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Recollection center location for end-of-life electric vehicle batteries using fleet size forecast: Scenario analysis for Germany

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Abstract

The number of electric vehicle batteries is expected to increase. Their integration into circular economy requires their recollection at end-of-life. Decision makers need tools to determine suitable locations of recollection centers, as the decision is not trivial. Lithium batteries are hazardous materials, which require a minimization of transport duration. Here, we develop a mathematical model for locating a number of battery recollection centers. We discuss the results on the case of Germany for the time period from 2020 to 2050. The aim is to identify the influence factors on the location choice and therefore enable a founded decision.

Keywords: End-of-life Electric Vehicle Batteries; Fleet Size Forecasting; Reverse Logistics; Scenario Analysis.

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1. Introduction

In 2019, the size of the global electric vehicle fleet was 7.2 million. Ninety-two percent of vehicles were used in the People's Republic of China, Europe, and the United States [1]. According to the International Energy Agency (IEA), in 2030 global electric vehicle sales will reach 25 million, while the stock will be 140 million units [1]. The electric vehicle market is in growth phase.

Batteries are crucial parts of electric vehicles and have become a hot topic in research and development [2]. Within the last decade the capacity density increased by 300% [3].

Global Battery Alliance predicts that total weight of end-of-life (EOL) Lithium-Ion-Batteries (LIBs) will increase more than threefold between 2018 and 2025 [4]. We must prevent formation of battery landfills. Therefore, EOL vehicle batteries must become a part of a circular economy value chain.

Circularity demands for repurposing batteries to second-life applications through remanufacturing and recycling. As an initial step, recollection is required. Locations for recollection must be determined appropriately.

The goal of this paper is to determine the locations of recollection centers by means of minimization of the transport duration.

The paper is organized as follows. In Section 2, we give an overview of the research about repurposing of vehicle batteries and the facility location related to EOL vehicle batteries. In Section 3, we define the problem for determination of recollection center locations, and, in Section 4, we present the mathematical model. In Section 5, we solve and discuss instances of the model based on information from Germany. In Section 6, we conclude and present further research activities.

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2. Literature review

The majority of batteries in vehicles are LIB. After eight to ten years of driving, battery storage capacity drops to 80% of its original capacity, which is unsatisfactory for the user [5]. Repurposing of EOL batteries instead of recycling is a possible lifecycle scenario.

Repurposing is the use of a product in an application other than its original purpose. The repurposed vehicle batteries can be used in peak-time energy shifting at homes, offices and retail stores or for energy leveling of renewable energy sources [6]. Examples of successful applications are listed in [7–10]. Repurposing applications will become more widespread, as the supply of EOL batteries increases.

Repurposing of batteries becomes feasible, if it ensures a certain performance in the next lifecycle. Batteries have to be reprocessed in order to complete condition monitoring, repair, maintenance, and refurbishing [11]. We expect that the reprocessing and repurposing operations will be conducted in a specialized facility. Hence, EOL vehicle batteries should be efficiently recollected and transported to these facilities.

Current electric vehicles do not have a standardized LIB. Even the vehicles of the same manufacturer use different battery types. The further technological development of batteries will lead to greater product variety and increase complexity of the recollection process [12]. In order to cope with the challenge of high product variety, repurposing and recollection centers should adapt principles of flexible mass customisation. These facilities should efficiently classify the batteries according to future lifecycle scenarios and perform necessary operations.

Questions regarding the selection of processes for repurposing and reprocessing, determination of the capacity and locations for recollection are still open. In this paper, we aim to determine the location for recollection of vehicle batteries, independent of the EOL or second-life operations.

We use facility location models to develop a decision tool for recollection center location for vehicle batteries. Facility location is an area of operations research [13]. In these models, a set of regions is served by a set of facilities, while a cost function is minimized. The minimization is applied in various areas such as waste management and transportation systems [14]. Since every application has its own characteristics, models developed for other settings cannot be directly used and must be adapted.

Application of facility location models to vehicle battery recollection is limited. In [15], inspection and recycling centers are determined based on fleet size projections for Sweden and minimizing total cost of operations. The fraction of vehicles in the regions of Sweden is assumed to be constant through time. However, in reality this fraction is dynamic.

