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Research article

Enhancing circularity in the car sharing industry: Reverse supply chain network design optimisation for reusable car frames

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ABSTRACT

The transportation sector is a great contributor of global carbon emissions, thus technical, regulatory, and behavioural efforts are being made to move towards more sustainable mobility, reducing the sector's environmental impact. Among the proposed solutions, car sharing is an appealing alternative for both environmental and societal reasons. However, society is facing another challenge with the rapid increase of vehicles that have reached the end of their life. As a result, regulatory initiatives drive car manufacturers towards a circular economy paradigm that incorporates reuse, remanufacturing and recycling processes in their supply chains. This work proposes and optimises the design of a reverse supply chain that enables circular economy pathways for the automotive sector with particular focus on car sharing vehicles' components that are reusable. Car sharing vehicles are selected due to their high mileage, short service life and rapidly increasing demand. This is the first work that identifies optimal reverse supply chains for reusable car sharing vehicle parts. The particular investigated case study involves a reusable and remanufacturable carbon fiber reinforced polymer car frame, which is selected due to its long-life span and light weight properties. The results indicate that the per unit and overall system cost is minimised when the percentage of frames remanufactured increases, thus efforts are required regarding the design of frames with remanufacturability in mind. The impact of economies of scale in cost reduction is demonstrated. Finally, the reusable frame appears to be advantageous compared to the single use one both environmentally and economically.

1. Introduction

In recent years, focus has been placed on sustainable mobility and efforts have been made to improve the environmental sustainability of the transportation sector (Holden et al., 2019). Following the zero carbon emissions initiative, European and global targets have been placed in order to reduce the emissions from the transportation sector by 2050 by >60% compared to the 1990 levels (EuropeanCommission, 2020). Transportation sector is one of the most significant final consumers of total energy and contributors to global emissions (Solaymani, 2019). Specifically, the transportation sector contributed >37% of the global carbon emissions emitted from the end-use sectors (transportation, industry and residential) in 2020 (IEA, 2021). It is the second most polluting sector in Europe (Tiseo, 2021) and it was estimated that it contributed 27% of the total greenhouse gas (GHG) emissions in Europe in 2017, with a 2.2% increase compared to the previous year (European Environment Agency, 2019). In the literature there has been great attention to quantify and improve the carbon footprint of the transport sector, with special focus being placed on the urban public sector (Ghate and Qamar, 2020; Yang et al., 2016) or freight transport (Bínová et al., 2021; Galati et al., 2021). In specific, authors have adopted methods such as Life Cycle Assessment (Ghate and Qamar, 2020) or multi-criteria decision making (Yang et al., 2016) to quantify the environmental benefits of different public transport projects in order to improve the urban sector sustainability. Others discuss the benefits of electric freight vehicles for the carbon footprint reduction derived by freight transport (Galati et al., 2021) or introduce a life cycle approach to quantify the emissions from road freight transport (Bínová et al., 2021).

Passenger vehicles alone constitute approximately 12% of the CO_2 emissions, which is the main greenhouse gas, in Europe (EuropeanCommission, 2019). Therefore, it is imperative to reduce the emissions from passenger vehicles in order to achieve the aforementioned European targets (Zhou and Kuosmanen, 2020). There are four main approaches in order to achieve this: technical, legislative,

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behavioural or infrastructure-related solutions (Temenos et al., 2017). A variety of options are being considered in order to improve the environmental impact of passenger vehicles in the transportation sector, such as technological improvements with focus on electric vehicles as well as behavioural changes: cycling, walking or shifting the form of ownership (Svennevik et al., 2021).

The latter solution is highly promoted and a shift in the form of ownership from 'owning car' to 'being mobile' is observed (Enzi et al., 2021). Car sharing appears as a prominent solution in this regard (Temenos et al., 2017), since it promises a reduction on distance driven (Svennevik et al., 2021) and as a result on the emissions (Goldman and Gorham, 2006). Car sharing has been first introduced in 1948 and since then it has experienced significant growth (Nansubuga and Kowalkowski, 2021). It is defined as 'a vehicle access scheme, usually delivered by a digital platform, which allows and facilitates communal rather than private access to a pool of vehicles distributed in the city for personal use' (Amatuni et al., 2020). Car sharing is a service that allows customers to reserve a vehicle by the hour conveniently by their phone or computer (Goldman and Gorham, 2006), offering both one or two way renting system (Boyacı et al., 2015). There are different business models developed for car sharing, varying on the duration of rent, vehicle type, destination, organisational ownership and others (Remane et al., 2016).

Recently, car sharing has become even more appealing and popular due to the fact that major industrial players have introduced the possibility to be able to leave the car anywhere in the city and not just in predefined spots (Ramos et al., 2020). It is estimated that 2095 cities worldwide have this service (Phillips, 2018). Globally, there is a fleet size of >157,000 vehicles, with Asia constituting 40% of the market and Europe 37% (Phillips, 2018). In addition, a 24% mean annual growth is expected in Europe between 2021 and 2027 (GraphicalResearch, 2021). Car sharing experiences great interest in some countries, as in the United Kingdom with an estimated market increase of 10% from 2020 to 2025 (Medica, 2020).

The reason for the rising popularity of car sharing lies in the following: it is a sustainable solution (Münzel et al., 2020) that mitigates carbon emissions, it reduces the need of each individual to have a private car, and it reduces demand for parking areas (Ramos et al., 2020). Therefore, it is a feasible solution both for environmental and societal issues in dense urban areas. It is estimated that the introduction of car sharing just in Ireland could lead to annual reduction of 895 kt CO_2 emissions (Rabbitt and Ghosh, 2013). Similarly, it is forecasted that a wider adoption of shared mobility could lead to 30% carbon emissions reduction in urban areas by 2050 (OECD, 2019). This is apprehended by the users and the environmental as well as the economic incentive of car sharing services has a very important role in selecting them (Mattia et al., 2019; Prieto et al., 2019). Furthermore, other benefits are that it gives the opportunity for users to use trendy and fuel efficient cars (Goldman and Gorham, 2006); even more so in the cases where regulations mandate to have an environmentally friendly car. Finally, car sharing offers advantages regarding the reduction in traffic in urban centres as well as the resources used (Seign et al., 2015).

On another sustainability front, a high increase on waste products' volume has been observed in the last decade (Chen and Chen, 2019), which is a result of the continuous growth of the economy as well as the decrease of most products' life (Mao et al., 2021). In response to that, governments and regulatory bodies have adopted policies to reduce the accumulating waste. A waste treatment hierarchy has been proposed with reuse and recycling being prioritised, whereas landfilling is the last option (EuropeanCommission, 2008). Specifically in the automotive industry a rapid increase of the number of End-of-Life (EoL) vehicles is observed, and it was estimated that in 2018 > 6 million passenger cars and light goods vehicles were scrapped in Europe (Eurostat, 2018). Various incentives have been initiated regarding the vehicles' EoL treatment (ELV Directive 2000/53/EC) in order to support this waste treatment hierarchy; the European Union (EU) directive stresses that 'new vehicles may only be sold in the EU if they may be reused and/or recycled to a minimum of 85% by mass or reused and/or recovered to a minimum of 95% by mass' (EuropeanCommission, 2000).

As a result, these initiatives have greatly impacted car manufacturers, who are moving towards a circular economy paradigm, defined as a 'regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops' (Geissdoerfer et al., 2017). Therefore, original equipment manufacturers (OEMs) are incorporating reuse, remanufacturing and recycling processes in their supply chains, thus moving towards more circular supply chains compared to the traditional linear paradigm that considered the resources availability as 'unlimited' (Martins et al., 2021).

This shift towards circularity entails the introduction of cars that could be easier to upgrade, repair, maintain, in addition to dismantle at their EoL in order to recover the parts/materials of value (Martins et al., 2021). It is important that OEMs consider, along with the cost of car parts production, the cost associated with the EoL of the car in accordance to the ELV directive (Anthony and Cheung, 2017). Therefore, new design guidelines are introduced promoting the reuse, remanufacturing and recycling concepts from the early phases of the product design (Bovea and Pérez-Belis, 2018). As a result, the need arises for circular pathways that consider designing cars with components that are 'easily repaired, changed, or adjusted using the minimum effort' (Martins et al., 2021). It is also supported that OEMs need to take into consideration the different materials employed and their environmental impact (Gallimore and Cheung, 2016), throughout the car's lifetime and thus aim for design for sustainability (McAuley, 2003). Additionally, car sharing has been acknowledged as a business model that can improve the Reuse, Recycling and Recovery performance of the sector, due to increased resource monitoring, control of parts and materials and resource reclamation (Despeisse et al., 2015).

Therefore, the aim of this work is to propose and optimise a reverse supply chain network design for the automotive sector that enables the shift towards circular economy pathways and introduces reuse, remanufacturing and recycling in the supply chain. The work focuses on vehicles used for car sharing services due to their aforementioned increasing demand, unique requirements and interest in more sustainable and efficient technologies. Another favourable characteristic is their very high mileage in conjunction with short service life that leads to car parts with significant remaining life after the vehicle's EoL. Finally, car sharing vehicles are also promising in terms of investigating their reverse supply chain design, since access to them at the EoL could be facilitated by the fact that there are few stakeholders involved in their ownership and management compared to privately owned cars (Despeisse et al., 2015).

The attention is placed on car components that are reusable or easily remanufactured, such as structural parts, which have a longer life than the short service life of the car sharing vehicles, thus rendering their reuse and remanufacturing an attractive solution to enhance the circularity in the automotive sector. The specific part selected for the analysis is a car frame designed for electric vehicles, since it is one of the largest, heaviest (Haberling and Heil, 2015) and most valuable parts, that does not deteriorate significantly within the lifecycle of a car. In addition, it is a part that could be used in different car models, especially nowadays with many of the new electric cars sharing the same key components, such as the frame. The proposed model could be potentially expanded to other reusable parts. The material proposed for the reusable frame is Carbon-Fiber Reinforced Polymer (CFRP) due to its long life and light weight properties; however, the method proposed can be applied for any reusable car component and car type.

