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Reverse supply network design for circular economy pathways of wind turbine blades in Europe

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Abstract: Wind energy installations are increasing rapidly and so is their end-of-life waste. Wind turbine blades consist primarily of glass fibers and are usually landfilled. Given the significant amounts of blade waste expected in the future, circular economy pathways need to be identified for this waste stream. This study investigates the feasibility of the circular economy pathway of mechanical recycling for reuse of end-of-life blades at composite material manufacturing, while optimising the required reverse supply network design in Europe, for 2020 and for 2050. This is achieved through formulating and solving to optimality a Mixed Integer Linear Programming model for the wind blades Supply Chain Network Design problem. The findings indicate a semi-decentralised optimal network design, with 3-4 processing facilities proposed around Europe in all scenarios. The proposed circular economy pathway is economically viable without additional policy support only in 2050; while focusing the efforts only in more favourable areas of end-of-life blade availability can reduce system-wide costs. This study contributes to academic knowledge by formulating and solving for the first time the Supply Chain Network Design problem for end-of-life wind blades and to practice and policy-making by providing insights on the optimal network design, its feasibility and the related implications.

Keywords: glass fibers; reverse logistics; optimisation; wind turbine blades; circular economy; recycling

1. Introduction

To achieve the Paris Agreement targets, wind energy will need to supply more than one third of the global electricity production by 2050 (IRENA, 2019) and 25% in Europe (EuropeanComission, 2016). To achieve this, the global cumulative installed capacity of wind energy is expected to be increased ten-fold for onshore and 35 times for offshore by 2050 compared to 2018, while the respective values for Europe are three-fold and eleven-fold (IRENA, 2019).

The last decade, the first generation of onshore wind turbines in Europe have been reaching their End of Life (EoL), after 20-25 years of service (Andersen et al., 2016). This leads to a significant amount of wind blade waste material, estimated at approximately 100,000 t yearly in Europe in 2020, with a high expected increase rate, reaching 325,000 t yearly by 2050 (Lichtenegger et al., 2020).

Wind turbine blades mainly consist of fiber reinforced composites (Cousins et al., 2019), due to their enhanced technical properties and long life span (Yang et al., 2012). Glass Fiber Reinforced Polymers (GFRP) are commonly used in long blades for offshore and onshore turbines (Schubel & Crossley, 2012): It is estimated that approximately 82% per weight on average of a wind turbine blade is Glass Fibers (GF) with epoxy resin (Colledani et al., 2018). As a result, a great amount of highly engineered GFRP material will reach the waste streams soon, and the amounts will increase steeply over the coming years, raising issues regarding the related environmental impact and supporting the case for recovering this material.

Currently, the status quo for EoL wind turbine blades in Europe is landfilling (Cousins et al., 2019). However, there are regulatory drivers in Europe, US and Japan that support the recovery of this type of waste (Kumar & Putnam, 2008). European Waste Catalogue classifies most of fiber reinforced polymers as non-hazardous waste, while the EU Directive 99/31/EC has introduced regulations that prohibit large composite parts landfilling, such as wind turbine blades (Cousins et al., 2019). The majority of European countries have imposed a landfill tax to discourage landfilling. The tax value differs for each country (see Figure A1 in supplementary material); however, in some cases, such as the United Kingdom, it can reach £140 t^{-1} for 2020-2021 (including transportation cost). Finally, some countries, like Germany, Netherlands and Finland, have even enacted stricter regulatory policies that in some cases ban landfill as well as incineration of composites. These policies are expected to be adopted by more European countries, such as France (WindEurope et al., 2020).

As a result, there is increasing interest in identifying more circular pathways for GFRP. The only current commercially available facilities for GFRP recycling are in Germany, where GFRP is added to cement kilns (Gu & Ozbakkaloglu, 2016). However, this does not provide a sustainable option due to transportation, for a number of European countries (Job, 2013). Another drawback of this process is that it reduces the value of the glass fibers to that of calcium carbonate (Job, 2013). Alternatively, the blades can be incinerated for energy recovery, but this approach has negative impact on the flue gas cleaning systems (Beauson & Brøndsted, 2016). Even though other alternatives exist in theory for GFRP recycling, such as retrieving the fibers through pyrolysis, the low cost of virgin GF material renders these costly recycling methods infeasible.

The limitations regarding the traditional waste management practices along with the challenges for composites recycling render identifying potential reverse supply chain pathways for reinforced composites crucial. Therefore, this study investigates the feasibility of potential recycling options for the EoL wind turbine blades. This is achieved through modelling of the reverse supply network, one that enables a circular economy pathway for GFRP, and optimising the network structure and characteristics in order to minimise the network's annual costs. This study contributes to knowledge by formulating and solving for the first time the Supply Chain Network Design problem for end-of-life wind blades, thus enabling a circular-economy oriented approach for this type of waste. The scope of this study is the largest part of Europe, comprising of the 28 European Union member states (EU-28); however, the method developed can be applied in any geographical context. Therefore, this study also contributes to practice and policy making by providing insights on the optimal reverse supply chain network design for EU-28, its feasibility and the related implications, as well as by providing a tool for performing similar analyses in other regions. The implications of this study are significant for the wind blade owners, the third-party waste collectors as well as the regulatory bodies and policy makers, as well as for researchers in related fields.

The rest of this paper is organised as follows. Section 2 discusses the state of the art in closed loop and reverse supply chains optimisation and synthesises the key findings regarding wind blade EoL solutions. Section 3 introduces the proposed circular economy pathway and describes the mathematical model for reverse supply network optimisation. Then the proposed reverse supply network is discussed for Europe in Section 4 and the empirical results from the model application are presented in Section 5. Section 6 discusses the managerial implications for the decision-makers. Concluding remarks are summarised in Section 7.

2. Literature Review

This section presents the state of the art in the subjects of closed loop and reverse supply chains optimisation as well as a summary of the solutions proposed for the EoL wind blades.

2.1 Closed Loop and Reverse Supply Chain Optimisation Models

In recent years, along with high quality and low prices, customers require more environmentally friendly operations throughout the supply chain (Niinimäki & Hassi, 2011). In addition, there are new regulations pressing to increase manufacturers responsibility for the product after their EoL (Krikke et al., 2003). As a result, companies experience pressure to adopt more sustainable processes, and one of the most impactful ways to achieve this is to design and operate a closed loop supply chain (Kim et al., 2018).

Closed loop supply chain management is defined as 'the design, control and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time' (Guide et al., 2003). In a closed loop supply chain the returned flow from the user should be incorporated in addition to a re-processing stage of the EoL product to a useable one (French & Laforge, 2006). Therefore, supply chains must expand from the traditional focus on the forward flow of materials to consider the entire product life cycle (Kocabasoglu et al., 2007) and proceed to the optimisation of the supply chain from a total cost overview (Linton et al., 2007). The structural adaptation required to transition between different supply chain designs can be supported by frameworks such as the viable supply chain (Ivanov, 2020) and the reconfigurable supply chain (Dolgui et al., 2020).

Although closing the loop between the manufacturer and customer is a stepping-stone for sustainable development and has potential for environmental benefits, at the same time it may add significant cost (Kocabasoglu et al., 2007). As a result, there has been extensive literature investigating the reverse supply chain optimisation of different products with economic and other considerations (Govindan et al., 2017; Van Engeland et al., 2020) as presented in Table 1.

More specifically, Salema, Barbosa-Povoa, and Novais (2007) developed a Mixed Integer Linear Programming (MILP) model for a supply chain network optimisation with focus on strategic decisions, while including uncertainty considerations for the product return and demand. On the other hand, Liao (2018) proposed a hybrid algorithm for the bulk waste reverse supply chain design optimisation. Pochampally and Gupta (2012) proposed a linear optimisation decision-making model for selecting collection centres and evaluating the potential stream of the EoL product using fuzzy methods. Özçelik, Faruk Yılmaz, and Betül Yeni (2020) developed a robust optimisation method of a reverse supply chain design to tackle the uncertainties caused by the ripple effect. Kaya, Bagci, and Turkay (2014) developed a two-stage optimisation model for the strategic and operational decisions regarding the capacities at disassembly and refurbishing sites of a generic reverse supply chain.

A variety of models has been developed for optimising the supply chain network of different products. Linear optimisation models for the design of the reverse supply chain of electronic equipment that minimise costs (Achillas et al., 2010) or maximise profit (Tsai & Hung, 2009) have been proposed. Trochu, Chaabane, and Ouhimmou (2018) developed an optimisation model for the design of the wood reverse supply chain network of the construction, renovation, and demolition industry considering the uncertainties of the supply sources. The vehicles reverse supply chain has also attracted interest (Cruz-Rivera & Ertel, 2009; Gołębiewski et al., 2013).

Authors have also focused on optimising the traditional forward supply chain along with the reverse one. A MILP optimisation model was developed for the closed loop supply chain of the pulp and paper (Fleischmann, 2000) or electric equipment (Jayaraman et al., 1998) industry for minimising cost. Kim et al. (2018) proposed an optimisation model that maximises the profit for the design of a closed loop supply chain network in the fashion industry. On the other hand, Kannan, Noorul Haq, and Devika (2009) proposed a genetic algorithm (GA) for the cost optimisation of the design of the closed loop supply chain of plastic goods. Other authors proposed mathematical models to investigate the impact of the carbon price uncertainty on the closed loop supply chain of plastic recycling (Ren et al., 2020).

