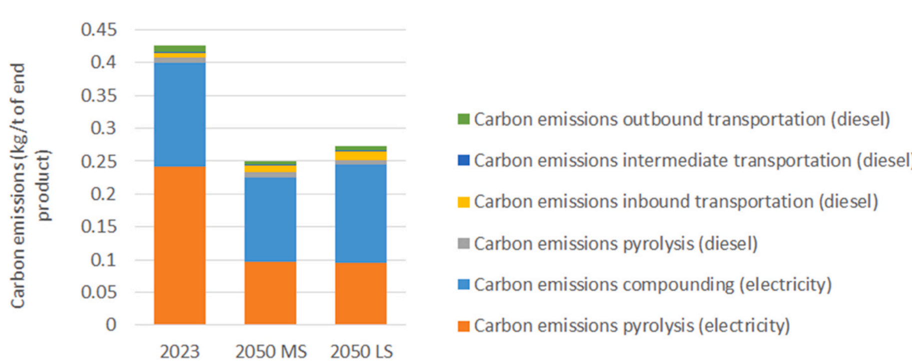

Fig. 13. Carbon emissions per tonne of end product.

found to significantly improve the system economics, reducing the recycled CF product breakeven price by 48%–62%.

6. Conclusions

A novel MILP optimisation model was presented in this study, aiming to optimise the proposed 4-tier reverse supply chain network design problem for recycling End-of-Life carbon fibre material. The proposed reverse supply chain network introduces a cross-sectoral circular economy pathway for carbon fibres, sourcing CFRP waste from End-of-Life cars and aircrafts, as well as CFRP waste from aviation manufacturing. The model developed was applied for the case of European Union 27 member countries and UK.

This study contributes to the field of OR by providing for the first time a 4-tier Supply Chain Network Design decision support system for the CFRP, that can be applied in any geographical context. The case study of the EU-27 and UK involving the automotive and aviation sectors can support stakeholders such as waste owners, waste management companies, policy makers and regulators to take the required actions to facilitate the emergence of a circular economy paradigm in the