The method entails developing a three-tier optimisation model for the reverse supply chain network design that contains both existing and new actors of the reusable car frame value chain. An optimal structure of the proposed supply chain network is derived that minimises the system-wide costs for the current (2023) and future (2050) scenarios. These two points in time were selected, one in the near and one in the far future, in order to investigate the required evolution of the network, when more car sharing vehicles will be reaching their end of life. The geographical scope of this work is the United Kingdom, due to availability of relevant data and an emerging car sharing market. However, the model can be applied in any geographical context. This is the first attempt to propose a reverse supply chain network design optimisation model for reusable car parts of car sharing vehicles.

This paper is organised as follows. Section 2 discusses the relevant literature, whereas the proposed reverse supply chain network design is introduced in Section 3, along with the developed model. Section 4 reports and discusses the results of the model application. Finally, the conclusions are drawn in Section 5.

2. Literature review

The introduction of circular economy in the automotive industry has been gaining interest both from the academia and industry and efforts are made for the transition from linear to circular economy business models. In the literature, it is indicated that circular pathways display a high applicability potential in the automotive industry and the majority of the parts after the vehicle EoL could be introduced again in the forward supply chain (Chan et al., 2012). The extent to which circular economy approaches have been adopted depends heavily on the regulatory framework; for example, the EU (Saidani et al., 2019a) and Japan (Despeisse et al., 2015) are mentioned as examples of strong regulatory frameworks and existence of recycling and recovery targets, whereas in the US these do not exist (Saidani et al., 2019b). In some countries, such as India, the role that the informal sector can play in the success of circular economy in automotive has been acknowledged (Arora et al., 2019). Ultimately, the regulatory framework, industrial practices and local specificities currently affect the level of circular economy adoption in various parts of the world. While these affect the current practices, several authors have concluded that some best practices could be transferred between different countries (Despeisse et al., 2015; Saidani et al., 2019a). Attempts to assess the circular economy level include a framework focusing on the required key performance indicators in order to monitor the targets set for circular economy models in the automotive sector (Kanellou et al., 2021). On the other hand the barriers and drives to introduce circularity in the sector have also been investigated (Baldassarre et al., 2022; van Bruggen et al., 2022).

Several decision support tools for the circular pathways of vehicles have been developed in the literature. Cost breakdown models to assess the economic viability of various recovery processes have been developed (Anthony and Cheung, 2017; Coates and Rahimifard, 2006; Ladjouze and Rahimifard, 2004; Xu et al., 2014). A model was introduced to support decisions for China's EoL vehicles recovery system, considering recovery of steel, aluminium, coper and non-metal parts under different remanufacturing scenarios (Liu et al., 2020). The waste management of EoL vehicle batteries has been extensively discussed in the literature (Hua et al., 2021; Malinauskaite et al., 2021; Mayyas et al., 2019) investigating potential pathways to close the loop. The alternative between the reuse or recycling of a car battery was evaluated through a Life Cycle Assessment, highlighting the benefits of the former process (Kotak et al., 2021). On the other hand, potential circular economy pathways were discussed for the EoL electric vehicle batteries in Brazil, concluding that both recycling and remanufacturing are essential (Duarte Castro et al., 2021). In addition, the EoL vehicle recycling processes were investigated regarding their feasibility and economic challenges (Bellmann and Khare, 2000). A tool was proposed to evaluate the environmental and economic impact of remanufacturing, indicating that the remanufacturing of conventional car chassis has a clear environmental benefit (van Loon and Van Wassenhove, 2018). Along the same lines, the vehicle engine remanufacturing was assessed in comparison with recycling in respect to material losses, concluding that remanufacturing has more positive impact (Zhang et al., 2021). Finally, the percentage of a catalytic converter in the automotive sector that could be reused was estimated and the environmental and economic repercussions of not reusing it were quantified (Saidani et al., 2019b). Therefore, the economic and environmental benefits of introducing waste recovery options for whole or parts of EoL vehicles were observed. It is highlighted that in many cases reusing and remanufacturing are more advantageous than recycling.

At the same time, a need arises for identifying methods to optimise the waste management of EoL vehicles. Review studies on waste management methods in the automotive industry indicate that focus has been placed on life cycle assessment approaches, whereas there were limited cases where a mathematical optimisation model was developed and in the majority of these cases, linear programming methods were used (Karagoz et al., 2020). Therefore, the need for optimisation models to facilitate the management of EoL vehicles is highlighted.

Furthermore, focus has been placed on developing a viable reverse supply chain for the EoL vehicles. Researchers have attempted to identify a cost and time efficient disassembly sequence (Go et al., 2011) since it is considered a significant step for the automotive recycling (Yu et al., 2017). Network graphs were used to optimise the disassembly of car parts by employing the shortest path problem (Yu et al., 2017). Furthermore, the disassembly decision making process was optimised for electric vehicle batteries, with environmental and economic considerations (Alfaro-Algaba and Ramirez, 2020). The evaluation and optimisation of the dismantling process of EoL automotive transmission has been proposed in order to support the recycling process of the waste product (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). Similarly, location-allocation problems were developed for the optimisation of the collection points location in Mexico (Cruz-Rivera and Ertel, 2009), and the car dismantlers location in Poland (Gołębiewski et al., 2013). It is evident that in the aforementioned literature only specific stages or processes of the reverse supply chain have been investigated. However, it is supported that the most important issues that need to be addressed when optimising the reverse supply chain of the EoL vehicles are the position of the additional collecting points and dismantlers as well as the routes of the material flow (Ahn et al., 2005). Thus, it is significant to consider the whole reverse supply chain, when attempting to close the loop in the automotive industry.

As a result, some researchers have attempted to model and optimise the whole reverse or closed-loop supply chain of specific car parts. An optimisation model for the reverse supply chain of EoL batteries has been proposed, with consideration of three battery handling strategies, such as recycling, remanufacturing, and disposal (Wang et al., 2020) while also considering government subsidy (Gu et al., 2021). A closed-loop supply network for the plastic parts of EoL vehicles in Germany was proposed with focus on recycling and landfilling (Schultmann et al., 2006). A linear optimisation model was developed to optimise the closed loop supply chain of EoL cars in Turkey, focusing on all the car parts of a conventional vehicle, whilst considering both recycling and landfilling (Özceylan et al., 2017). The closed loop supply chain of cast products in automotive in Iran was optimised with consideration of the uncertainty of the various inflows (Shahparvari et al., 2021). The location allocation optimisation of EoL vehicles considering the basic parts of the car was developed for China (Xiao et al., 2019) and Turkey (Yildizbaşi et al., 2018) with considerations of the carbon emissions.

The existing literature indicated the need for developing methods to assess the benefits of circular economy pathways for EoL vehicles, which are critical in order to facilitate the shift from linear business models. Various waste recovery options for automotive parts have been assessed and it was supported that reuse and remanufacturing have a better environmental and economic impact than recycling.

Thus, the importance of optimising the waste management options for EoL vehicles was highlighted and the development of various reverse supply chain models was reviewed. It was indicated that a great part of the literature focuses on specific stages of the reverse supply chain, such as disassembly; however, it was derived that the whole supply chain should be considered. The existing models developed to optimise the whole reverse or closed-loop supply chain of specific car parts were reviewed. However, despite the great interest on the fate of vehicles after the end of their service life, no studies were found focusing on proposing feasible reverse supply chains for car parts that are built to be reused, especially for the car sharing vehicles that have a very short service life and high utilisation. Hence, the main contribution of this research is twofold; firstly, developing an optimisation model for reverse supply network design with focus on innovative parts made to be reused and secondly, investigating the feasibility of such a network in a case study in the UK specifically for car sharing vehicles, to facilitate decision making and informing policy.

3. Methods

In this section, the proposed reverse supply chain network of a reusable CFRP car frame is introduced and the respective mathematical model developed for the network design optimisation is presented.

3.1. Problem description

In recent years, attention is placed on including lightweight materials for the vehicle structural parts (Zhang et al., 2020) and specifically CFRP parts on the car body (Ahmad et al., 2020; Solvay, 2018). CFRP is preferred due to its long life span (Yang et al., 2012) and light weight properties (Roberts, 2007), thus being able to support fuel energy consumption reduction and, as a result, carbon emissions reduction (Li et al., 2016). It is estimated that a reduction of the vehicle weight by 100 kg results in approximately 20 g/km CO_2 emissions reduction (Ishikawa et al., 2018). For this reason, a steep increase in the use of CFRP in the transportation industry is observed and it was estimated that specifically in the automotive, the use of carbon composites constitutes 24% of the global use of the material (Witten et al., 2018) with a rapid growth being acknowledged (Zhang et al., 2020).

The reverse supply chain network investigated in this work is based on a proposed scenario of using CFRP frames for electric car sharing vehicles. The reverse supply chain is driven by the fact that car sharing vehicles have a short service life and usually the damage on the car frame is minor after the vehicle EoL. As a result, the frame would be inspected and either reused directly, remanufactured and then reused on another similar purpose vehicle or recycled at the vehicle EoL, depending on its condition. In addition, in the former cases the frame could be used independently on a different car model but with similar functionality. The network structure with the considered entities and their transportation links are presented in Fig. 1. The boundaries of the system investigated in this work are depicted with the red line.