Table 1. Reverse and closed loop supply chain optimisation literature

Sources	**Supply chain**	**Decisions**	**Method**	**Product**	**Objective**
(Achillas et al., 2010)	Reverse	Strategic	MILP	Electronic equipment	Cost
(Cruz-Rivera & Ertel, 2009)	Reverse	Strategic	Lagrangian Relaxation linear programming	Automotive	Cost
(Fleischmann, 2000)	Closed loop	Strategic	MILP	Paper and pulp	Cost
(Gołębiewski et al., 2013)	Reverse	Strategic	MILP	Automotive	Cost
(Jayaraman et al., 1998)	Closed loop	Strategic	MILP	Electronic equipment	Cost
(Kannan et al., 2009)	Closed loop	Strategic	Multi-echelon distribution inventory model	Plastic goods	Cost
(Kaya et al., 2014)	Reverse	Strategic &operational	MILP	Generic product	Cost
(Kim et al., 2018)	Closed loop	Strategic	MILP	Fashion industry	Profit
(Liao, 2018)	Reverse	Strategic	MINLP	Furniture	Profit
(Özçelik et al., 2020)	Reverse	Strategic	MILP	Household appliances	Recovered products
(Pochampally & Gupta, 2012)	Reverse	Strategic	Linear physical programming	Generic product	Cost, quality, etc

(Ren et al., 2020)	Closed loop	Strategic	MILP	Plastic	Cost
(Salema et al., 2007)	Reverse	Strategic	MILP	Generic product	Cost
(Trochu et al., 2018)	Reverse	Strategic	MILP	Wood products	Cost
(Tsai & Hung, 2009)	Reverse	Strategic	MILP	Electronic equipment	Profit

2.2 Wind Turbine Blades End of Life Solutions

There is a relatively small but growing body of literature devoted to discussing solutions for the wind turbine blades at the end of their service lives. The EoL pathways for GFRP specifically is a subject that has attracted the attention of both academia and industry (Karuppannan & Timo, 2020). As discussed earlier, landfilling is the most common pathway even though more sustainable pathways would be the reuse, recycling and lastly the incineration for material or energy recovery (Correia et al., 2011).

Incineration for energy recovery is a common route for GFRP waste, usually for electricity production. This approach has some disadvantages, especially for structural composites like wind blades, because of the high content of inorganic material (Papadakis et al., 2009). After incineration, approximately 60% of the original material is left as ash residues, which might be pollutant due to the inorganic loads on the composites (Larsen, 2009). In addition, the presence of glass fibres in the flue gas might damage the filters of the gas cleaning system (Papadakis et al., 2009). These residues require post treatment and are sent for either landfilling, requiring significant capacity for their disposal, or used as a construction material.

Incineration of GFRP for material recovery is another pathway proposed for the wind sector by using the waste material in the cement sector (Yazdanbakhsh et al., 2018). The EoL blades are incinerated in cement kilns, where the incombustible GFRP replaces the clay and limestone fillers in concrete (Correia et al., 2011), while fuel use in concrete production is reduced.

Despite the aforementioned current solutions, it has been stressed by Wegman at Reichhold and European Composites Recycling Services Company (ECRC) that in the future ‘recycling is going to become more important.… For environmental reasons, but also for economic reasons.’ (as quoted in Larsen 2009). There are different technologies that support the blade waste recycling such as thermal, mechanical and chemical. Among all the potential recycling routes for blade waste, mechanical recycling is one of the most attractive alternatives due to the low energy requirements and the fact that it does not require chemical processing (Yazdanbakhsh et al., 2018), leading to lower environmental impact (Ribeiro et al., 2015). In addition, it does not require complex equipment and it therefore leads to lower cost. Along with the fact that in both thermal and chemical processes the recycled fibers often have lower mechanical properties than virgin ones (Mamanpush et al., 2018), hence lower value, thus rendering these processes economically prohibitive.

In the existing literature, very few studies focused on the reverse supply chain of waste blades. Tazi et al. (2019) quantified the waste material flows of wind turbines in a region in France from 2002 to 2020, considering different waste streams for the material flows and concluded that an optimisation algorithm for the recycling facilities allocation would be a significant step. Sultan et al. (2018) developed a mathematical model to identify suitable locations in the United Kingdom (UK) to process the waste from wind blades; however, the study focused only on the upstream material flow from the wind farms to the recycling facilities, without considering the downstream flow to potential users.

From the literature analysis it is apparent that limited work has focused on the optimisation of the reverse supply network of the turbine blades waste material, and there is a gap in supply network optimisation models with an end-to-end scope, i.e. from the EoL wind blade availability to the end customers of the recycled blades. This gap is critical to be addressed, since the regulatory pressures for more responsible waste treatment, the rising amount of wind turbine blades waste and the complexity of glass fibers treatment, require identification of circular economy solutions to close the loop.

3. Supply Chain Network Design Problem for Blade Waste

In this section, a reverse supply chain network for the blade waste, which constitutes a circular economy pathway, is proposed. In addition, the mathematical model developed to optimise the reverse supply chain network design is presented and the main assumptions adopted are discussed.

3.1 Network definition

The relevant literature acknowledges that in the majority of reverse supply chains, the lead role in recycling and disposal is undertaken by a third party (Kocabasoglu et al., 2007). For this reason, in the proposed circular economy pathway, the wind blades recycling is assumed to be performed by an independent third-party recycling company.

As discussed earlier, the most promising recycling process for GFRP from wind blades is through mechanical treatment. The key process stages in order to retrieve the mechanically treated glass fibers are: disassembly of the wind turbine to retrieve the blades, cutting and shredding of the blades. However, the disassembly is considered to be outside the boundaries of the reverse supply network investigated, as it would occur anyway when decommissioning the wind farm, and thus is not an additional activity incurred due to the blades recycling process. The mechanically recycled fibers are ultimately supplied to end customers. In this work, the customers of the recycled fibers are assumed to be the Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) manufacturers, where the fibers are used as fillers.

The potential of employing recycled glass fibers as fillers in new thermoset polymer composites such as SMC/BMC so that the amount of virgin glass fiber used is reduced has been discussed in the literature (DeRosa et al., 2005; Mamanpush et al., 2018; Palmer et al., 2009; Ribeiro et al., 2015). Another advantage of this solution is that SMC/BMC manufacturing is widespread around the world, and the composite components produced are used in several sectors, including automotive, transportation, electronics and construction, therefore offering a cross-sector circular economy pathway. A closed loop supply chain option that would return the recycled glass fiber material to the wind blade sector would not be feasible, since the recycled material would not meet the stringent material properties required.

Two alternative generic recycling process stages scenarios are considered for the reverse supply chain as presented in Figure 1. In Scenario 1, the wind blades are cut into 6-7m length pieces at the wind farm, which is the current practice of the EoL wind blades transportation for landfilling. Then they are transported to the recycling facility, where the second stage cutting is performed, to reduce the pieces size to the appropriate one for feeding into the shredder. The last processing stage is shredding into 2-10mm powder, which is the final recycled product transported to the end customer.

In scenario 2 the wind blades are cut into 1-2m size and then pre-shredded at the wind farm to 20-40mm size, using mobile shredders. Then they are transported to a central facility for final shredding to the appropriate size. In both scenarios, the final shredding is performed in the recycling facility due to dust formation that requires specialised dust control equipment for containing it.

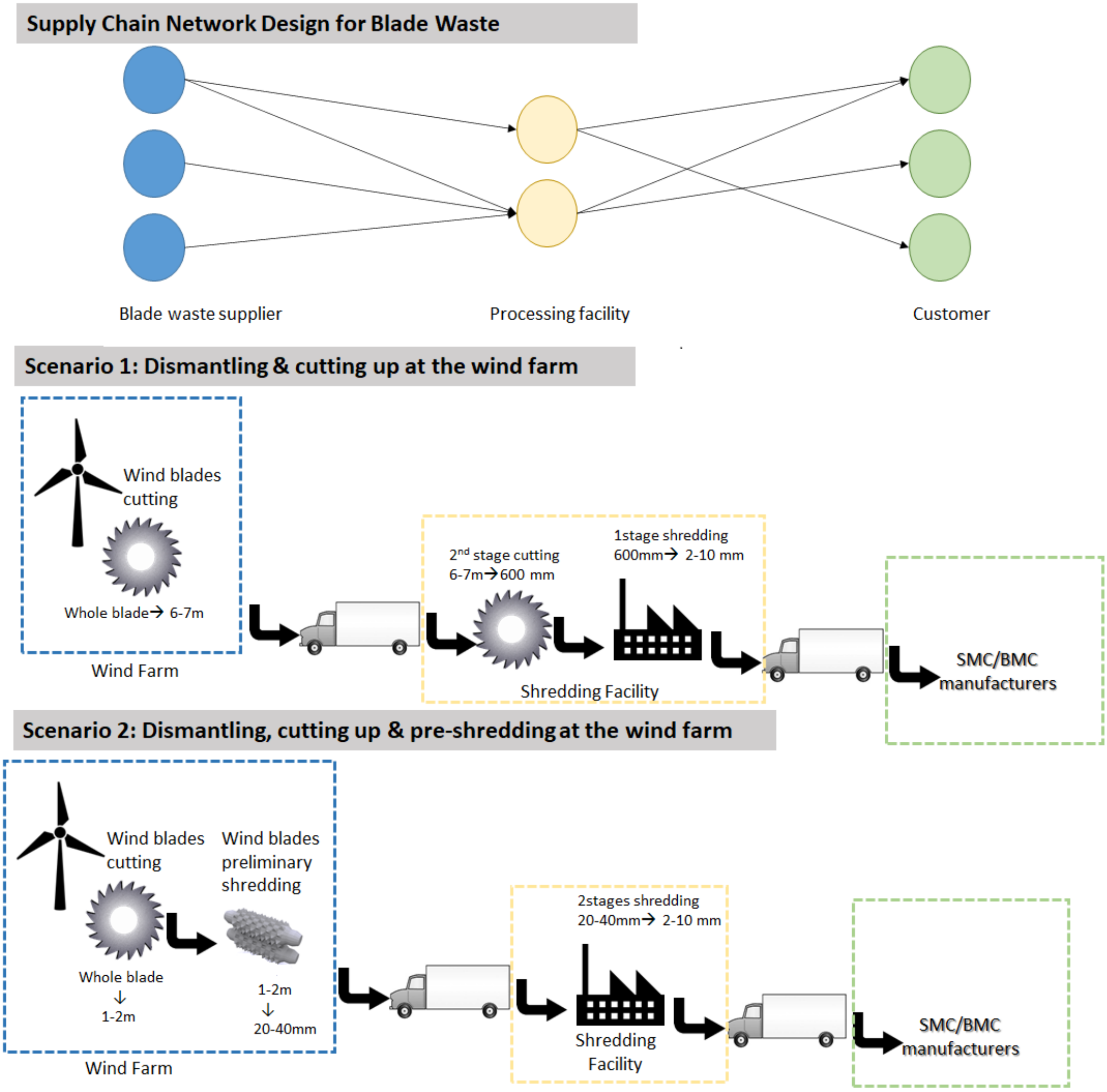

Figure 1. Reverse supply network structure and processing scenarios

These scenarios for the reverse supply chain network are modelled in the following section.