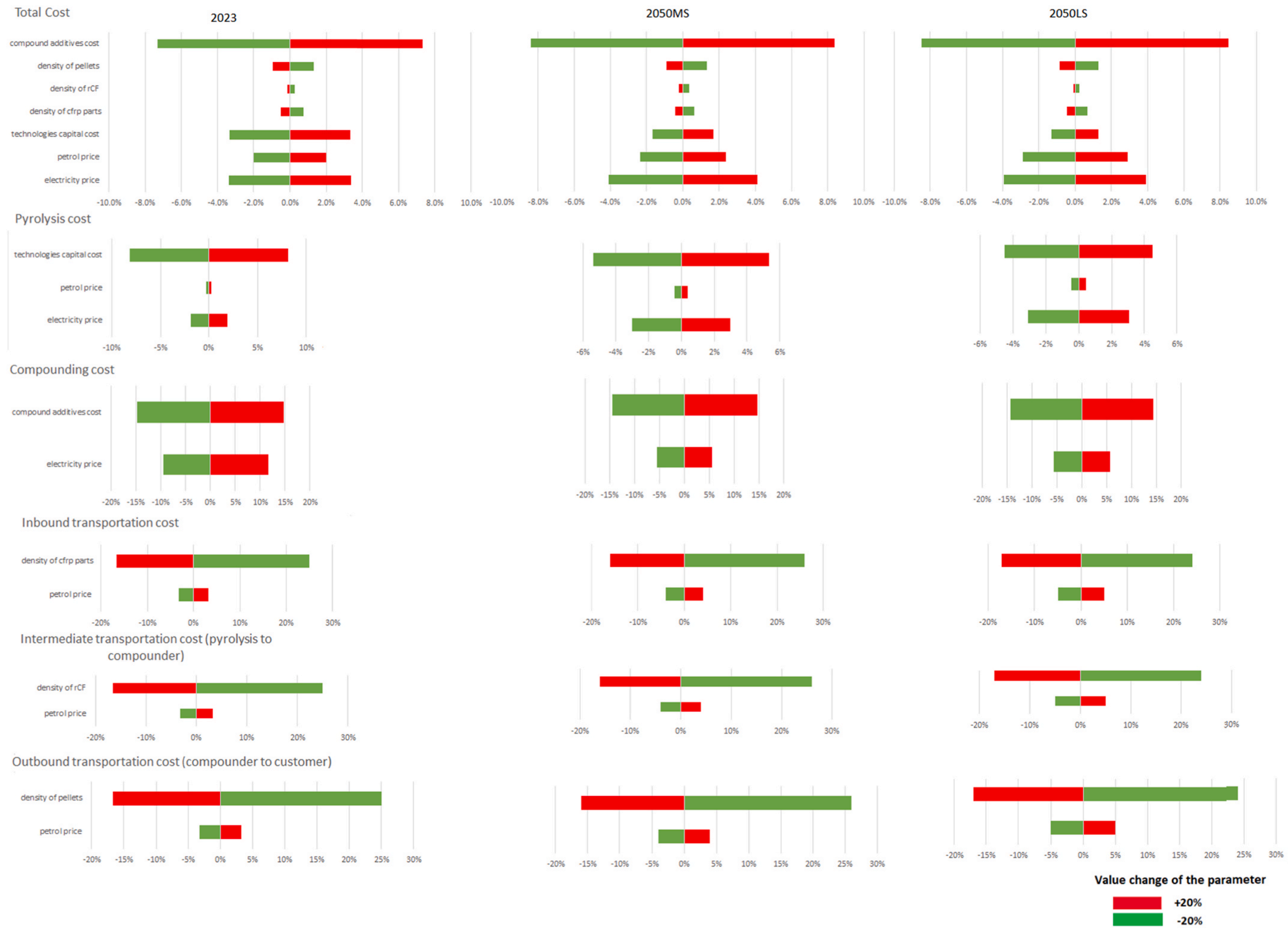

Fig. 14. Sensitivity analysis for 2023 and 2050MS and 2050LS

emerging, high-value carbon fibre material.

The recycling process considered was thermal treatment through pyrolysis with and without recycling the resin component, and the rCF was assumed to be sent to compounding facilities to be transformed into CF pellets to be ultimately supplied to 1st tier car part manufacturers. In this supply chain network design model application, the locations and capacities of the pyrolysis facilities were optimised for 2023 and 2050; however, existing facility locations have been used for the compounding stage.

The outputs of the optimisation model indicate that the optimal network design is centralised in 2023 with only two facilities proposed around Europe, which is justified by the very low material volumes available. The network design becomes more decentralised in 2050 with up to five facilities proposed, as the waste material volumes increase. In addition, managing to recycle and sell the UP resin at the pyrolysis stage as a second recycled product, beyond just selling the rCF, significantly improves the economics of the system and more than halves the respective breakeven price of the rCF or the pellets. The breakeven price of the rCF appears quite competitive against virgin CF material; however, for a fair cost comparison one would need to consider the drop in fibre properties and performance after pyrolysis and use them in less demanding application with lower value than virgin fibres. This is the reason the rCF were not assumed to be used in the aviation industry but rather in automotive, where usually the requirements are not equally strict in terms of material performance. The system cost in this case appears particularly sensitive to changes in the compounding additives price, the energy costs and the technological capital costs.

This study could be expanded in the future to include more potential source and end use sectors for the recycled CF, to increase the waste material volumes, since these are currently quite low compared to other waste streams and result in centralised systems with long transportation distances. Furthermore, the optimisation problem could be transformed into multi-objective, by considering the carbon footprint or other environmental objectives simultaneously with the economic performance.

CRediT authorship contribution statement

Nikoletta L. Trivyza: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Visualization, Formal analysis, Investigation. **Athanasios Rentizelas:** Supervision, Project administration, Funding acquisition, Conceptualization, Methodology, Validation, Writing – review & editing. **Sarah Oswald:** Formal analysis, Conceptualization, Investigation. **Stefan Siegl:** Conceptualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Appendix A