The core supply streams of the system are the car sharing companies providing EoL vehicles. New entities are introduced, i.e. the repair/remanufacturing facilities, with the skills and the equipment to disassemble, inspect, repair and reassemble the CFRP frames, as this is a process that currently does not exist. The other parts of the car are then distributed to the specialised entities and they are out of the scope of this work. The repair/remanufacturing facilities receive the EoL cars, with the granularity level of their potential location assumed to be the main towns and cities. Therefore, all car sharing spots are aggregated to the centroid of the respective main towns and cities. This assumption was made due to the trade-off between the number of potential sites and the computational effort for the optimisation. In the repair/remanufacturing facilities the car frame is dismantled to the level required, inspected, cleaned and then it is decided whether the frame should be reused with minor cleaning and repair, or remanufactured and reused, or recycled if not in good condition. The output of the first two options is either whole frames or parts re-assembled into whole frames, which are transported to the final tier of the reverse supply chain network, the existing car assemblers (OEMs), to be reused in new car assemblies. This is the point at which the repaired/remanufactured frame is re-introduced for reuse into the forward automotive supply chain. Since there is no specific demand assumed from each OEM due to product being novel, the flow from the repair/remanufacturing facility to the OEMs is defined by the optimisation model; this means that any existing OEM is assumed to be capable of incorporating these frames in their production line. The final entity of the reverse supply chain network is the CFRP recycling facilities, which recycle the material from frames or frame parts unfit for reuse. Existing CFRP recycling facilities are considered, and their capacity is assumed sufficient to recycle the flow of frames that are not suitable for remanufacturing. It should be noted that the recycling or reuse processes of the other parts of an EoL car are beyond the scope of this work.

Despite the fact that the model could handle multiple types of car frames, a single frame type has been assumed for the purposes of this work to serve cars of similar expected functionality, such as car sharing. This is aligned with the current practices of car manufacturers in using the same frame in a series of models and even brands (Palmer, 2022).

Furthermore, it is assumed that all CFRP frames returned/recovered that are fit for reuse will be reused, and that the demand for this type of cars will be continuously increasing. This argument is supported by the increasing trend of the estimated forecasts in following sections.

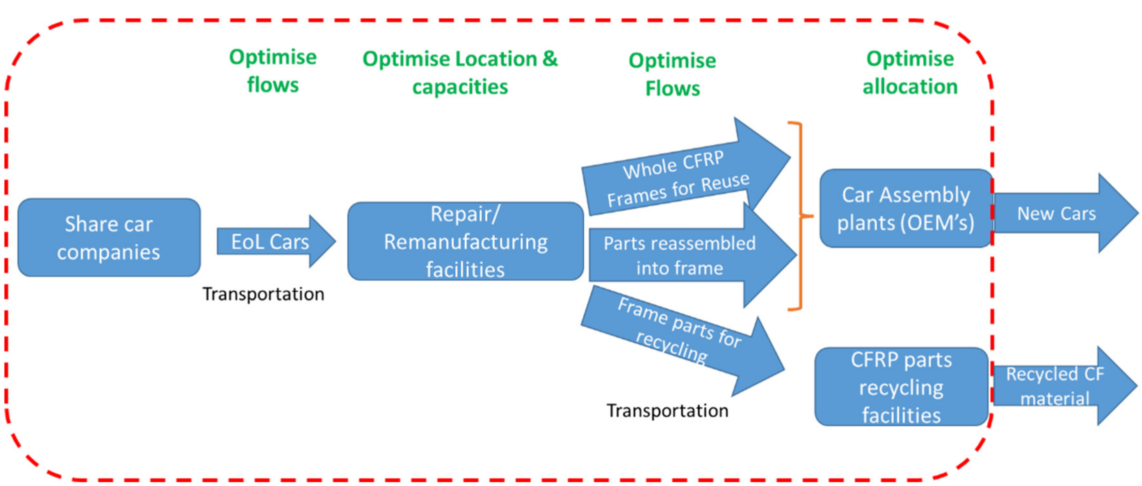

Fig. 1. CFRP car frame reverse supply chain network.

Therefore, the demand for frames is greater than the availability of remanufactured/ reusable frames at any point in time. In addition, the car frames will be available after the end of the car service life, which is assumed 4 years for car sharing,[1] based on an average usage of 30,000–40,000 km/year.[2]

Finally, three scenarios for the reverse supply chain network of frames are investigated, since the proposed CFRP car frames are an innovative product idea and there is currently no empirical evidence on the properties deterioration after each life cycle: 1) optimistic (99% of frames reused-1% of frames recycled), 2) average (95% of frames reused-5% of frames recycled), and 3) pessimistic (90% of frames reused-10% of frames recycled). The scenarios have been derived from car designers and manufacturing industry experts in the automotive engineering industry specialised on sustainable mobility. The unit of analysis is 'equivalent' frames, thus in the case of recycling it is assumed as the amount of frame parts equivalent to one frame per weight.

3.2. Mathematical model formulation

The mathematical model developed for the proposed reverse supply chain network is formulated as a Mixed-Integer Linear Programming (MILP) model (Nayak, 2020) and is presented in this section. The nomenclature used for the representation of the sets and parameters can be found in the Appendix.

In the model, the following decision variables are used:

- The EoL car frame flow $k_{f,l}$ from the local hub/supplier $f \in F$ (EoL cars collection point), to the repair/remanufacturing facility $l \in L$.
- The repaired/remanufactured frame flow $k_{l,c}$ from the repair/remanufacturing facility $l \in L$ to the OEM $c \in C$.
- The frame/material flow $k_{l,r}$ from the repair/remanufacturing facility $l \in L$ to the recycling facility $r \in R$.
- Finally, the binary variable $y_{l,s}$ concerns the existence of a repair/remanufacturing facility of size $s \in S$ at the location $l \in L$. The size of the facility 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 annualised investment cost *(Ci)*, the annualised building cost (*Cst*), the maintenance cost *(Cm)*, the variable *(Cov)* and fixed *(Cof)* operational costs, the outbound transportation cost (*Ctout*), and the cost of carbon emissions *(CO2el, $CO2fu_{o2}$, $CO2fu_t$)*.

$$Min\ F = Ctin + \frac{Ci}{an} + \frac{Cst}{an} + Cm + Cov + Cof + Cmi + Ctout + co2t\ (CO2fu_{o2} + CO2fu_t + CO2el) \quad (1)$$

The inbound cost from the EoL vehicle collection spot to the repair/remanufacturing facility (*Ctin*) is calculated as a function of the unitary inbound transportation cost considering the labour, insurance, maintenance *(tcin)* and the fuel cost *(tcinf)* as well as the distance $d_{f,l}$ and the amount of EoL car frames $k_{f,l}$ transported.

$$Ctin = \sum_{f=1}^{F}\sum_{l=1}^{L}(tcin + tcinf)d_{f,l}\,k_{f,l} \quad (2)$$

The investment cost *(Ci)* of the repair/remanufacturing facility technologies is estimated as a function of the yearly investment cost of a facility with capacity *s* and the binary variable $y_{l,s}$ that concerns the existence of a repair/remanufacturing facility of capacity s.

$$Ci = \sum_{s=1}^{S} ci_s \sum_{l=1}^{L} y_{l,s} \quad (3)$$

The building cost (*Cst*) is a function of the building cost *(cst_s)* for plant size with capacity Cap_s and the binary variable $y_{l,s}$ that concerns the existence of a repair/remanufacturing facility of capacity *s*.

$$Cst = \sum_{l=1}^{L}\sum_{s=1}^{S} cst_s Cap_s y_{l,s} \quad (4)$$

The maintenance cost of the facility *(Cm)* is estimated as a percentage *(cm_s)* of the annualised investment cost *Ci*.

$$Cm = \sum_{s=1}^{S} cm_s ci_s \sum_{l=1}^{L} y_{l,s} \quad (5)$$

The operational costs of the repair/remanufacturing facility include variable (*Cov*) and fixed *(Cof)* costs. The variable costs depend on the amount of EoL car frames $k_{f,l}$ that are processed in the repair/remanufacture facility according to the scenario considered *(rf)* and they consist of electricity cost estimated from the electricity consumption *(coe)* and the cost of electricity *(ce)*, consumables consumption *(coc)* and other variables costs, such as water consumption *(cow)*.

$$\mathrm{Cov} = \sum_{l=1}^{L}\left[(cow + coe\ ce + coc)\sum_{f=1}^{F} k_{f,l}\,rf\right] \quad (6)$$

The fixed costs are comprised of the yearly investment cost (*Cmi*) and fuel cost (*Cmf*) for the forklift machinery, the personnel costs (*cols*) that depend on the capacity of the facility (Cap_s), the forklift and facility insurance costs that are a percentage (*cmins* and $cins_s$, respectively) of the facility investment cost. Similarly, the forklift investment cost (*Cmi*) is assumed as a percentage (*cmi*) of the facility investment cost, whereas the forklift fuel cost (*Cmf*) depends on the capacity of the facility, the fuel consumption cost of the machinery (*cmf*) and the cost of diesel (*cdf*).

$$Cof = \mathrm{Cmi} + Cmf + cols\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L} y_{l,s}\right) + cmins\sum_{s=1}^{S} ci_s \sum_{l=1}^{L} y_{l,s} + \sum_{s=1}^{S}\left(cins_s ci_s \sum_{l=1}^{L} y_{l,s}\right) \quad (7)$$

$$Cmi = cmi\sum_{s=1}^{S} ci_s \sum_{l=1}^{L} y_{l,s} \quad (8)$$

$$Cmf = cmf\ cdf\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L} y_{l,s}\right) \quad (9)$$