3.2 Mathematical model formulation

The mathematical model of the reverse supply chain network design optimisation is formulated as a MILP problem. The model belongs to the wider family of location-allocation optimisation problems and specifically to the Supply Chain Network Design problems. The optimisation problem was implemented in GAMS and was solved with LINDO in an Intel(R) Core^{TM}8 i7-2600 CPU at 3.40GHz, with computational times between 70,000-100,000 seconds. The global optimal solution was identified and the results are presented in Section 5.

The EoL wind blades are transported from the waste suppliers (f=1…F) to the processing facilities, whose location (l=1...L) and capacity (s=1…S) is optimised. The recycled material is finally delivered to the customers (c=1…C). The objective function of the optimisation problem is the annual total cost of the reverse supply network, including all process stages (ps=1…PS) up to delivery of the recycled product to the end users. The reverse logistics system carbon emissions are also analytically calculated to provide an understanding of the environmental impact.

The decision variables of the supply network optimisation model are:

- $x_{f,l}$ waste material flow from supplier f to processing facility l, f=1…F , l=1...L
- $y_{l,s}$ binary variable that takes value 1 if processing facility of capacity s is opened at a specific location l, and 0 otherwise, l=1...L, s=1…S
- $z_{l,c}$ recycled material flow from processing facility l to customer c, l=1...L, c=1…C

The mathematical model nomenclature is presented in Appendix 1.

The objective function of the model for scenario 1 and 2 is described by eq.1 and 2, respectively.

Scenario 1:

$$Min\ F = Cfs + Cov_0^c + Ctin + Cst + Cov_1^c + Cov_1^s + Cm + Cof + \frac{Ci}{an} + Cmi + Cmf + Ctout + co2t\ (CO2\mathrm{fu}_{o2} + CO2\mathrm{fu}_{\mathrm{t}} + CO2el) - Rdisp \quad (1)$$

Scenario2:

$$Min\ F = Cfs + Cov_0^c + Cov_0^{ps} + Ctin + Cst + Cov_1^s + Cm + Cof + \frac{Ci}{an} + Cmi + Cmf + Ctout + co2t\ (CO2\mathrm{fu}_{o1} + CO2\mathrm{fu}_{o2} + CO2\mathrm{fu}_{\mathrm{t}} + CO2el) - Rdisp \quad (2)$$

$$Cfs = \sum_{w=1}^{W} (cset_w + cper_w), \qquad w = 1..W \quad (3)$$

$$Cov_0^c = (coc + colc) \sum_{l=1}^{L} \sum_{f=1}^{F} x_{f,l}, \qquad f = 1..F, l = 1..L \quad (4)$$

$$Ctin = \sum_{f=1}^{F} \sum_{l=1}^{L} (tcin + tcinf) conv_1 (dfl_{f,l} + d1_{\mathrm{f}})\ x_{f,l}, \qquad f = 1..F, l = 1..L \quad (5)$$

$$Cst = \sum_{st=1}^{ST} \sum_{l=1}^{L} \sum_{s=1}^{S} cst_{st} Cap_s y_{l,s}, \qquad st = 1..ST, l = 1..L, s = 1..S \quad (6)$$

$$Cov_1^s = \sum_{l=1}^{L} \left[(cos + coe\ ce_l) \sum_{f=1}^{F} x_{f,l} conv_1 \right], \qquad l = 1..L, f = 1..F \quad (7)$$

$$Cov_1^c = (cocf + cpcf) \sum_{l=1}^{L} \sum_{f=1}^{F} x_{f,l} conv_1, \qquad l = 1..L, f = 1..F \quad (8)$$

$$Cof = cols \sum_{s=1}^{S} \left(Cap_s \sum_{l=1}^{L} y_{l,s} \right) + cmins \sum_{s=1}^{S} \left(Cap_s \sum_{l=1}^{L} y_{l,s} \right) + \sum_{s=1}^{S} \left(cins_s \sum_{l=1}^{L} y_{l,s} \right), \qquad s = 1..S, l = 1..L \quad (9)$$

$$Cov_0^{ps} = conv_1\ \mathrm{cfps} \sum_{f=1}^{F} cdf_f \sum_{l=1}^{L} x_{f,l} + conv_1 \left(\mathrm{cwps} + \mathrm{csps} + \mathrm{cpps} + \frac{cips}{an} \right) \sum_{f=1}^{F} \sum_{l=1}^{L} x_{f,l} \qquad f = 1..F, l = 1..L \quad (10)$$

$$Cm = \sum_{s=1}^{S} cm_s ci_s \sum_{l=1}^{L} y_{l,s}\,, \qquad s = 1..S, l = 1..L \tag{11}$$

$$Ci = \sum_{s=1}^{S} ci_s \sum_{l=1}^{L} y_{l,s}\,, \qquad s = 1..S, l = 1..L \tag{12}$$

$$an = \frac{1 - \frac{1}{(1+df)^Y}}{df}, \tag{13}$$

$$Cmi = cmi \sum_{s=1}^{S} Cap_s \sum_{l=1}^{L} y_{l,s}\,, \qquad s = 1..S, l = 1..L \tag{14}$$

$$Cmf = cmf \sum_{l=1}^{L} cdf_l \sum_{s=1}^{S} Cap_s y_{l,s}\,, \qquad l = 1..L, s = 1..S \tag{15}$$

$$Ctout = (tcout + tcoutf) \sum_{l=1}^{L} \sum_{c=1}^{C} dlc_{l,c}\, z_{l,c}\,, \quad l = 1..L, c = 1..C \tag{16}$$

$$CO2el = \mathrm{coe} \sum_{l=1}^{L} co2\mathrm{ee}_l \sum_{s=1}^{S} Cap_s y_{l,s} / 10^6, \qquad l = 1..L, s = 1..S \tag{17}$$

$$CO2fu_{o1} = \mathrm{conv}_1 cfps\; efd \sum_{l=1}^{L} \sum_{f=1}^{F} x_{f,l} / 10^6, \qquad l = 1..L, f = 1..F \tag{18}$$

$$CO2fu_{o2} = \mathrm{cmf\;efd} \sum_{s=1}^{S} Cap_s \sum_{l=1}^{L} y_{l,s} / 10^6, \qquad l = 1..L, s = 1..S \tag{19}$$

$$CO2\mathrm{fu}_t = fct\; \mathrm{efd} \left[\sum_{l=1}^{L} \sum_{f=1}^{F} \left(dfl_{f,l} + \mathrm{d1_f} \right) x_{f,l} + \sum_{l=1}^{L} \sum_{c=1}^{C} dlc_{l,c}\, z_{l,c} \right] / 10^6,$$

$$l = 1..L, f = 1..F, c = 1..C \tag{20}$$

$$Rdisp = \sum_{f=1}^{F} cdisp_f \sum_{l=1}^{L} x_{f,l}\,, \qquad \mathrm{f = 1..F, l = 1..L} \tag{21}$$

subject to:

$$\sum_{c=1}^{C} z_{l,c} = \sum_{f=1}^{F} x_{f,l} \prod_{ps=1}^{PS} conv_{ps}, \qquad l = 1 \dots L \qquad (22)$$

$$sup_f = \sum_{l=1}^{L} x_{f,l}\,, \qquad f = 1 \dots F \qquad (23)$$

$$dem_c \geq \sum_{l=1}^{L} z_{l,c}\,, \qquad c = 1..C \qquad (24)$$

$$sup_f \geq \sum_{l=1}^{L} x_{f,l}\,, \qquad f = 1 \dots F \qquad (25)$$

$$dem_c = \sum_{l=1}^{L} z_{l,c}\,, \qquad c = 1..C \qquad (26)$$

$$\sum_{s=1}^{S} y_{l,s} \leq 1, \qquad l = 1..L \qquad (27)$$

$$conv_1 \sum_{f=1}^{F} x_{f,l} \leq \sum_{s=1}^{S} Cap_s\, y_{l,s}, \qquad l = 1..L \qquad (28)$$

$$z_{l,c} \geq 0, \qquad l = 1..L, c = 1..C \qquad (29)$$

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

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

The annual reverse supply network cost consists of: the administrative costs for on-site processing regarding set up and permit at each wind farm w (w=1…W) (eq. 3); the variable cost of each processing stage ps (ps=1...PS), which are expressed as function of the quantity of EoL wind blade material ($x_{f,l}$): cutting on-site (eq. 4), cutting in plant (eq. 8), shredding in plant (eq. 7) and pre-shredding on-site (eq. 10); the storage cost of the input and output material at the processing facility (eq. 6); the fixed costs of the processing facility (eq. 9), which includes the personnel and insurance cost for the facility and forklifts; the maintenance cost (eq. 11), which is expressed as a function of the investment cost; the annualised investment cost of the processing facility (eq. 12) with the annuity estimated by eq. (13); the forklift machinery renting and fuel cost (eq. 14 and 15), which are expressed as a function of the facility capacity. Furthermore, the inbound (waste supply to processing facilities - eq. 5) and outbound (processing facilities to end customers - eq. 16) transportation costs between the supply network nodes are calculated, as a function of the amount of material transported. It should be noted that the inbound transportation consists of two distance elements, the first from the wind farms to theoretical material aggregation nodes, and the second from these nodes to the processing facilities. This was done for computational complexity reasons, as explained in section 4.2. In addition, the carbon emissions from: on-site operations (eq. 18), facility operation electricity and fuel consumption (eq. 17, 19) and transportation (eq. 20) are calculated. For the emissions related to electricity consumption in the processing facility, the electricity carbon emission factors at the country level are used, whereas for emissions due to use of diesel fuel, a standardised carbon emissions factor has been used (see Table A.1 in supplementary material). The savings from avoiding landfilling the waste (eq. 21) are considered as a revenue of the system. Equations (10) and (18), which describe the pre-shredding costs and carbon emissions from the operations at the wind farm, are used in scenario 2 only.