Nomenclature

Sets

Symbol	Description
C	set of all potential customers c = 1..C
F	set of all the aggregated CFRP waste material suppliers f = 1..F
L	set of potential pyrolysis facility locations (NUTS2 regions centroids) l = 1..L
M	set of potential compounding facilities locations m = 1..M
Ps	set of processing stages (pyrolysis, compounding) ps = 1..PS
S	set of potential pyrolysis plant sizes s = 1..S
St	set of storage stages (before processing in plant, after processing in plant) st = 1..ST

Parameters

Symbol	Description	Unit
An	annuity factor estimated according to the equivalent annual cost function	(–)
Cac	variable operating cost of additives for compounding	(€ t^{-1} of material processed)
Cap	variable operating cost of additives for pyrolysis	(€ t^{-1} of material processed)
Cap_s	processing capacity of pyrolysis plant size s	(t of input waste yr^{-1})
Cdf	cost of diesel per country or region	(€ l^{-1})
$cdisp_f$	cost of disposing 1 t of waste (depends on location of supplier)	(€ t^{-1} of waste material)
Ce	cost of electricity (depends on the location)	(€ kWh^{-1})
Cec	variable compounding electricity consumption for waste transformation to recycled fibre	(kWh t^{-1} of input material processed)
Cep	variable electricity consumption for pyrolysis	(kWh t^{-1} of material processed)
Ci	total facility investment cost	(€ yr^{-1})
ci_s	investment cost for s plant size	(€)
$cins_s$	insurance cost for s plant size	(€ yr^{-1})
Cm	total facility maintenance cost	(€ yr^{-1})
cm_s	maintenance yearly cost for s plant size	% of original investment
Cmf	total fuel cost for forklift machinery	(€ yr^{-1})
Cmf	fuel consumption for forklift machinery per year and facility capacity	(l yr^{-1} t^{-1} plant capacity)
Cmi	total investment cost for forklift machinery	(€ yr^{-1})
Cmi	rental cost for forklift machinery	(€ yr^{-1} t^{-1} plant capacity)
Cmins	insurance cost for forklift machinery	(€ yr^{-1} t^{-1} plant capacity)
co2ee	carbon emissions factor from electricity per country	(g CO_2 kWh^{-1})
$CO2_{el}$	carbon emissions from electricity per year for pyrolysis facility	(t_{CO2} yr^{-1})
$CO2_{el2}$	carbon emissions from electricity per year from compounding	(t_{CO2} yr^{-1})
$CO2fu_{o1}$	carbon emissions from fuel combustion per year from pyrolysis facility operation	(t_{CO2} yr^{-1})
$CO2fu_t$	carbon emissions from fuel combustion per year from transportation	(t_{CO2} yr^{-1})
co2t	carbon emissions cost	(€ t_{CO2}^{-1})
Cof	total facility fixed operational cost: insurance and labour cost	(€ yr^{-1})
Cols	fixed operating personnel cost for processing facility	(€ t^{-1} plant capacity)
$conv_{ps}$	Material conversion efficiency of each processing stage ps	(%)
Convup	conversion factor for UP resin derived after the pyrolysis process	(%)
Cov_1^p	total variable operational cost from processing in the facility (pyrolysis): energy consumption, chemical additives and tool wear	(€ yr^{-1})
Cov_2^{co}	total variable operational cost from second stage processing (compounding): energy consumption and chemical additives	(€ yr^{-1})
Cst	total storage cost	(€ yr^{-1})
cst_{st}	Storage cost at storage stage st	(€ t^{-1} plant capacity)
Ctc	variable tool wear cost for recycled fibre compounding	(€ t^{-1} material processed)
Ctin	total cost of waste transportation from all suppliers to the pyrolysis facility	(€ yr^{-1})
Ctint	total cost of product intermediate transportation from pyrolysis facility to compounding facility	(€ yr^{-1})
Ctout	total cost of product outbound transportation from compounding facility to the customers	(€ yr^{-1})
Ctp	variable operating cost of tool wear for waste pyrolysis	(€ t^{-1} material processed)
$d1_f$	first stage distance between the waste material availability location and the aggregated material supplier location (NUTS2 centroids)	(km)
dem_c	Material demand of customer c per year	(t yr^{-1})
Df	Discount rate	(%)
$dfl_{f,l}$	Second stage distance between the aggregated material supplier f and a pyrolysis plant l	(km)
$dlm_{l,m}$	distance between first stage processing plant l and second stage processing plant m	(km)
$dmc_{m,c}$	distance between second stage processing plant m and customer c	(km)
Efd	carbon emission factor for diesel	(g_{CO2} l^{-1})