The outbound cost (*Ctout*) reports the transportation cost of the frames from the repair/remanufacturing facility to the car assembly facilities (OEMs) as well as to the recycling facility, in the case that the frames cannot be remanufactured. It is calculated as a function of the unitary outbound transportation cost considering the labour, insurance, maintenance *(tcout)* and the fuel cost *(tcoutf)* as well as the distance (*dl, c* for the OEMs and $d_{l,r}$ for the recycling facility) and the amount of the repaired/remanufactured frames $k_{l,c}$ and $k_{l,r}$ respectively transported to the different locations.

$$Ctout = (tcout + tcoutf)\sum_{c=1}^{C}\sum_{l=1}^{L} d_{l,c}k_{l,c} + (tcout + tcoutf)\sum_{r=1}^{R}\sum_{l=1}^{L} d_{l,r}k_{l,r} \quad (10)$$

The cost of the carbon emissions emitted in every stage of the reverse supply chain network is also estimated, considering the emissions from the electricity (*CO2el*) that depend on the carbon emission factor of the country (*co2ee*) and the emissions from the fuel consumed in

[1] Source: Car sharing industry sources.
[2] Source: Automotive industry sources.

the facilities *(CO2fu$_{o2}$)* that is according to the carbon emissions factor of diesel (*efd*). Finally, the emissions from the transportation operations *(CO2fu$_t$)* are also accounted.

$$CO2el = \text{coe}\ co2\text{ee} \sum_{l=1}^{L} \sum_{s=1}^{S} Cap_s y_{l,s} / 10^6 \tag{11}$$

$$CO2fu_{o2} = efd\ cmf \sum_{l=1}^{L} \sum_{s=1}^{S} Cap_s\ y_{l,s} / 10^6 \tag{12}$$

$$CO2\text{fu}_t = fct\ \frac{efd}{10^6} \left[\sum_{l=1}^{L} \sum_{f=1}^{F} d_{f,l}\ k_{f,l} + \sum_{l=1}^{L} \sum_{c=1}^{C} d_{l,c}\ k_{l,c} + \sum_{l=1}^{L} \sum_{r=1}^{R} d_{l,r}\ k_{l,r} \right] \tag{13}$$

Finally, the annuity factor *(an)* is estimated according to the assumed discount rate *(df)*.

$$an = \frac{1 - \frac{1}{(1+df)^Y}}{df} \tag{14}$$

Mass balance constraints are imposed in each node. First, in order to ensure that from each existing repair/remanufacturing facility the amount of frames remanufactured equals the amount of products that are supplied to the customer from this facility (15), whereas the rest of the frames supplied to the facility are recycled (16) according to the assumed scenario. In addition, the mass balance between the EoL CFRP frames available and the EoL CFRP frames provided to the repair/remanufacturing facilities from each EoL car location are ensured in (17).

$$\sum_{c=1}^{C} k_{l,c} = \sum_{f=1}^{F} k_{f,l}\ rf, l = 1..L \tag{15}$$

$$\sum_{r=1}^{R} k_{l,r} = \sum_{f=1}^{F} k_{f,l}\ (1 - rf), l = 1..L \tag{16}$$

$$sup_f = \sum_{l=1}^{L} k_{f,l}, f = 1..F \tag{17}$$

In addition, a constraint is modelled to ensure that there is a single capacity for each repair/remanufacturing facility (18) and that the capacity for each facility is sufficient to process all the frames (19).

$$\sum_{s=1}^{S} y_{l,s} \leq 1, l = 1..L \tag{18}$$

$$\sum_{f=1}^{F} k_{f,l} \leq \sum_{s=1}^{S} Cap_s y_{l,s}, l = 1..L \tag{19}$$

Finally, constraints to specify the variables that are considered in the model are also imposed, to ensure that the material flows between the nodes are positive (20,21,22), whereas the variable for the location and capacity of the repair/remanufacturing facilities is modelled as binary in (23).

$$k_{l,c} \geq 0, l = 1..L, c = 1..C \tag{20}$$

$$k_{f,l} \geq 0, l = 1..L, f = 1..F \tag{21}$$

$$k_{l,r} \geq 0, l = 1..L, r = 1..R \tag{22}$$

$$y_{l,s} = 0\ or\ 1, l = 1..L, s = 1..S \tag{23}$$

4. Results and discussion

The reverse supply chain network optimisation model was applied to the case study of the UK, using the input parameters presented in the Appendix.

The car sharing locations, which are the potential supply of the EoL CFRP car frames, are derived from the current car sharing spots. The amount of available cars in each location in 2020 is derived from existing databases (CoMoUK, 2021). In order to forecast the amount of EoL frames until 2050, a 20% increase is assumed between 2021 and 2027 according to existing forecasts (Global Market Insights, 2021). A trend analysis is performed from 2015 to 2026 in Minitab and the quadratic polynomial is selected since it demonstrates the lowest error according to statistical indicators. The developed forecast for the EoL car sharing vehicles until 2050 that estimates the amount per location can be found in the Appendix. A finite number of 179 urban settlements are considered as suitable potential locations for the repair/remanufacturing facilities, shown in the Appendix. Existing CFRP recycling facilities are considered, the location of which in the UK is visible in the results section.

The model has been implemented in GAMS, version 27.2 and was solved using LINDO solver, on an Intel(R) CoreTM8 i7–2600 CPU at 3.40GHz operating system. The findings for the optimal reverse supply chain networks for EoL car frames are presented and discussed in the following section.

4.1. Optimal configuration

The number of optimal facilities and their capacity along with the capacity utilisation for the scenarios examined are presented in Table 1. Overall, a high utilisation is identified with the lowest being 33% in the 2050 scenarios for a very small facility, due to the predetermined capacities the model selects from.

For 2023 all the scenarios indicate as optimal a centralised facility with 10,000 frames per year capacity due to the low number of car frames available. It is evident from Fig. 2, which depicts the material flows of the optimal network, that the facilities are located in all the scenarios in the same proximity, which is very close to the location of a car assembler (OEM). However, for the pessimistic cases the facility location is slightly closer to the recycling facility. The decision for the location of the facility is driven by the high concentration and amount of EoL cars that are available in close proximity to this location at the SE of England, and the distance from the car assembly facility, rather than the waste recycling facility. This can be justified by the fact that the volumes for recycling are a maximum of 10% in the worst-case scenario, meaning that inbound transportation effort to repair/remanufacturing facility and outbound to car assembler is much higher compared to that for transportation of materials to the recycling facility. From a

Table 1
Optimal facilities.

	Facilities	Capacity (frames/year)	Capacity Utilisation
2023_optimistic	1	10,000	99%
2023_average	1	10,000	99%
2023_pessimistic	1	10,000	99%
2050_optimistic	1	5,000	96%
	2	5,000	100%
	3	5,000	100%
	4	5,000	33%
	5	5,000	100%
	6	75,000	100%
	7	75,000	100%
	8	1,000	77%
2050_average	1	5,000	96%
	2	5,000	100%
	3	5,000	100%
	4	1,000	94%
	5	5,000	100%
	6	75,000	100%
	7	75,000	100%
2050_pessimistic	1	75,000	85%
	2	75,000	100%
	3	32,000	100%

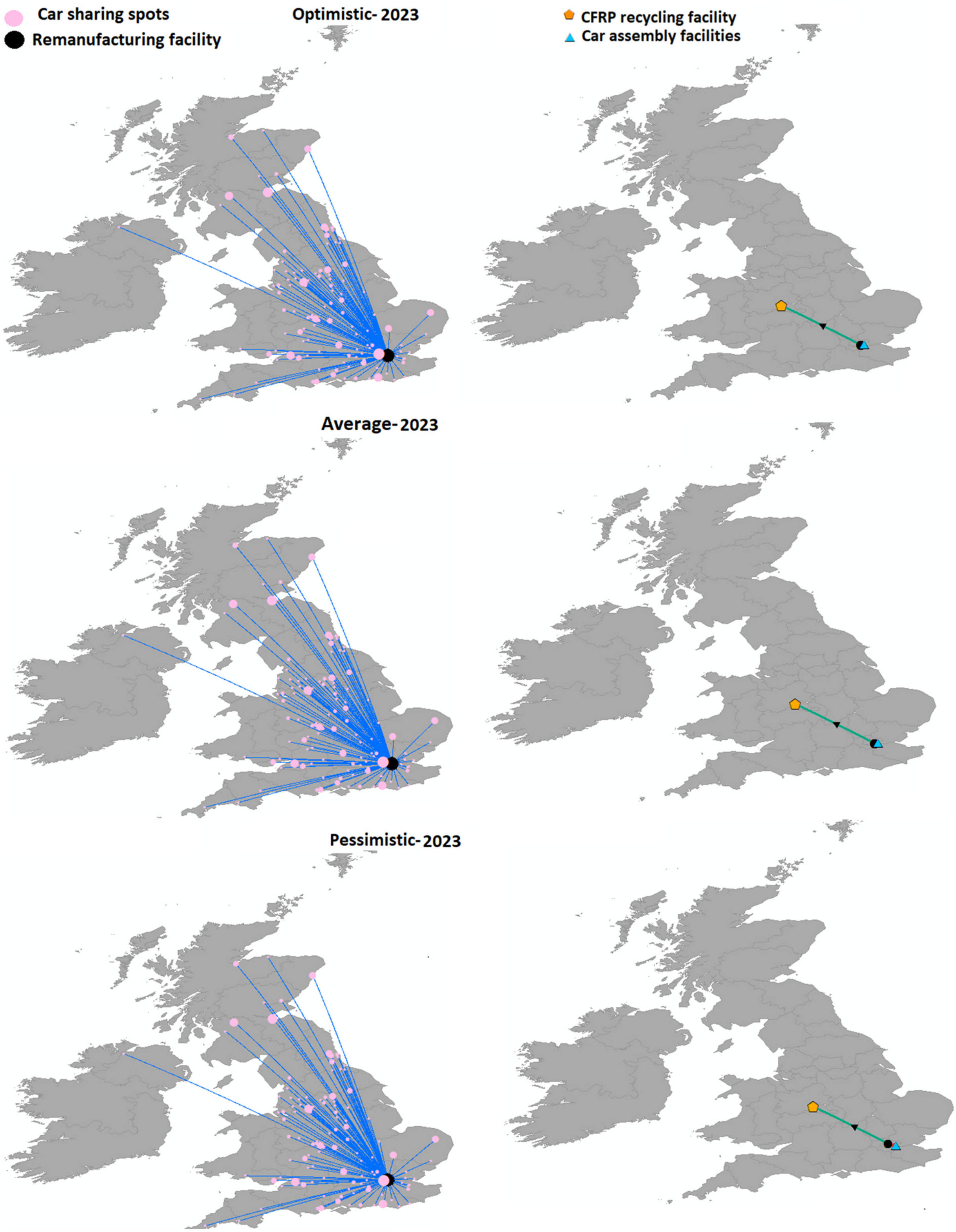

Fig. 2. Optimal network for 2023 (left: inbound transportation flows; right: outbound transportation flows).

reverse supply chain design perspective, it is apparent that the remanufacturing facility location is not significantly impacted by the scenario chosen.