Another example is [16]. Here, the authors use a location-allocation analysis to determine the optimal facility locations for recycling. The objective is to minimize the total weighted distance that the batteries must travel from their initial collection points to their second-life locations and finally to a single EOL facility. However, the number of facilities depends on the required capacity as well as on the amount of batteries.

There is a need to develop a facility location model for a situation, where fraction of vehicles in each region is dynamic and more than one facility is operational.

As next, we describe such a recollection process and describe a decision problem for this setting.

3. Problem definition

In this section, we briefly describe the recollection process of vehicle batteries, discuss factors that influence recollection center location decisions and define the problem of the paper.

We assume that a battery at its EOL will be brought to a collection point near to the owners' residence. This collection point might be a car workshop or a recycling yard. From these points, the batteries are transported to the recollection centers, which have the required equipment and security measures for identification and sorting.

The decision, where to locate the recollection centers, is not trivial. There are several influence factors, which have to be considered. One significant factor, both economic as ecological, is the safety of the transportation. LIBs are made of hazardous and highly reactive materials [17]. Even on new units, occasional errors can occur, which can trigger a battery fire. For used batteries, the risk increases as its state of health is unknown. In the last years, media has reported several truck fires during transportation [18]. To reduce the risk of uncontrolled fire, the transportation distance to the recollection center should be minimized.

The decision maker can influence the location selection through economic incentives and long-term land use planning. A favorable location should therefore be determinable in advance.

There are regulations about maximum work time of a truck driver. For example in Germany, work time should not exceed ten hours [19]. Therefore, the distance from anywhere to the recollection center shall be measured in driving hours and not in kilometers and shall not exceed ten hours. This enables the LIB to be transported within one day.

Due to high investment cost, the recollection centers will be established sequentially. A new recollection center shall be established, when the first center nearly reaches its available capacity. It is therefore necessary to determine locations of new centers depending on the previous ones. Once a recollection center starts operations, it will continue to operate until the end of all time periods.

A population region is assigned to one recollection center. However, the assigned recollection center to the population region may change during other time periods.

Based on this description, we formulate our problem as follows: The objective is to minimize total time for transportation of all batteries from population centers to recollection centers.

4. Model

In this section, we explain the mathematical model for facility location problem of recollection centers for vehicle batteries and a methodology to calculate model parameters. Parameters of the model are dynamic, and it is possible to locate more than one facility.

We have the following sets:

i: Population regions, $i = 1,...,I$.

j: Possible locations of recollection centers, $j = 1,...,J$.

t: Time periods, $t = 1,...,T$.

We use the following parameters:

d_{ij}: Travel duration from the population region i to the recollection center in location j, $i = 1,...,I$, $j = 1,...,J$.

b_{it}: Total battery inventory in the population region i in time period t, $i = 1,...,I$, $t = 1,...,T$.

We define the following decision variables:

x_{ijt}: Whether the population region i is assigned to the recollection center j in time period t, $i = 1,...,I$, $j = 1,...,J$, $t = 1,...,T$.

y_{jt}: Whether a recollection center operates in location j in time period t, $j = 1,...,J$, $t = 1,...,T$.

Our objective is to minimize the sum of the transportation time of all batteries for all time periods (Eq. 1).

The mathematical model is the collection of equations 1-6 and expressions 7-8.

$$\min \quad \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} x_{ijt} d_{ij} b_{it} \tag{1}$$

If a recollection center does not operate in location j in time period t, no population region is assigned to the location j in time period t (Eq. 2).

$$x_{ijt} \le y_{jt} \qquad \forall\, i = 1,\dots,I, j = 1,\dots,J, t = 1,\dots,T. \tag{2}$$

If a recollection center operates in location j in time period t, it should continue to operate until the last time period T (Eq. 3).

$$y_{jt} \le y_{j(t+1)} \qquad \forall\, j = 1,\dots,J, t = 1,\dots,T-1. \tag{3}$$

A population region i is assigned to only one recollection center in every time period t (Eq. 4).

$$\sum_{j=1}^{J} x_{ijt} = 1 \qquad \forall\, i = 1,\dots,I, t = 1,\dots,T. \tag{4}$$