Mass balances are imposed on each node, to ensure that from each existing facility the amount of products produced equals the amount supplied to all customers (eq. 22).

In addition, the model is developed both as supply driven, i.e. driven by the assumption that the recycled material demand exceeds the waste material available, thus all the waste is used, and as demand driven, i.e. driven by the assumption that the waste material available exceeds the recycled material demand, hence all demand is satisfied while not utilising all the waste. The relationship between the mass of the waste available from each of the waste material supplier and the waste provided to all the facilities in a supply driven (eq. 23) or in a demand driven (eq. 25) model is modelled. Finally, the relationship between the mass of the material demand from each customer and the recycled material flow from all facilities to each customer is represented in (eq. 24) for a supply driven model or (eq. 26) for a demand driven.

A constraint is added to ensure that there is only one capacity chosen for each processing facility location (eq. 27) and that the capacity for each location is sufficient to process all the waste allocated to it (eq. 28). Finally, there are logical constrains to ensure positive (eq. 29), (eq. 30) and binary values of decision variables (eq. 31).

4. Supply Chain Network of Blade Waste in Europe

The proposed model presented in the previous section is applied to context of Europe, and specifically the 28 member states of the European Union (EU-28). The blade waste material availability from onshore and offshore wind in Europe from 2020 to 2050 are adopted from (Lichtenegger et al., 2020).

4.1 Network Definition

As discussed in the previous section, the customers for the recycled wind blades are the SMC/BMC manufacturers. 11 SMC/BMC manufacturers were identified in Europe with an estimated production of 287,000 t in 2018 and a 1-2% annual growth expected (Witten et al., 2018). The mechanically treated short glass fibers can substitute the filler materials that constitute around 40-50% of SMC/BMC (Witten et al., 2018). However, according to experts, only 45% of the fillers can be substituted by recycled GFRP in reality, since the rest of the SMC/BMC products should use flame retardant material such as aluminium hydroxide. According to these assumptions, the amount of SMC/BMC material demand by each of the 11 SMC/BMC manufacturers is presented in Figure 2. It is noted that the actual production output was known only for three out of eleven manufacturers; for the rest, the remaining amount from the total is evenly distributed due to the lack of more detailed data.

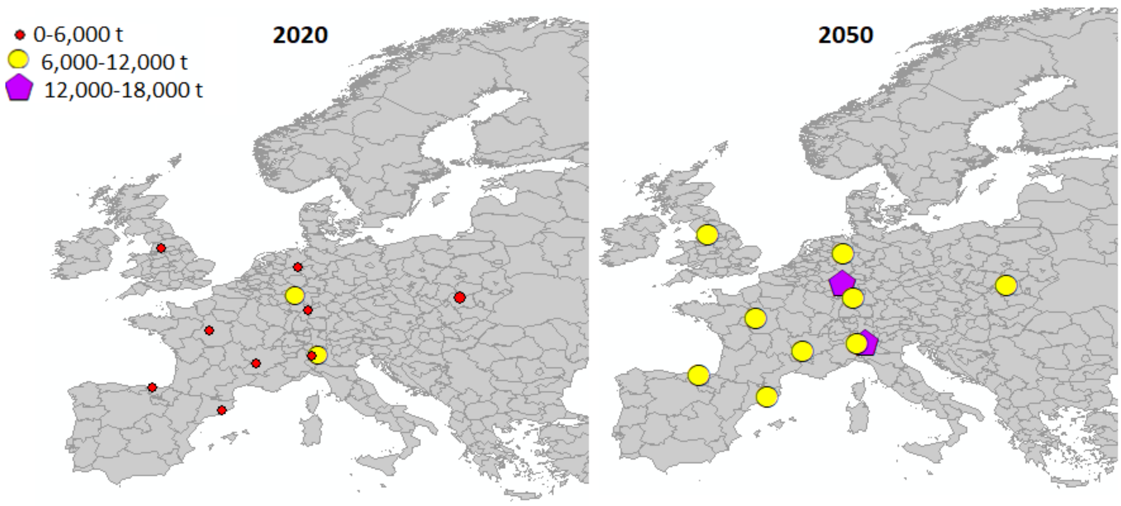

Figure 2. Recycled GF demand from SMC/BMC manufacturers

4.2 Network assumptions

Regarding the reverse supply network nodes location, it was assumed that the explicit geographic location of the wind farms is at the centroids of the 254 Nomenclature of Territorial Units 2 (NUTS2) regions of EU-28 countries they belong to. This approach is based on a trade-off between achieving a relatively high granularity level while not prohibitively increasing the computational time of the optimisation, which would be an issue if the 23,353 existing wind farms were modelled independently. However, to minimise the error to the actual transportation distances introduced from this assumption, a weighted average distance per NUTS2 region was calculated from the wind farms to the exact centroid location and was subsequently added to the inbound transportation stage distance. The potential location of the recycling facilities is considered in a similar manner as the centroid of the NUTS2 regions. Finally, for the demand side, the exact location of the existing SMC/BMC manufacturers has been considered, assuming any future capacity increase will happen at the same locations.

Regarding the reverse supply network arcs, the actual driving distances between the different nodes of the supply network were estimated using ArcGIS and the network analyst tool. Only primary roads and motorways were considered, while for points that were not located near primary roads, their location was allocated to the nearest primary road. For the locations in islands, artificial routes were created to the port they are usually connected with. The ports considered are those listed in the Core and Comprehensive traffic network of the European Commission (EuropeanCommission, 2014), along with those explicitly assigned as suitable for offshore wind installing and maintenance (4Coffshore, 2019).

Only road transportation by truck is considered in mainland due to its flexibility that makes it ideal for the dispersed nature of the reverse logistics networks investigated. The transportation cost is estimated while considering the truck volumetric and weight capacity, the material density as well as the change of the material volume after processing. For scenario 1, AutoCAD was used to identify the optimum cutting size (pieces of 6-7m) and arrangement to fit the wind blades into containers. It is estimated that for one wind blade of 47m length, two trucks are needed carrying two containers each. However, for scenario 2 a walking floor truck was assumed for the pre-shredded material transportation, according to logistics experts.

Cutting on-site at the wind farm requires permissions with respective administrative costs, while this is not needed for in-plant treatment. The set up and administrative/permission costs for the on-site cutting are accounted once for each wind farm as a fixed cost.

It is assumed that the recycling facilities operate 4680 hours per year, therefore considering maintenance and downtime. The facility cost is estimated according to a scale factor derived from the literature for grinding equipment (0.65 according to Remer and Chai (1990)) and the reference capacity and operating costs are derived from industrial data (Table A.1 in supplementary material).

5. Numerical Results Analysis

In this section, the results from the optimisation for the two scenarios, which were defined in section 3, for both 2020 and 2050 are presented. Hereafter, the terms SC1-20 and SC1-50, will denote the scenario 1 for 2020 and 2050 respectively, whereas SC2-20 and SC2-50 will denote scenario 2.

The current waste disposal cost is considered as a revenue of the proposed circular economy pathway and is derived for 2020 for each country from current landfill gate fees (Fig. A1 in Supplementary material). Where landfilling is banned, the available alternative is considered, i.e. the gate fee for incineration in the cement industry. For 2050, GFRP landfilling is assumed to be banned everywhere and the only alternative for disposal is in cement kilns (gate fee: 155€/t). The input parameters used for the application are presented in Table A.1 of the supplementary material. The waste material and demand amounts are reported in Table 2.

Table 2. Material amounts in 2020 and 2050

	2020	**2050**
Total waste material	72,112 t	255,703 t
Total material after processing	68,536 t	243,021 t
Total demand	69,741 t	126,326 t
Model Type	Supply driven	Demand driven

5.1 Optimal supply network

The optimal processing facility locations and capacities for the two scenarios are presented in Table 3. Furthermore, the utilisation of the capacity of each facility is reported; it should be noted that utilisation of less than 100% of a facility's capacity is a result of the model selecting capacities from a set of predefined values, resulting in a total system overcapacity to meet the capacity availability constraint.

For both scenarios in 2020, 3 to 4 facilities of medium capacity are proposed in similar locations in central Europe and the UK, with favoured Germany and Spain. In scenario 1, larger facilities are selected compared to scenario 2 due to technological economies of scale. This is due to the fact that in scenario 2 the facilities cost is lower since the pre-shredding stage is already done on-site. In both cases, the utilisation of the capacity is quite high. Ultimately, the compromise between logistical costs and economies of scale leads to multiple facilities of size between 10,000 – 35,000 t yr^{-1} that are geographically located in the major hotspots of waste material availability.

For 2050, it is evident that the same number of facilities (four) with very similar capacities in the same countries are selected between the two scenarios. Therefore, no matter which scenario is adopted for the recycling process, the ideal supply chain network would be similar in terms of processing facility locations. In this case, the optimal solution proposes a large facility in Germany, and three small ones spread around Europe, covering the material availability hotspots.

Generally, from all combinations of scenarios and years, a trend is identified to have the largest facility in Germany; this is due to the high supply and demand in and around this country. In addition, smaller facilities in Spain are selected due to the SMC/BMC demand there. Finally, even though in 2020 the UK is not an optimal location, in 2050 it is proposed in every scenario. This is due the fact that the available waste in UK is expected to increase significantly in parallel to the SMC/BMC demand.