On the other hand, for 2050 the reverse supply chain network is decentralised, with 8 facilities on the optimistic scenario, 7 on the average and 3 on the pessimistic. The optimal network for the three scenarios for 2050 is displayed in Fig. 3. It is evident that the facilities are selected in similar locations and specifically the network of the optimistic and average scenarios are quite similar. However, the network tends to become more centralised at the pessimistic scenario. For the

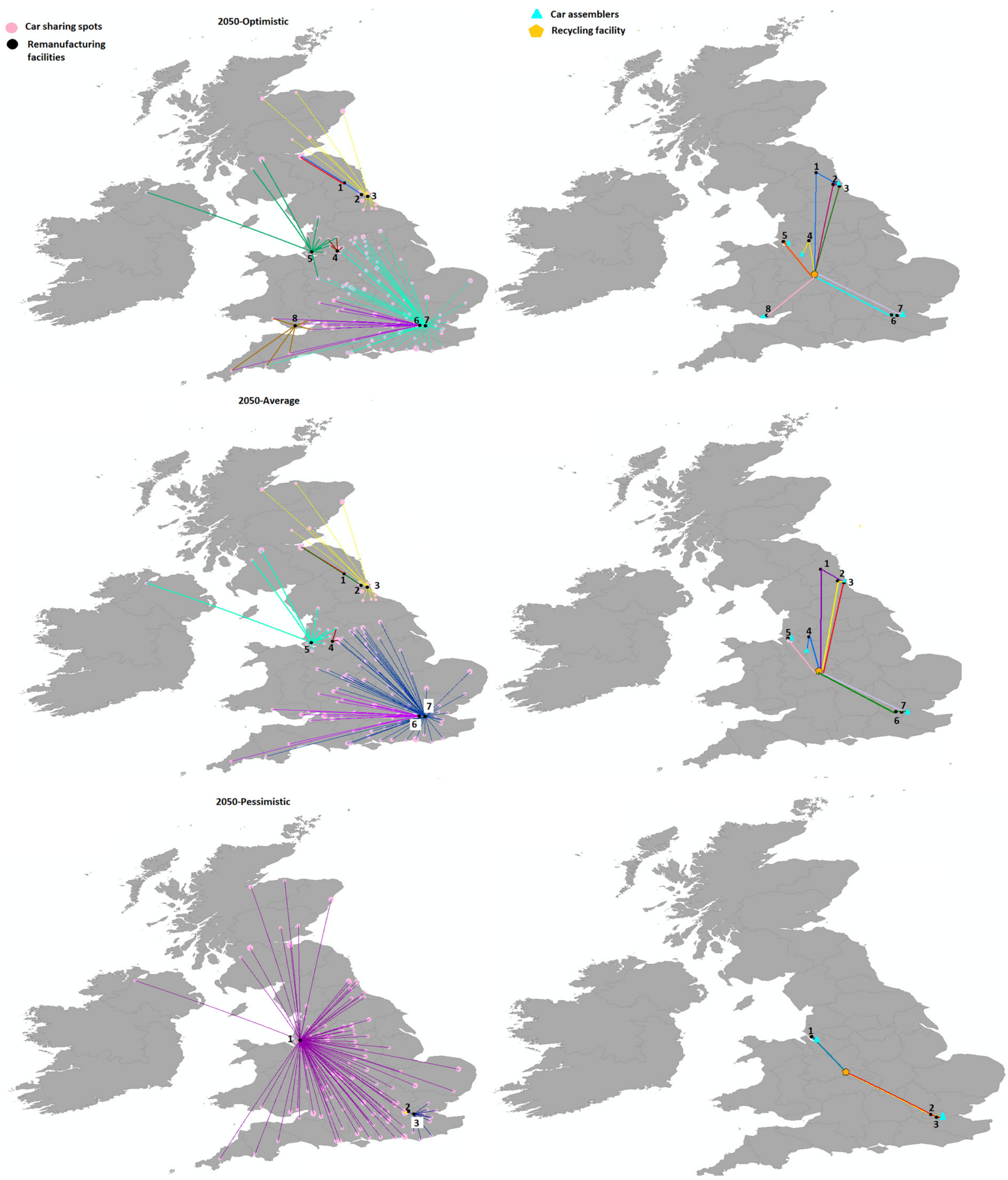

Fig. 3. Optimal network for 2050 (left: inbound transportation flows; right: outbound transportation flows).

optimistic scenario the facilities 6 and 7 are the largest and are located closer to the hotspot of the sharing cars' location. The rest of the facilities tend to be much smaller in capacity. It is evident from the outbound network that all the facilities are located near the car assembly facilities.

Regarding the average scenario, two larger (6 and 7) facilities are again located near the hotspot of car sharing locations. The 8th facility of the optimistic network is not selected in the average one (but this had a very low capacity in the first place) and one of the smallest facilities (4th) of the optimistic scenario is increased in capacity. Ultimately, it can be said that the optimistic and average scenarios have very similar supply chain network structures with very minor differences, and that the proposed structure is not sensitive to changes of the car frame recycling percentage between 1% to 5%.

Finally, the network proposed for the pessimistic scenario is much more centralised with only three high-capacity facilities proposed. This network is benefiting from the economies of scale, with one of the largest facilities (2) being located near the identified hot spot and the other large facility (1) closer to the recycling facility. The latter has as a result the outbound transportation cost minimisation. Therefore, it is concluded that the higher percentage of recycled frames for the pessimistic scenario (10%) leads to the decision to locate one of the largest facilities nearer the recycling centre and leads to a more centralised network design in general.

As a result, it can be inferred that the optimal facility that is identified in 2023 near the hotspot of car sharing availability, will have to be expanded with capacity of 75,000 cars per annum for 2050. It should be noted that the maximum capacity assumed for each facility in the model was 75,000 cars per annum, which indicates that if a higher capacity was possible, the model would most likely propose such a facility at the SE of England. In addition, depending on the scenario, other smaller facilities are recognised as optimal at the South East part of the UK.

4.2. Economic assessment

In this section, the economic assessment of the optimal networks proposed is discussed. In Table 2, the total annual processing system cost and the cost per remanufactured frame per scenario for 2023 and 2050 is displayed. Regarding the total system costs, it is evident that it is lowest for the optimistic scenario in 2023, whereas it is lowest for the average scenario in 2050. The range difference of the total system costs between the highest cost scenario to the lowest is quite small, with a maximum of 3.9% difference for 2023 and 4.7% for 2050. However, it should be noted that each scenario involves different number of frames remanufactured yearly.

The per frame remanufactured cost range between the highest and lowest cost scenarios is 16.1% and 12.6% respectively in 2023 and 2050. Essentially the per frame remanufactured cost is equivalent to the repair/remanufacturing cost that the car assembler should at least pay to source the remanufactured frame for the reverse system to be viable. It is evident that the most economically viable option is the optimistic scenario in both 2023 and 2050, due to the lower amounts of waste and higher number of frames being remanufactured. In 2050, due to the higher amount of EoL frames compared to 2023, the reverse supply chain network is more cost efficient, leading to a 17–22% reduction in the per remanufactured frame cost, due to the benefits from the economies of scale at the processing stage, as well as the reduced transportation effort due to the more decentralised nature of the proposed reverse supply chain network. It should also be mentioned that the cost per remanufactured/reused car frame ranges between 11% and 15% (depending on the scenario) of the estimated cost of making a new CFRP car frame of the same specifications, indicating a significant financial incentive for adopting a circular approach.

In Fig. 4 the breakdown of the cost of each scenario is presented. It is evident that the greatest contribution to the cost of the repair/remanufacturing facility is the personnel cost followed by the annualised investment cost. It can be observed that even though all the costs increase proportionally for 2050 due to the higher amount of material, the investment cost does not, due to the economies of scale. In addition, the processing cost of the facilities is reduced in the average scenario, while this reduction is even more evident in the pessimistic scenario. This is due to the lower operational cost of repair/remanufacturing, since a higher number of frames is not remanufactured and is transported to the recycling facility instead.

Table 2
Cost per scenario.

Scenarios	Cost per remanufactured frame (€)	Total processing cost (€)
2023_optimistic	230.53	2,263,255.56
2023_average	249.59	2,351,459.64
2023_pessimistic	261.52	2,334,151.09
2050_optimistic	190.26	32,162,136.76
2050_average	193.87	31,447,532.96
2050_pessimistic	214.20	32,916,874.31

On the other hand, the transportation cost for 2023 is highest for the pessimistic scenario. This is due to the increase on the outbound cost to the recycling facility, which increases with the higher amount of material transported there. The outbound transportation to the car assemblers is lower for the optimistic and average scenario since the facilities are closer to the car assembler compared to the pessimistic one.