(continued on next page)

(*continued*)

Symbol	Description	Unit
Fct	fuel consumption of full load heavy duty truck	(l t^{-1} km^{-1})
$Rdisp_f$	revenues from avoiding disposing the waste for each waste supplier f	(€ yr^{-1})
Rup	revenues from selling recycled UP resin	(€ yr^{-1})
sup_f	mass of waste generated by CFRP supplier f in a year	(t of waste material yr^{-1})
Tcin	Unitary cost of waste inbound transportation: labour, insurance, maintenance	(€ t^{-1} km^{-1})
Tcinf	Unitary cost of waste inbound transportation: fuel	(€ t^{-1} km^{-1})
Tcint	Unitary cost of recycled product intermediate transportation: labour, insurance, maintenance	(€ t^{-1} km^{-1})
Tcintf	Unitary cost of recycled product intermediate transportation: fuel	(€ t^{-1} km^{-1})
Tcout	Unitary cost of recycled product outbound transportation: labour, insurance, maintenance	(€ t^{-1} km^{-1})
Tcoutf	Unitary cost of recycled product outbound transportation: fuel	(€ t^{-1} km^{-1})
Up	resin price	(€ t^{-1} of resin)
Y	useful life of operation	(year)

Decision Variables

Symbol	Description	Variable type	Unit
$t_{m,c}$	recycled material flow from compounding facility m to customer c	positive variable	(t yr^{-1})
$x_{f,l}$	waste material flow from CFRP waste supplier to pyrolysis facility l	positive variable	(t yr^{-1})
$y_{l,s}$	Existence of pyrolysis facility at location l of size s	binary	–
$z_{l,m}$	recycled material flow from facility l to compounding facility m	positive variable	(t yr^{-1})

Appendix B

The majority of the input parameters are derived by industrial sources and is represented in Tables B1, B2 and B3.

Table B1
Input parameters used for pyrolysis calculations

Stage	Description	Value
Pyrolysis	Investment cost for a facility per capacity	15211*Capacity^0.6603
	Chemical additives cost	49 € t^{-1}
	electricity consumption	560 kWh t^{-1}
	Fibres yield factor	39%
	Resin yield factor	36%
	Resin price	1,10 € kg^{-1}
	tool wear-every 5 years change of components is annually allocated	22 € t^{-1}
	density of fibres after pyrolysis	174 kg/m^3
	yearly capacity of facility	500/1000/2000/5000/10,000 /15,000/20,000/30,000/40,000 tonnes per year
	storage cost	14.4 € of m^2 of required space per facility capacity
	maintenance cost	2% of investment cost
	rental cost of forklift	4.55% of investment cost
	forklift fuel consumption	3.54 l yr^{-1} t^{-1} of facility capacity
	forklift insurance cost	0.22% of investment cost
	personnel cost	34,615€/year*(0.001*capacity+2.4)
	Facility hours of operation considering maintenance and downtime	4680 h per year

Table B2
Input parameters used for compounding calculations

Stage	Description	Value
Compounding	Electricity consumption	835 kWh t^{-1}
	Additives	4908 € t^{-1}
	Density of pellets	393 kg/m^3
	Compound to rCF ratio	3.03
	Car parts density	350 kg/m^3

Table B3
Input parameters used for transportation and other calculations

Stage	Description	Value
Transportation	truck capacity	40 m^3
	inbound transportation cost	0.055€ t^{-1} km^{-1}
	outbound1 transportation cost (from processing facility to compounder)	0.123€ t^{-1} km^{-1}
	outbound2 transportation cost (from compounder to customers)	0.054€ t^{-1} km^{-1}
Others	percentage of CF on automotive	40%
	diesel carbon emission factor	2640 g CO^2 l^{-1}
	diesel price for each country	average price of 2019
	electricity cost for each country	prices for medium size industries in 2017 (Eurostat)
	emissions from electricity per country	carbon intensity of electricity traded with upstream after pumping and own use (Ecometrica)

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