Table 3. Optimal facilities locations, capacities and utilisation

	Facilities location	**Capacity (t yr^{-1})**	**Capacity utilisation**
Scenario 1 2020	Spain	10,000	96%
	Germany	35,000	96%
	Switzerland	35,000	72%
Scenario 1 2050	Poland	10,000	96%
	UK	10,000	96%
	Spain	15,000	96%
	Germany	105,000	88%
Scenario 2 2020	Spain	10,000	96%
	UK	10,000	57%
	Italy	15,000	96%
	Germany	35,000	95%
Scenario 2 2050	Spain	10,000	96%
	UK	10,000	96%
	Poland	15,000	96%
	Germany	105,000	88%

In Figures 3-6 a graphic representation of the optimal material flows from (downstream) and to (upstream) the processing facilities is presented. On the upstream side (Figures 3 and 5), the bubbles indicate the NUTS2 centroid where the waste material is gathered, while the arrows link each NUTS2 centroid to the processing facility the waste material is sent to. Bubbles of the same colour indicate the catchment area of a specific processing facility. On the downstream side (Figures 4 and 6), the lines indicate the recycled material flows from a specific processing facility (circles) to a specific SMC/BMC manufacturer (triangles), with lines of the same colour indicating all flows from one specific processing facility.

In Figure 3, where the upstream material flows for scenario 1 are presented, it is evident that the two largest capacity facilities (Germany and Switzerland) have much larger waste material catchment areas compared to the facility in Spain. On the other hand, the supply flows in 2050 indicate a more local collection of material around all facilities, since the supply is higher than the demand, so not all the waste material needs to be processed; instead, selection of material from locations with high availability and low transportation distances is proposed.

Figure 4 presents the downstream side of the network flows for scenario 1. The facilities location is close to the SMC/BMC manufacturers and in some cases even in the same NUTS2 region. The larger facilities provide material to more than one customer while in many cases, the demand of one customer is fulfilled by more than one facility, indicating a complex supply network.

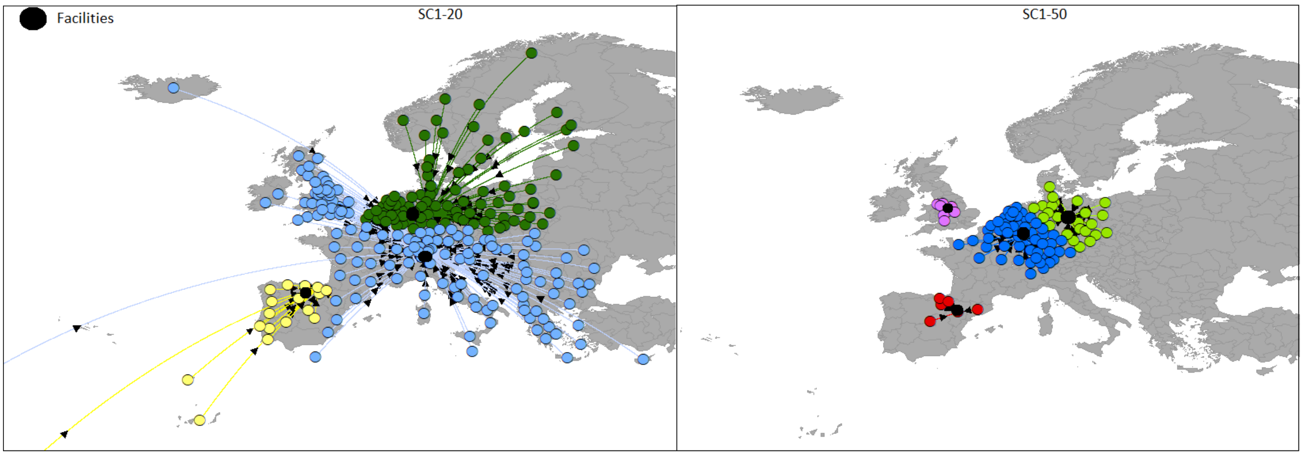

Figure 3. Optimal upstream network flow for 2020 and 2050 for Scenario 1

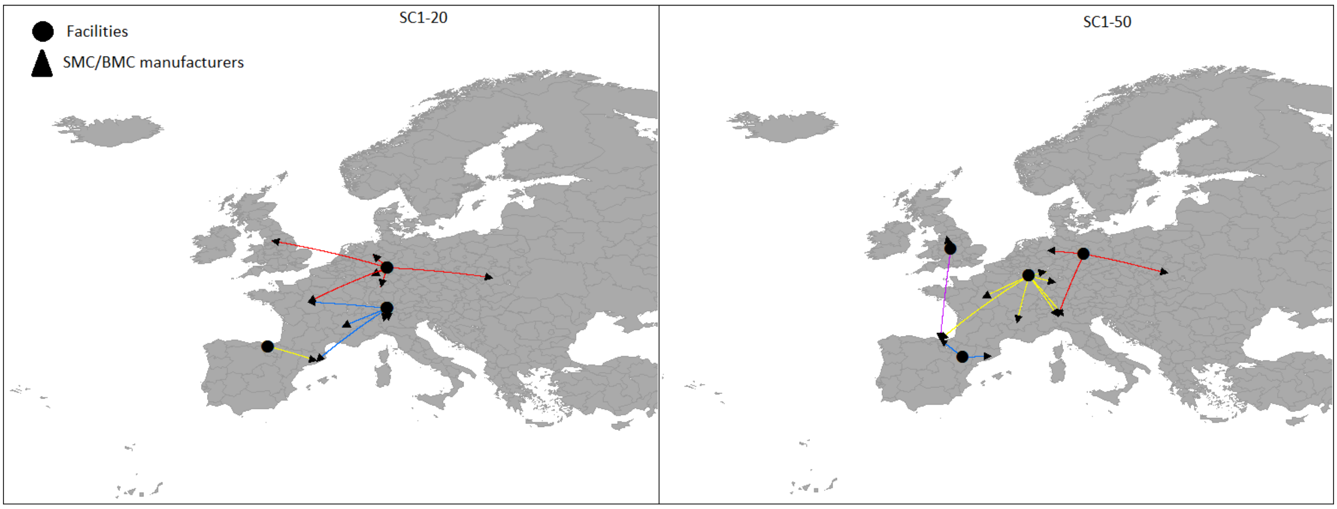

Figure 4. Optimal downstream network flow for 2020 and 2050 for Scenario 1

In Figure 5, the supply side of the network for scenario 2 is presented, whereas in Figure 6, the respective demand side. Similar observations with the scenario 1 can be made. The facilities location is almost the same, as well as the demand flows. The only difference is that in 2050 the demand in the UK is not satisfied completely from the facility in the UK but partly from the large facility in Germany. In addition, in 2050 it is more cost efficient to invest in a facility in Poland near the SMC/BMC manufacturer, reducing the transportation distances for the supply and demand flows, while the large facility in Germany covers the demand that in 2020 the facility in Italy did.

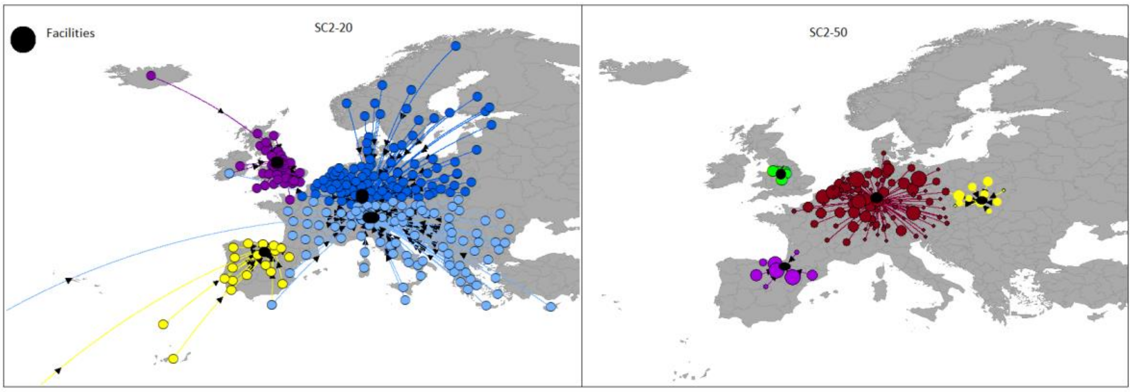

Figure 5. Optimal upstream network flow for 2020 and 2050 for Scenario 2

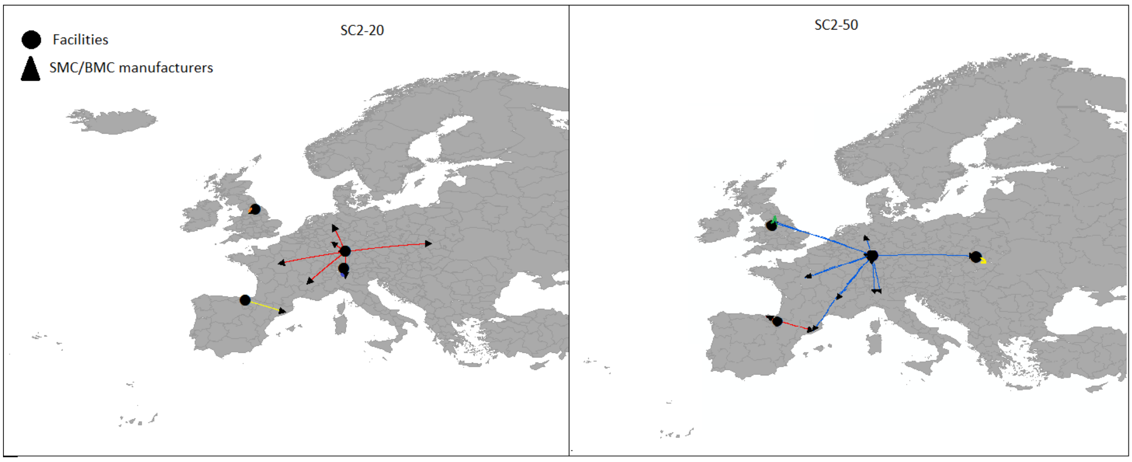

Figure 6. Optimal downstream network flow for 2020 and 2050 for Scenario 2

5.2 Economic Analysis

Figure 7 displays, for all combinations of scenarios and years, the annual revenues from avoided waste disposal, the annual total reverse supply network costs for implementing the material recycling alternative pathway, and their difference (i.e. the resulting total annual recycling system cost, before considering any potential income from selling the recycled material. This is expressed as ‘profit/loss before recycled material sales’).