In the 2050 scenario, the transportation cost to the recycling facility increases with the increase of material transported there. The inbound cost is quite similar in the optimistic & average scenarios but higher on the pessimistic scenario due to the fact that there are fewer facilities, therefore the transportation effort (measured in frame*km) is higher in this case. The outbound transportation in all the cases is on the same range since all the facilities are located very close to a car assembler. The low transportation cost of the optimistic scenario, due to the lower transportation cost to the recycling facility, is the reason that even though the processing cost is higher, ultimately, the overall cost is quite similar to the other scenarios. Therefore, a trade-off can be observed when the amount of waste versus frames to be remanufactured increases, as more transportation is required, compared to less processing effort due to lower number of frames to remanufacture.

4.3. Environmental assessment

In this section, the environmental assessment of the optimal configurations is discussed. The carbon emissions from all the processing stages are presented in Fig. 5, where it is observed that the electricity consumption has the greatest contribution on the overall emissions, followed by the inbound transportation emissions due to the inefficient transportation of the EoL cars. It is observed in Table 3 that the optimistic scenarios have the lowest carbon emissions per frame, both in 2023 and 2050. However, the differences are quite small between scenarios. Even though the optimistic scenario leads to the highest emissions in absolute values, this is counterbalanced by producing the highest amount of remanufactured frames. The values of Table 3 lead to CO_2 equivalent emissions of around 7% – 7.4% of those related to manufacturing a new CFRP car frame, indicating the significant environmental benefits of reusing and remanufacturing this particular car part, which entails energy-intensive manufacturing processes.

In the discussion of the findings two key drivers that affect the optimal reverse supply network structure are analysed. The first is the percentage of CFRP frames reused, which defines the three considered scenarios. The second driver is the scale of operations, which is expressed by the absolute number of frames processed by the system, represented by the year investigated in the scenarios. The main effects of these drivers are summarised in this paragraph. Regarding the first driver, the scenarios characterised by a lower percentages of reused frames display repair/remanufacturing facilities closer to the recycling facility, compared to the scenarios with higher percentages, in which they are located closer to the OEMs in order to reduce the outbound transportation. Still, in all cases the location of the repair/remanufacturing facilities is primarily driven by the OEM location, rather than the recycling facility. In addition, as the percentage of frames to be recycled increases, the number of facilities is reducing, when there are sufficient quantities for multiple facilities. This affects the inbound transportation effort, which is higher due to the lower number of facilities. When considering the second driver, the increase of EoL frames impacts the network design, with facilities being more decentralised. This leads to lower inbound transportation costs and slightly lower carbon emissions. Furthermore, when increasing the number of EoL frames, the cost per unit decreases, demonstrating that the system is exploiting the economies of scale. However, this is also affected by the percentage of frames recycled, as mentioned about the first driver. Therefore, a trade-off is observed between the transportation cost, that is reduced with a more decentralised network of smaller facilities

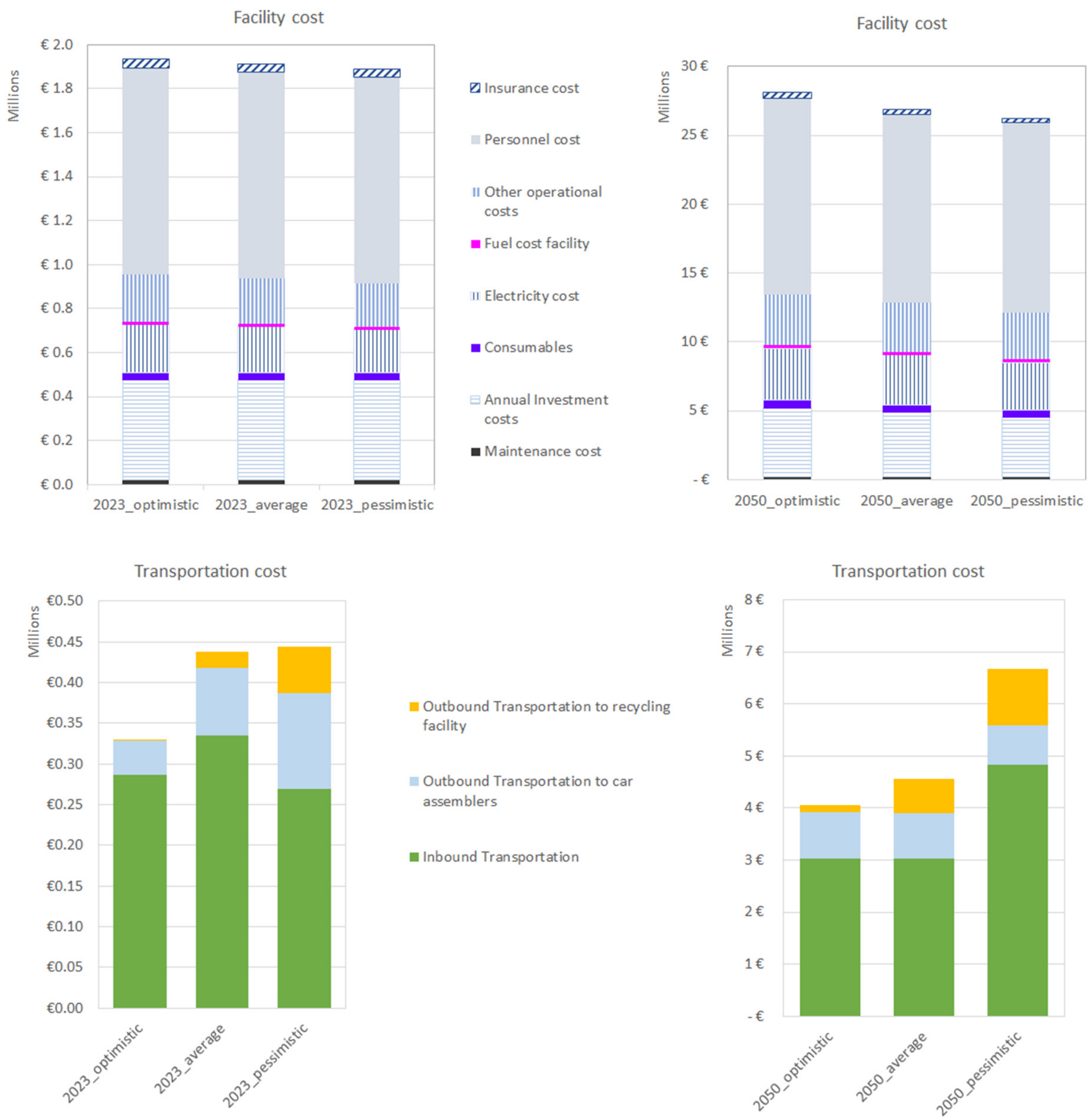

Fig. 4. Economic breakdown of each stage.

and the facility processing cost, which is increased in the same case, due to loss of economies of scale.

4.4. Sensitivity analysis

In this section, the sensitivity analysis of the most uncertain parameters on the reverse supply chain network optimisation is performed against the total cost. The parameters considered include the electricity and petrol price since they depend greatly on the market conditions. In addition, the technologies cost is considered since this is a novel technology with a not so well-defined process, and there is uncertainty on its cost. The labour cost is one of the factors investigated due to the fact that it has the greatest contribution on the overall costs and the final factor is the density of the transported products due to the assumptions made regarding this parameter and the related uncertainty.

The results are presented for 2023 and 2050 in the Appendix. It is evident that for all the scenarios the most impactful parameter is the labour cost, which when changing by 20% can increase or decrease the total cost by >8%. This can be attributed to the labour-intensive nature of repair/remanufacturing processes. The technology capital cost affects significantly the total cost, specifically in the 2023 scenario; this is because in 2050 larger facilities are selected that benefit from economies of scale. On the other hand, the changes on the electricity prices have a greater impact on cost in 2050, due to the higher contribution of electricity costs compared to capital costs. Finally, the density of the parts has the highest impact at the 2050 pessimistic scenario, where there is significant transportation effort for recycling material too.

5. Conclusions

This work proposed a reverse supply chain network design for the innovative idea of using reusable CFRP car frames for cars aimed specifically for car sharing applications. The proposed network consists of local city hubs where end-of-life cars would be collected; car frame

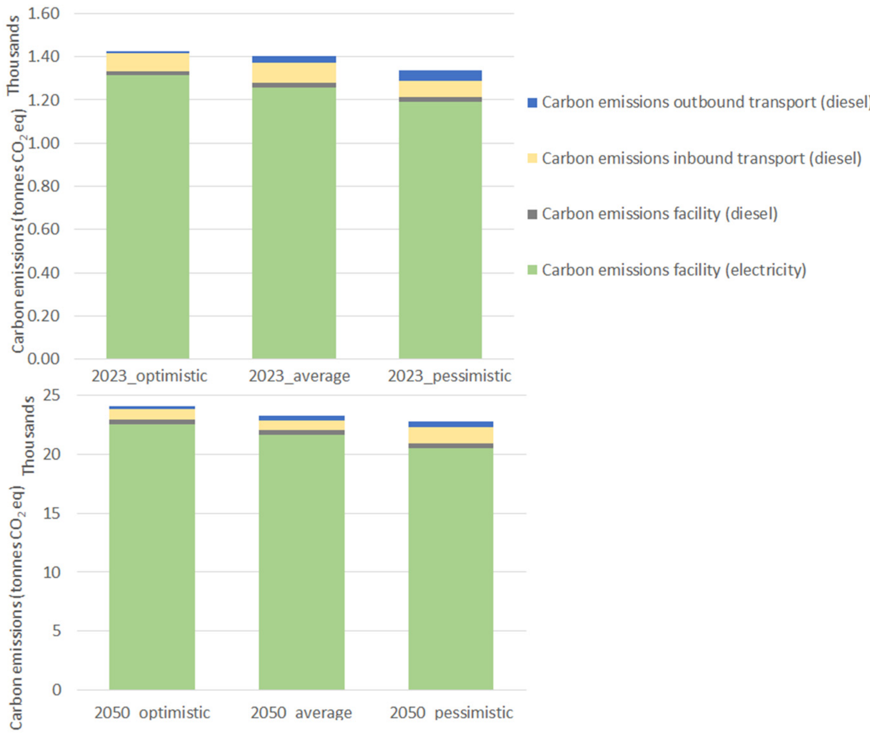

Fig. 5. Annual carbon emissions per stage.

repair/remanufacturing facilities where the EoL cars are transported, dismantled, inspected and remanufactured; and OEMs where the remanufactured car frames are reused in new cars for car sharing, as well as recyclers of CFRP material where the non-remanufacturable frames would be recycled.