The economic assessment of the optimal reverse supply networks indicates that the disposal revenues from avoiding landfilling or alternative disposal for each investigated year are the same for both scenarios since all the waste material is recycled in 2020 and the same alternative disposal cost is assumed for all countries in 2050 (Fig. 7).

In 2020, scenario 2 leads to lower recycling cost, whereas for 2050 the opposite holds true (Fig. 7). This can be attributed primarily to the much more significant difference between the transportation costs of the two scenarios in 2020 than in 2050 (see Fig. 8).

Finally, the total profit/loss for each scenario, considering the revenue from avoiding landfilling/disposal but before consideration of the recycled material sales revenue, is presented in Fig. 7. All scenarios exhibit a loss, indicating the need for additional income from selling the recycled material for the respective systems to be viable. SC1-50 exhibits the lowest loss, indicating the benefit from technological economies of scale and reduced logistics costs, due to more local waste collection areas. Both scenarios for 2050 have a lower loss, despite the significantly higher material volumes handled.

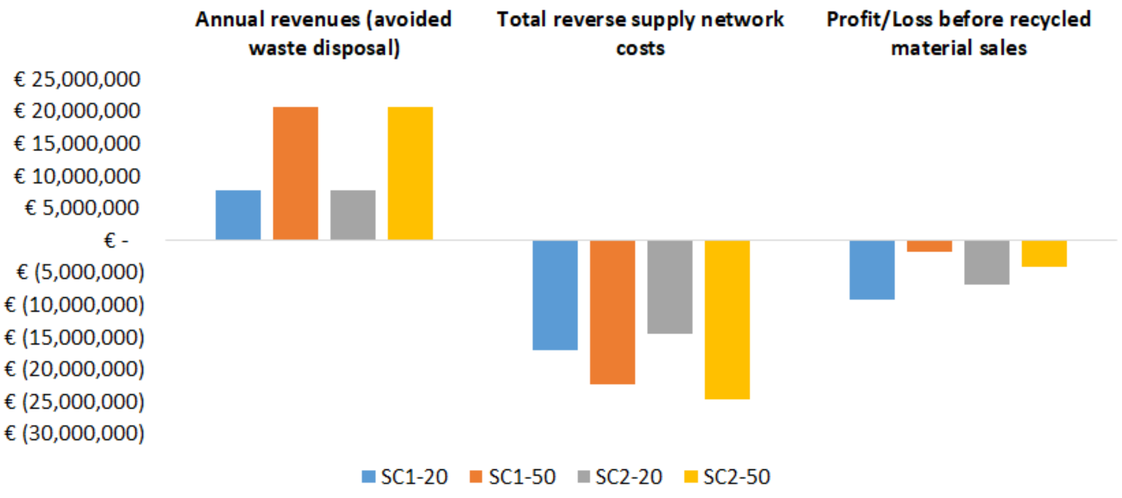

Figure 7. Economic analysis (annual values)

The breakeven recycled material price for each scenario has also been calculated, and is presented in Table 4. This represents the ultimate price of the end product in the market required in order for the whole system to breakeven. Most economically viable are the 2050 scenarios, with lowest price for scenario 1 in 2050. For benchmarking purposes, this breakeven price should be compared to the cost of materials currently being used as fillers in SMC/BMC, the most common of which is calcium carbonate ($CaCO_3$) (Lucintel, 2016) and whose commercial price can be as low as 50€ t^{-1} according to industrial sources. This means that with the current virgin filler material prices, both scenarios in 2020 would not be feasible, but both 2050 scenarios could be profitable.

Table 4. Breakeven prices for the scenarios

Scenarios	Breakeven price (€ t^{-1} product delivered)
SC1-20	134
SC1-50	14
SC2-20	98
SC2-50	32

In Figure 8, the cost breakdown for each processing stage is presented, to provide a better insight into the differences between the scenarios. It is evident that the shredding in plant costs increase with the amount of material. However, for scenario 2 the processing cost is lower compared to scenario 1 because the cost for pre-shredding is not included, since this process is performed on-site. In addition, there is no cost for second stage cutting since the material is pre-shredded.

The cutting on-site costs are much higher for scenario 2 as the wind blades are cut into smaller pieces (1-2m) in order to be prepared for the pre-shredder. Especially the personnel cost exhibits significant increase due to the high labour cost factor for operations at the wind farm. The pre-shredding on-site has a significant contribution to the total cost, even though it reduces the required investment at the processing facility.

Finally, the transportation cost in scenario 1 is much higher, especially the inbound, due to the density difference between the cut and pre-shredded blades, which leads to low utilisation of the transportation capacity for large blade pieces. The outbound transportation cost for scenario 2 is slightly lower than scenario 1 in 2020, as in scenario 2 the facilities are more decentralised and closer to the end users and waste material availability hotspots. The difference in total transportation cost between the two scenarios is much more profound in 2020 than in 2050, due primarily to the much smaller inbound transportation distances in 2050 stemming from more local collection of blade waste material.

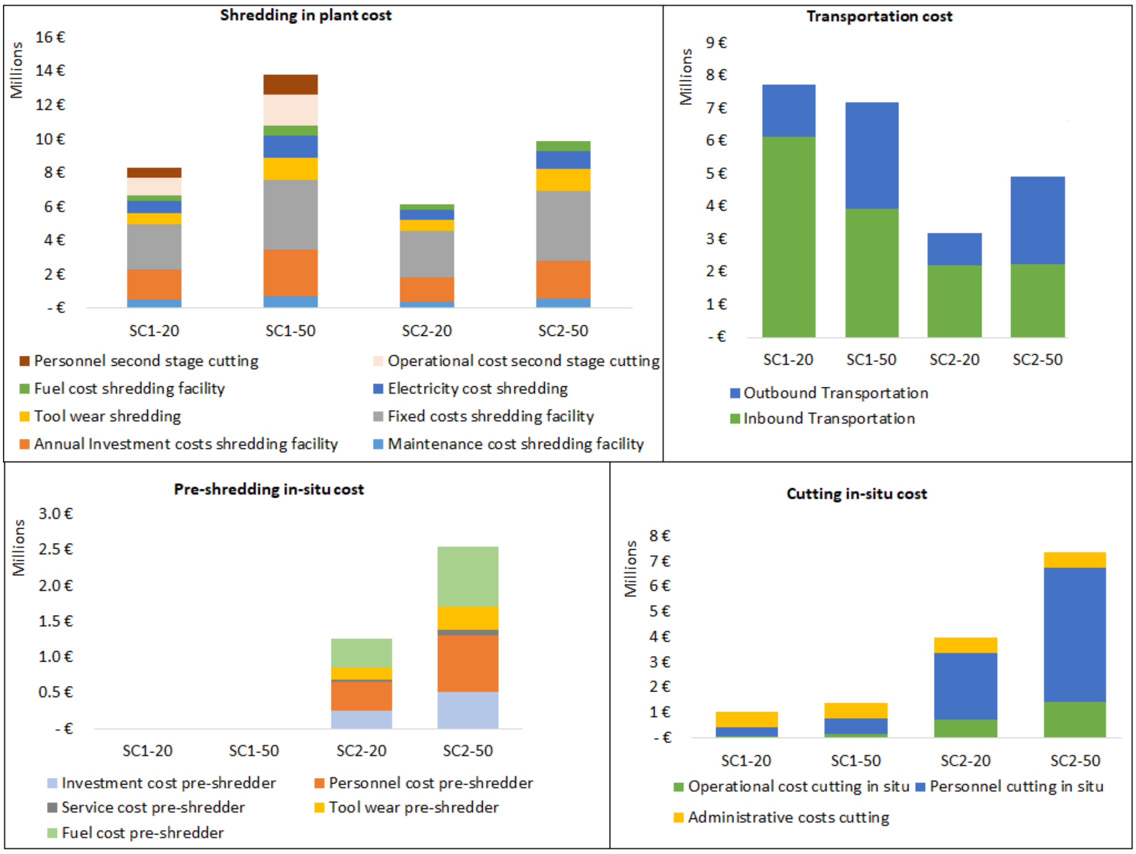

Figure 8. Annual cost breakdown per processing stage

5.3 Environmental Analysis

Despite the fact that the circular economy pathways discussed in this work are inherently sustainable, since they promote material recycling instead of landfilling, it is still interesting to understand the environmental impact – in terms of carbon footprint- from the reverse supply network scenarios implementation. In Figure 9, the carbon emissions per processing stage are displayed, for all scenarios investigated. The process that has the greatest contribution on the emissions is shredding, due to the respective electricity consumption.

It is worth noting that the transportation carbon emissions per tonne of material delivered decrease proportional to the material volumes, i.e. in 2050 they are lower compared to 2020. This is due to the fact that in 2020 all the material is pushed into the network, whereas in 2050 the model selects the closest wind farms locations to the facilities for the supply side, therefore reducing the transportation distance and the respective emissions. Ultimately, it can be concluded that location decisions for the processing facilities can significantly affect the carbon footprint of the whole network.