The network design was optimised using a MILP model for three scenarios of proportion of car frames that would be reusable at the end of the car life, for the case study of the UK. The optimisation was performed for two points in time, in 2023 and 2050, since the car sharing industry is expected to experience significant growth. For 2023, the optimal network design was very similar in all scenarios, with only one processing facility for the whole of the UK. On the other hand, in 2050, the optimal network design becomes more decentralised, with up to 8 repair/remanufacturing facilities proposed in the UK, with the proximity to OEMs being the primary influencer of the selected locations. The network design demonstrates differences for the three scenarios in 2050, especially in the case of the lowest frame reuse rate. Therefore, the frame reuse rate is a parameter that should be carefully estimated before designing the reverse supply network.

The total cost for remanufacturing the CFRP frames is greatly reduced by up to 22% in 2050 compared to 2023, depending on the scenario, benefiting from the economies of scale and reduced transportation requirements, as a direct effect of the more decentralised network.

Table 3
Carbon emissions per frame remanufactured.

Scenarios	Carbon emissions (t/frame remanufactured)
2023_optimistic	0.143
2023_average	0.147
2023_pessimistic	0.148
2050_optimistic	0.140
2050_average	0.142
2050_pessimistic	0.146

The work presented has several implications for practitioners and policy makers. It demonstrates the potential for a new Circular Economy pathway in automotive from both economic and environmental aspects, involving reuse of CFRP car frames dedicated to car sharing vehicles. Policy makers could use the findings of this work to make informed decisions on promoting a change in personal commuting towards shared vehicles and enhancing circularity in the automotive sector, by promoting reuse of key car parts instead of the current case of recycling. Policy makers are also informed about the environmental benefits expected by adopting the proposed idea. With the current electricity mix in the UK, significant environmental benefits can be obtained by reusing and remanufacturing this particular car part, as it leads to around 7% – 7.4% CO2 equivalent emissions compared to manufacturing a new CFRP car frame. Still, given that 90% of the reverse supply chain network carbon emissions are due to electricity use at the remanufacturing facilities, the decarbonisation of electricity supply or use of renewable electricity sources will lead to drastic reduction of the related carbon emissions in the future.

This work also identifies the critical parameters affecting the optimal system design, informing strategic and tactical managerial decisions, such as facility locations and material flows respectively. In this respect it was noted that the higher the percentage of car frames that can be reused through remanufacturing after their end-of-life, the lower the cost per frame. This means that these frames should be designed robustly and with remanufacturability in mind so that the overall system cost is minimised. In all the scenarios a significant financial incentive for adopting the proposed circular approach is identified: the cost of reusing & remanufacturing the CFRP frames is highly competitive to the cost of making a new one, ranging between 11% and 15% of the estimated cost of making a new CFRP car frame of the same specifications, with the lowest value for the 2050 scenarios and the highest for 2023. Additionally, the impact of economies of scale if evident. In this case, large-scale application of this concept is likely to lead to a reinforcing cycle of reducing the remanufacturing cost. This supports the economic aspect of the business case for managerial decisions for stakeholders interested in this concept, and identifies the opportunity for new stakeholders in the reverse value chain with skills to perform the disassembly, inspection and remanufacturing of CFRP frames.

Finally, researchers could also use the model presented to apply to different geographical context or to different parts or products. This work provides the first step towards investigating similar circular economy pathways with other car parts, or sets of car parts, in a more holistic manner.

This work has limitations related to long-term forecasting uncertainty. Linked to this, due to the fact that the car sharing industry is still evolving and little data is available, several assumptions had to be made that influence the outcomes, such as the future adoption of car sharing in the various parts of the UK. Also, the reusable CFRP car frame analysed in this work is a novel idea which is not yet adopted by the automotive industry at large scale. Therefore, its future adoption entails a degree of uncertainty. In this respect, the current work indicates the potential for this novel idea. In the future, the present work assumptions could be validated with more accurate predictions of the evolution of the car sharing market, as well as market research as to the willingness of people to use car sharing services and the willingness of the automotive industry to reuse key parts of EoL cars. In addition, further research could be done to consider including other potentially reusable and recyclable car parts to provide a more holistic perspective on the feasibility of circular pathways in automotive. Finally, to reduce the impact of the uncertainty, a stochastic or robust optimisation approach could be adopted.

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.

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Appendix A

Table A1
Nomenclature of sets.

Symbol	Description	Indices
c	set of all potential OEMs	c = 1..C
f	set of all the aggregated EoL car supplier spots	f = 1..F
l	set of potential repair/remanufacturing facility locations	l = 1..L
r	set of potential recycling facility locations	r = 1..R
s	set of potential repair/remanufacturing facility sizes	s = 1..S

Table A2
Nomenclature of parameters.

Symbol	Description	Unit
an	annuity factor estimated according to the equivalent annual cost function	(−)
Cap_s	processing capacity of repair/remanufacturing plant size s	(frames yr^{-1})
cdf	cost of diesel in UK	(€ l^{-1})
ce	cost of electricity in UK	(€ kWh^{-1})
Ci	total facility technology investment cost	(€)
$cins_s$	yearly insurance cost for s plant size	(€ yr^{-1})
ci_s	investment cost for s plant size	(€)
Cm	total yearly facility maintenance cost	(€ yr^{-1})
Cmf	total yearly fuel cost for forklift machinery	(€ yr^{-1})
cmf	fuel consumption for forklift machinery per year and unit of facility capacity	(l unit plant capacity $^{-1}$)
Cmi	Total yearly investment cost for forklift machinery	(€ yr^{-1})
cmi	rental cost for forklift machinery	(€ unit plant capacity $^{-1}$)
cmins	insurance cost for forklift machinery	(€ unit plant capacity $^{-1}$)
cm_s	maintenance yearly cost for s plant size	% of original investment
co2ee	carbon emissions factor from electricity in UK	(g_{CO2} kWh^{-1})
co2t	carbon emissions cost	(€ t_{CO2}^{-1})
coc	variable consumables consumption for frames repair/remanufacturing	(€ $frame^{-1}$)
coe	variable electricity consumption for frames repair/remanufacturing	(kWh $frame^{-1}$)
Cof	total yearly facility fixed operational cost: insurance and labour cost	(€ yr^{-1})
cols	fixed operating personnel cost for processing facility	(€ unit plant capacity $^{-1}$)
Cov	total yearly variable processing operational cost in the facility (repair/remanufacturing): energy consumption cost, consumables and other operational costs (e.g water consumption)	(€ yr^{-1})
cow	other variable operating costs for frames repair/remanufacturing (eg. Water consumption)	(€ $frame^{-1}$)
Cst	total building cost	(€)
cst_s	building cost for plant size s	(€ unit plant capacity $^{-1}$)
Ctin	total yearly cost of EoL car frame transportation from all car sharing locations to the repair/remanufacturing facility	(€ yr^{-1})
Ctout	total yearly cost of frame transportation from repair/remanufacturing facility to OEMs and to recycling facility	(€ yr^{-1})
CO2el	yearly carbon emissions from electricity per year for repair/remanufacturing facility	(t_{CO2} yr^{-1})
$CO2fu_{o2}$	yearly carbon emissions from fuel combustion per year from repair/remanufacturing facility operation	(t_{CO2} yr^{-1})
$CO2fu_t$	yearly carbon emissions from fuel combustion per year from transportation	(t_{CO2} yr^{-1})
df	Discount rate	(%)
$d_{f,l}$	Distance between the EoL car sharing spot to repair/remanufacturing facility l	(km)

Table A2 (*continued*)

Symbol	Description	Unit
$d_{l,c}$	Distance between the repair/remanufacturing facility l to OEM facility c	(km)
$d_{l,r}$	Distance between the repair/remanufacturing facility l to recycling facility r	(km)
efd	carbon emission factor for diesel	(g_{CO2} l^{-1})
fct	fuel consumption of fully loaded heavy duty truck	(l $frame^{-1}$ km^{-1})
$k_{f,l}$	EoL car flow from the EoL cars collection point f to the repair/remanufacturing facility l	(frame yr^{-1})
$k_{l,c}$	Repaired/remanufactured frame flow from the repair/remanufacturing facility l to the OEM c	(frame yr^{-1})
$k_{l,r}$	frames flow from each repair/remanufacturing facility to recycling facility r	(frame yr^{-1})
rf	percentage of frames that is remanufactured (depends on the scenario)	(%)
sup_f	Number of EoL frames generated by car sharing providers and aggregated in town f in a year	(EoL frame yr^{-1})
tcin	Unitary cost of inbound transportation: labour, insurance, maintenance	(€ EoL $frame^{-1}$ km^{-1})
tcinf	Unitary cost of inbound transportation: fuel	(€ EoL $frame^{-1}$ km^{-1})
tcout	Unitary cost of product outbound transportation: labour, insurance, maintenance	(€ EoL $frame^{-1}$ km^{-1})
tcoutf	Unitary cost of product outbound transportation: fuel	(€ EoL $frame^{-1}$ km^{-1})
Y	useful life of operation	(year)
$y_{l,s}$	the existence of a repair/remanufacturing facility of size s at the location l	(binary variable)

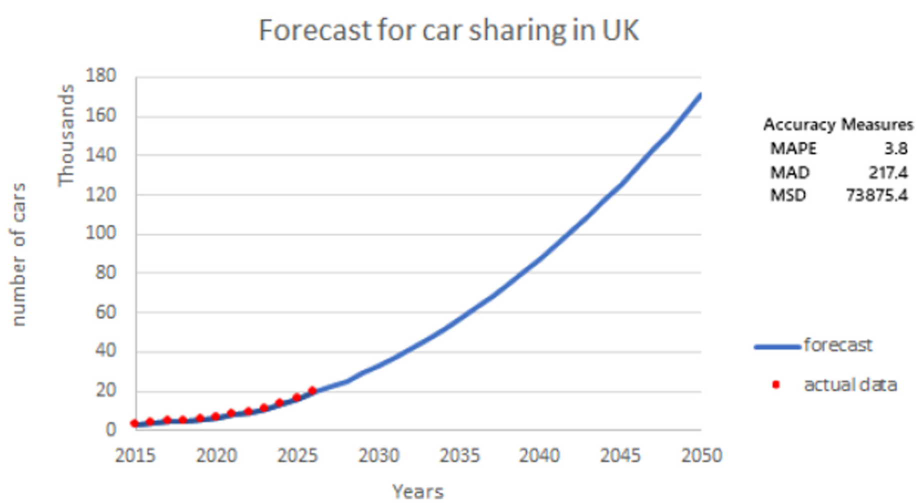

Fig. A1. Car sharing forecast in UK until 2050.

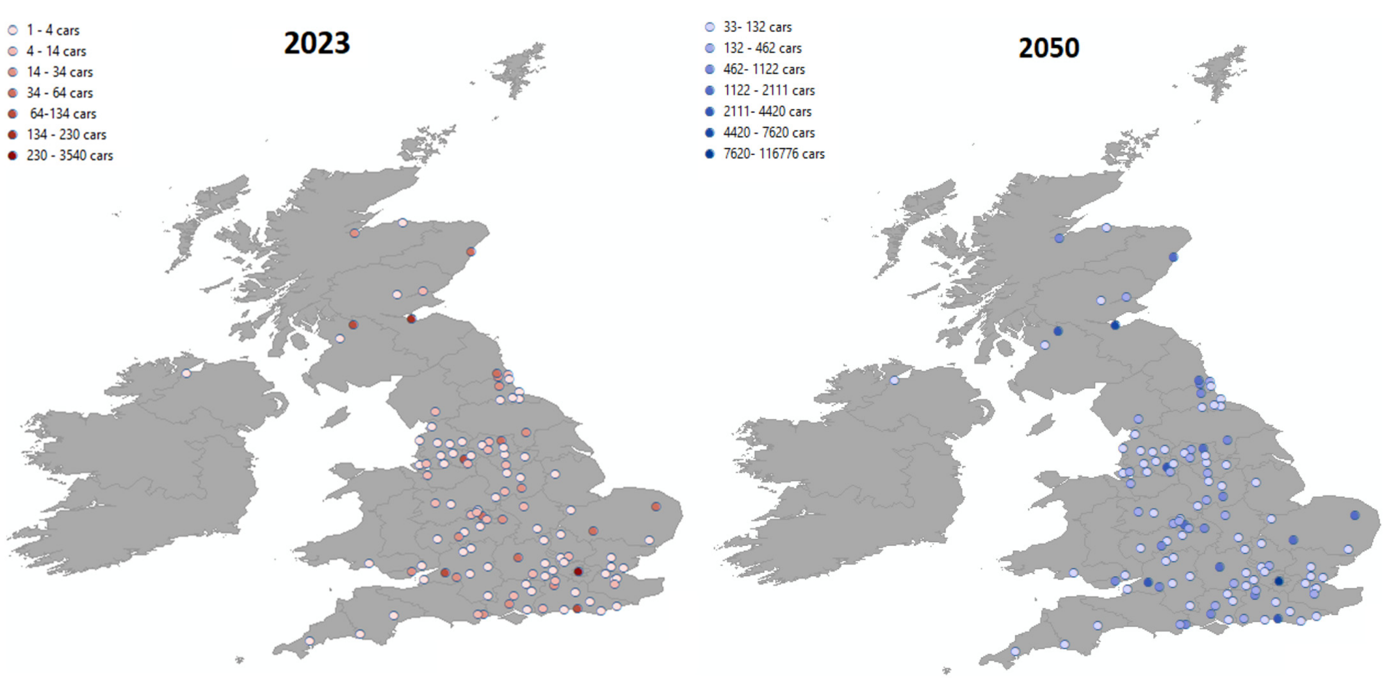

Fig. A2. Car sharing vehicle numbers in the UK in 2023 and 2050.

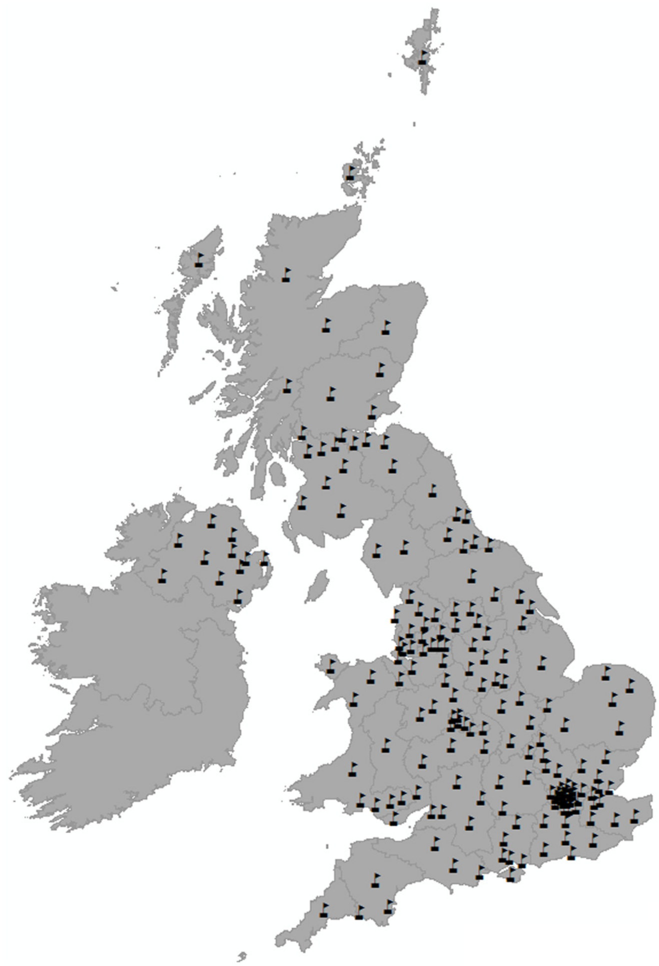

Fig. A3. Potential repair/remanufacturing sites in the UK.

Table A3
Input parameters.

Stage	Description	Value
Processing facility	Investment cost for a remanufacturing/repair facility (for technology)	3 M€ for a facility with two shifts and annual capacity of 20,000 frames
	Insurance cost for a facility	2% of investment cost
	Yearly capacity of different facility sizes	500/1000/5000/10,000/ 15,000/32,000/75,000 frames per annum
	Personnel cost for 1,000 cars yr^{-1} facility	221 € $frame^{-1}$
	maintenance cost (yearly)	1% of investment cost
	Consumables cost	3.6 € $frame^{-1}$
	electricity consumption	226 kWh $frame^{-1}$
	Other operating costs (e.g. water consumption)	22 € $frame^{-1}$
	Building facility cost	85,102 € for a facility with annual capacity of 3300 frames
	rental cost of forklift	4.55% yr^{-1} of facility investment cost
	forklift fuel consumption	0.78 l yr^{-1} $frame^{-1}$of facility capacity
	forklift insurance cost	0.22% yr^{-1} of facility investment cost
	Lifetime of the investment	10 years
Transportation	inbound transportation cost	0.22€car^{-1} km^{-1}
	outbound transportation cost (from processing facility to car assemblers)	0.25€ $frame^{-1}$ km^{-1}
Others	diesel carbon emission factor calculated according to (Ecoscore, 2020)	2640 g CO^2 l^{-1}
	diesel price for UK (average price of 2019)	1.47 €l^{-1}
	electricity cost for UK (prices for medium size industries in 2020) (Eurostat, 2020) (Eurostat)	0.22 € kWh^{-1}
	carbon footprint country specific electricity grid greenhouse gas emission factors (Carbonfootprint, 2020)	348 g kWh^{-1}

Fig. A4. Sensitivity analysis for 2023 and 2050.

The amount of cars for sharing in the UK in 2023 as well as the developed forecast until 2050 is displayed in Fig. A1.

The increase to the number of cars in each location by 2050 is considered proportional to the car sharing data of 2020, due to lack of data available with more specific forecasts.

The amount of EoL cars in the specific locations from car sharing is depicted in Fig. A2 for 2023 and 2050. In Fig. A3 the location of the potential repair/remanufacturing facilities is displayed.

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