Another observation is that, despite the fact that SC1-20 has higher electricity consumption for shredding in plant than SC2-20 (where pre-shredding happens at the wind farm), the emissions of the former are lower. This is due to the different facility locations selected and the electricity emission factors that depend on the country. However, for 2050 where both scenarios have selected the same facility locations, scenario 2 has lower emissions from shredding electricity consumption.

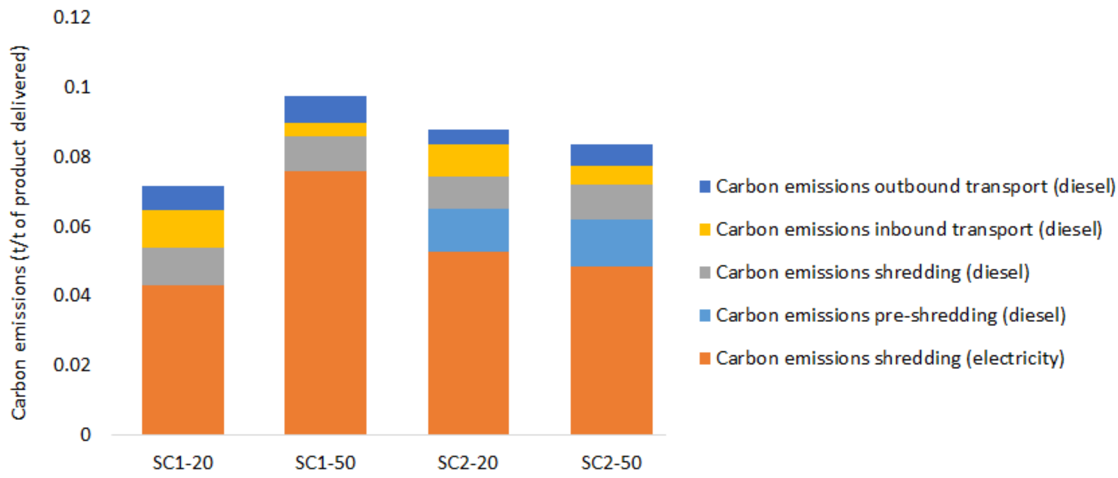

Figure 9. Carbon emissions per process stage

5.4 Sensitivity Analysis

In this section, a sensitivity analysis is performed on the cost of the optimal networks identified. The most uncertain parameters that are affected from market changes are considered, including the electricity price, the diesel fuel price and technologies cost. In addition, the density of the material transported is investigated because the values considered are derived from experimental assumptions or expert opinions and best practices on logistical aspects have not yet been established. All parameters are subject to a change of -20% and +20% of their base case values to investigate their impact. The base case values can be found in the supplementary material (Table A.1).

The sensitivity analysis results are presented in Figure 10, independently for each scenario. In all cases, the blade cut pieces density (inbound transport) has the greatest impact on the total cost with 20% density increase leading to 4%-6% total cost decrease, whereas the density decrease can increase the cost from 5%-8.5%. It is inferred that more compact transportation of the blades can improve significantly the reverse supply chain cost. On the other hand, the density of the shredded fibers (outbound transport) has a much lower impact on the cost. Another parameter that significantly affects the total cost is the technologies capital cost, with total cost reduction between 3.5% to 6% when capital cost is reduced by 20%. It is evident that the higher the investment the higher the impact it has on the total cost.

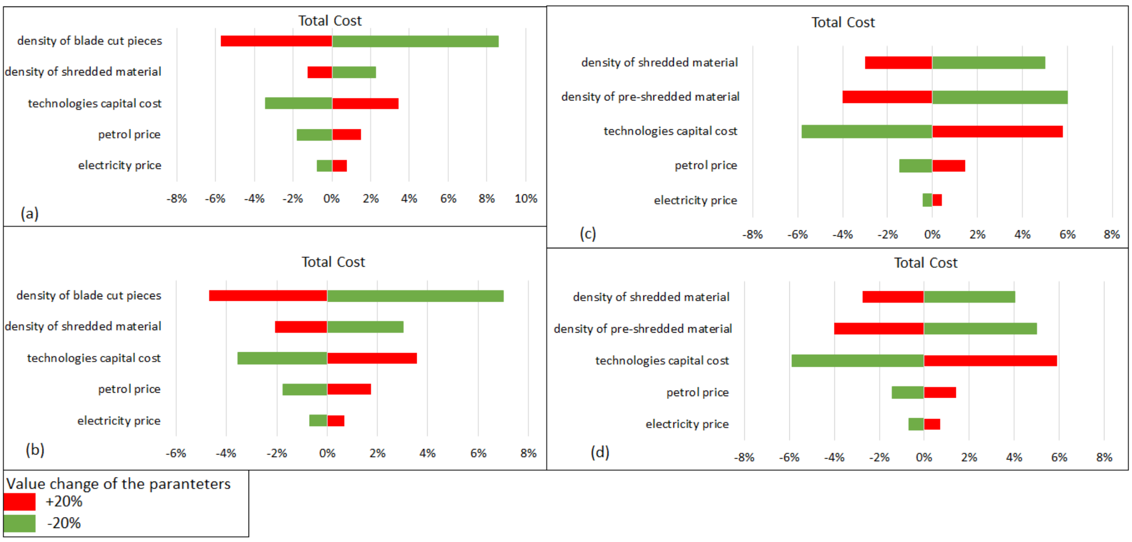

Figure 10. Sensitivity analysis: (a) SC1-20, (b) SC1-50, (c) SC2-20, (d) SC2-50,

6. Managerial Insights and Implications

The current work has significant implications both at managerial and policy making levels. Firstly, the investigation provides insights regarding a viable wind turbine EoL blades circular economy pathway. Assuming a market price in 2020 of virgin filler material of ~50 € t^{-1}, the circular economy pathways proposed would not be viable without any additional support. In 2050, all scenarios lead to much lower breakeven recycled material prices compared to 2020, and the pathways can be viable without additional support, indicating that high volumes of available waste material will improve significantly the economics of the whole reverse supply network system and facilitate its viability.

Another key point is that the trade-off between larger facilities for ensuring economies of scale, versus the need for more decentralised network with more and smaller facilities to reduce the logistical costs, has no obvious solution. Therefore, modelling tools such as the ones used in this work can support a better understanding of these trade-offs and allow investigation of the impact of alternative scenarios, policies or forecasts.

In addition, it is apparent that some locations will incur a higher cost to move the waste material for processing, therefore incentives from the policy makers' perspective should be considered for the reverse supply system to include this more 'expensive' waste. Another important lever in the hands of policy makers is the disincentives for alternative waste disposal pathways, such as landfilling or energy recovery. The revenues from not disposing the waste had a great impact on the optimal reverse supply networks. Thus, if policy makers ensure that the alternative options that divert the material from the circular economy become more expensive, they would automatically support the development of such recycling networks for reuse of the GFRP.

Moreover, the carbon footprint of the reverse supply chain depends highly on the location of the recycling facilities. This is due to the various carbon emission factors from electricity of the countries. In our model, the objective function represents only annual reverse supply network costs; however, if the carbon emissions were considered then the countries with the lower carbon emission factors would be more likely to be selected for locating recycling facilities, especially if carbon emissions were incurring a cost. Furthermore, in this work it has been assumed that the emission factors of 2050 will be the same as in 2020. However, the ongoing decarbonisation of electricity generation will likely reduce significantly the emissions per unit of product, therefore the values provided for 2050 in this work should be considered as worst case scenarios. The findings do point out though that locating the processing facilities in countries with low electricity emission factors is the key to reducing the carbon footprint of the waste recycling systems, since this is the major emissions source in the 2020 scenarios.

Another conclusion is that the optimal supply networks comprise of processing facilities large enough to require input material from several countries. This means that if the aim is to minimise the recycled end product cost, movement of waste and recycled material between countries should be allowed and any existing barriers removed, which is a key take away message for policy makers and regulators. For a successful circular economy approach, a change of perspective from ‘waste’ to ‘valuable raw materials’ for the EoL wind blades should be adopted.

Finally, it was also observed that FRP are generally materials with low density, which is not ideal for achieving logistical efficiencies. Despite the fact that there was not one approach identified as best, in most cases increasing the transported material density significantly reduces the overall system cost, as identified in the sensitivity analysis. Therefore, this issue would require further research and significant attention, in order to bring the costs down. Still, one would need to consider the whole network before focusing only on the logistics efficiency in a part of the network, as it was shown that increasing the transportation efficiency by pre-shredding at the wind farms ultimately may come at a disproportional cost due to the additional operations in remote locations.

7. Conclusions and Future Research

In this work a novel MILP optimisation model was presented, aiming to identify the optimal reverse supply chain network design specifically for EoL wind turbine blades. The model was applied to the context of the EU-28 to allow understanding how a circular economy-enabling supply network for waste material from EoL wind turbine blades might evolve in the future in Europe. The optimal processing facility locations and capacities, as well as the material flows between the various supply network stages were identified for two potential supply chain scenarios. The environmental impact of each network in terms of direct CO_2 emissions was also assessed. The optimal supply network identified is generally semi-decentralised, but still facilities should receive material in most cases from more than one country. Even with the optimal supply network, ultimately the breakeven price required for the recycled material is marginally competitive to the currently used virgin filler materials for the 2050 scenarios, and uncompetitive for the 2020 scenarios.

For future research, other end users for the recycled material should be identified, beyond SMC/BMC manufacturers considered in this work. In the 2050 scenarios, supply was higher than demand, thus revealing the need for identifying other applications for the recycled material. Additionally, the model could include also the CO_2 emissions in the objective function, in order to identify solutions that minimise the supply network carbon emissions together with the costs. Finally, it is worth noting that the models were developed as deterministic, whereas the parameters employed (amount of waste, demand, cost factors) are characterised by uncertainty in real life. In future work, the models could be extended to stochastic, therefore optimising the supply chain network under parameters uncertainty.

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Declaration of interest

There are no relevant financial or non-financial competing interests to report.

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Appendix 1

Nomenclature

Sets:

Symbol	Description
c	potential customers c=1..C
f	aggregated waste material suppliers f=1..F
l	potential facility locations (NUTS2 regions centroids) l=1..L
ps	processing stages (cutting in situ, shredding in plant) ps=1..PS
s	potential plant sizes s=1..S
st	storage stages (before processing in plant, after processing in plant) st=1..ST
w	wind farms w=1..W

Parameters:

Symbol	Description	Unit
an	annuity factor	(-)
Cfs	setting up and permit cost for blade cutting in each farm	(€)
Ci	total facility investment cost	(€)
Cm	total facility maintenance cost	(€ yr^{-1})
Cmf	total fuel cost for forklift machinery	(€ yr^{-1})
Cmi	total investment cost for forklift machinery	(€ yr^{-1})
Cof	total facility fixed operational cost: insurance and labour cost	(€ yr^{-1})
Cov_0^c	total variable operational cost from pre-processing of waste (cutting in situ): labour, tool wear and energy consumption	(€ yr^{-1})
Cov_0^{ps}	total variable operational cost from pre-processing of waste (pre-shredding in situ): energy consumption, tool wear, service cost, personnel cost, investment cost	(€ yr^{-1})
Cov_1^c	total processing variable operational cost in the facility (second-stage cutting): energy consumption, tool wear and personnel	(€ yr^{-1})
Cov_1^s	total processing variable operational cost in the facility (shredding): energy consumption and tool wear	(€ yr^{-1})
Cst	total storage cost	(€ yr^{-1})
Ctin	total waste transportation cost from all suppliers to the facility	(€ yr^{-1})
Ctout	total product transportation cost from facility to the customers	(€ yr^{-1})
Cap_s	processing capacity of plant size s	(t of input waste yr^{-1})
cdf	cost of diesel per country or region	(€ l^{-1})
$cdisp_f$	cost of disposing waste (per supplier location)	(€ t^{-1} of waste material)
ce_l	cost of electricity (per facility location)	(€ kWh^{-1})
cfps	fuel consumption of pre-shredder	(l t^{-1})

ci_s	investment cost for plant size s	(€ t^{-1} of capacity)
$cins_s$	insurance cost for plant size s	(€ yr^{-1})
cips	investment cost for pre-shredding	(€ t^{-1} of capacity)
cm_s	maintenance yearly cost for plant size s	% of original investment
cmins	insurance cost for forklift machinery	(€ yr^{-1} t^{-1} plant capacity)
cmf	fuel consumption for forklift machinery	(l yr^{-1} t^{-1} plant capacity)
cmi	rental cost for forklift machinery	(€ yr^{-1} t^{-1} plant capacity)
$co2ee_l$	electricity carbon emissions factor per country	(g CO_2 kWh^{-1})
CO2el	electricity carbon emissions for facility	(t_{CO2} yr^{-1})
$CO2fu_{o1}$	carbon emissions from fuel combustion from pre-shredder operation	(t_{CO2} yr^{-1})
$CO2fu_{o2}$	carbon emissions from fuel combustion from facility operation	(t_{CO2} yr^{-1})
$CO2fu_{\_t}$	carbon emissions from transportation	(t_{CO2} yr^{-1})
co2t	carbon emissions cost	(€ t_{CO2}^{-1})
coc	variable cutting operating cost (tool wear and electricity) for waste processing in situ	(€ t^{-1} of material processed)
cocf	variable cutting operating cost (tool wear and electricity) for waste processing in the facility	(€ t^{-1} of material processed)
coe	variable electricity consumption for waste shredding	(kWh t^{-1} material processed)
colc	variable cutting labour cost	(€ t^{-1} material processed)
cols	fixed operating personnel cost for processing facility	(€ t^{-1} plant capacity)
$conv_{ps}$	Material conversion efficiency of processing stage ps	(%)
cos	variable shredding operating cost (tool wear)	(€ t^{-1} material processed)
cpps	personnel cost for pre-shredding	(€ t^{-1} material processed)
cpcf	personnel cost for cutting in the facility	(€ t^{-1} material processed)
$cper_w$	permit cost for blade cutting in one farm	(€)
csps	service cost for pre-shredding	(€ t^{-1} material processed)
$cset_w$	set up cost for blade cutting in a farm	(€)
cst_{st}	Storage cost at storage stage st	(€ t^{-1} plant capacity)
cwps	tool wear cost of pre-shredding	(€ t^{-1} material processed)

$d1_f$	Average first stage distance between material availability location and aggregated material supplier location (for each NUTS2 region)	(km)
dem_c	Material demand of customer c	($t\ yr^{-1}$)
df	Discount rate	(%)
$dfl_{f,l}$	Second stage distance between aggregated material supplier f and plant l	(km)
$dlc_{l,c}$	distance between processing plant l and customer c	(km)
efd	carbon emission factor for diesel	($g_{CO2}\ l^{-1}$)
F	total annual cost of the reverse supply network	(€)
fct	fuel consumption of full load heavy duty truck	($l\ t^{-1}\ km^{-1}$)
Rdisp	revenues from avoiding disposing waste from waste supplier	(€ yr^{-1})
sup_f	waste available at supplier f	($t\ yr^{-1}$)
tcin	Unitary cost of waste inbound transportation from suppliers to processing facilities: labour, insurance, maintenance	(€ $t^{-1}\ km^{-1}$)
tcinf	Unitary cost of waste inbound transportation from suppliers to processing facilities: fuel	(€ $t^{-1}\ km^{-1}$)
tcout	Unitary cost of recycled product transportation from processing facilities to customers: labour, insurance, maintenance	(€ $t^{-1}\ km^{-1}$)
tcoutf	Unitary cost of recycled product transportation from processing facilities to customers: fuel	(€ $t^{-1}\ km^{-1}$)
Y	useful life of operation	(yr)

Decision Variables:

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

Supplementary material

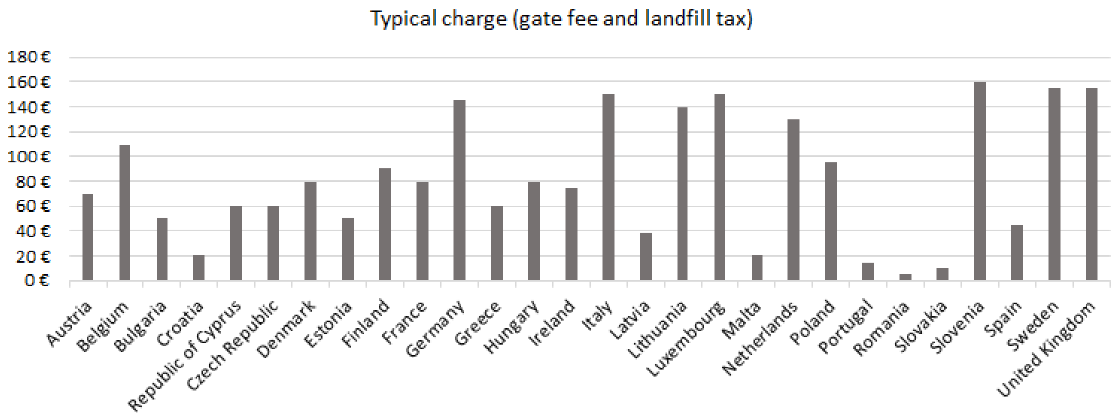

Figure A1. Typical charges of gate fee and landfill tax per country

Table A.1

Input parameters for the application

Stage	Description	Value
Cutting in situ	Set up cost	1,000 € per farm
	Permit for processing	1,000 € per farm
	Personnel cost on-site	36.74 € t^{-1}
	Operational cost (except personnel)	10 € t^{-1}
	bulk density of the cut pieces of blades (length 6-6.5 m)	87.25 kg m^{-3}
	yield factor	0.99
Shredding in situ (mobile facility)	diesel consumption	6.02 € t^{-1}
	service cost	0.57 € t^{-1}
	tool wear cost	2.3 € t^{-1}
	personnel cost	5.5 € t^{-1}

Stage	Description	Value
Shredding in plant	Investment cost for a facility with annual capacity 15,000t (scenario 1)	2,880,000 €
	Investment cost for a facility with annual capacity 15,000t without pre-shredding (scenario 2)	2,340,000 €
	electricity consumption (scenario 1)	128.7 kwh t^{-1}
	electricity consumption without pre-shredding (scenario 2)	102.96 kwh t^{-1}
	tool wear	10 € t^{-1}
	discount rate for a facility	10%
	density of fibers after shredding	645 kg m^{-3}
	Range of facility capacities options	10,000/15,000/35,000/70,000/105,000 t yr^{-1}
	storage cost	14.4 € t^{-1} of facility capacity
	maintenance cost	4% of investment cost yr^{-1}
	rental cost of forklift	4.55% of facility investment cost yr^{-1}
	forklift fuel consumption	3.54 l yr^{-1} t^{-1} of facility capacity
	forklift insurance cost	0.22% of facility investment cost
	personnel cost	21.2 € yr^{-1} t^{-1} of facility capacity

Stage	Description	Value
Transportation	Container truck capacity	40 m^3 volumetric & 24 t weight
	Walking floor truck capacity	90 m^3 volumetric & 23 t weight
	inbound transportation cost (scenario1)	0.223 € t^{-1} km^{-1}
	inbound transportation cost (scenario2)	0.048 € t^{-1} km^{-1}
	outbound transportation cost	0.048 € t^{-1} km^{-1}
	saturation ratio Vreal/Vnet of shredded fibers	1.1
Others	percentage of GF in wind blades	82%
	diesel carbon emission factor	2640 g_{CO2} l^{-1}
	diesel price for each country	average price of 2019
	electricity cost for each country	prices for medium size industries (for year 2017)
	emissions from electricity per country	carbon intensity of electricity traded with upstream after pumping and own use for 2018 source: (Moro and Lonza 2018)