Total number of operating recollection centers in time period t is R_t (Eq. 5).

$$\sum_{j=1}^{J} y_{jt} = R_t \qquad \forall\, t = 1,\dots,T. \tag{5}$$

Travel duration from a population region i to a recollection center in j should be less than D_{max} parameter for all time periods t (Eq. 6).

$$x_{ijt} d_{ij} < D_{max} \quad \forall\, i = 1,\dots,I, j = 1,\dots,J, t = 1,\dots,T. \tag{6}$$

Definition of binary variables are as follows:

$$x_{ijt} \in \{0,1\} \qquad \forall\, i = 1,\dots,I, j = 1,\dots,J, t = 1,\dots,T. \tag{7}$$

$$y_{jt} \in \{0,1\} \qquad \forall\, j = 1,\dots,J, t = 1,\dots,T. \tag{8}$$

We assume that recollection centers have unlimited capacity, as there is no available data of recollection centers that perform continuous repurposing operations.

We need to determine two types of parameters in order to solve an instance of the model: battery inventory and travel duration. Travel duration is a physical phenomenon and can be obtained from third-party applications. However, we need a methodology to calculate battery inventory in population regions. Here are three steps of the methodology:

1- Determining the aggregated total number of new vehicles for all population regions (Eq. 9).
2- Determining the aggregated total number of new vehicles with batteries for all population regions (Eq. 10).
3- Determining the number of EOL vehicle batteries for each population region (Eq. 11).

We have the following sets:

i: Population regions, $i = 1,...,I$.

z: Time periods, $z = 0,...,Z$.

We use the following parameters:

L: Lifetime of a vehicle battery.

S_1: The aggregated total number of new vehicles for all population regions in time period 1.

V_z: The aggregated total number of new vehicles with batteries for all population regions in time period z, $z=1,...,Z$.

E_{iz}: The number of vehicles with batteries in population region i in time period z, $i = 1,...,I$, $z=1,...,Z$.

$k_{(z,\, z+1)}$: Change rate of the aggregated total number of vehicles for all population regions from time period z to $z+1$, $z=1,...,Z-1$.

p_z: Penetration ratio of vehicles with batteries in time period z, $z=1,...,Z$.

m_{i0}: Ratio of number of vehicles that are in population region i in time period 0 to the aggregated total number of all vehicles for all population regions in time period 0, $i=1,...,I$.

n_{i0}: Ratio of vehicles with batteries that are in population region i in time period 0 to the aggregated total number of vehicles with batteries for all population regions in time period 0, $i=1,...,I$.

$$S_{z+1} = S_z\left(1 + k_{(z,z+1)}\right) \qquad \forall\, z = 1,\dots,Z-1. \tag{9}$$

$$V_z = S_z p_z \qquad \forall\, z = 1,\dots,Z. \tag{10}$$

$$E_{iz} = V_z\left(n_{i0} + (z)\frac{(m_{i0} - n_{i0})}{Z}\right) \ \forall\, i = 1,\dots,I, z = 1,\dots,Z. \tag{11}$$

We make variable b_{it} in the model equal to $\lceil E_{iz} \rceil$ for $i=1,\dots,I$, $t=1,\dots,T$ and $z=1,\dots,Z$, such that $t=z$. In reality, time period $t=1$ corresponds to L time periods after time period $z=1$, because a vehicle battery has a lifetime of L time periods.

As next, we apply the described model for the case of Germany.

5. Case study for Germany

In this section, we present and discuss an application of our model to three instances using data from Germany. First, we list the used data and assumptions. Then, we discuss the results.

1. i, j: Population regions and possible locations of recollection centers: $i,j=1,\dots,400$.

Kraftfahrt-Bundesamt (KBA, in English Federal Motor Transport Authority, German official institution) provides in its reports official facts and figures relating to motor vehicles in Germany in various degree of grid, from federal states, up to the division into regional communities.

The division into federal states is too rough to achieve a satisfying accuracy. The gradation into regional communities is very fine, which makes the model computationally intensive. “Bezirks”, in English “districts”, represent a coarser subdivision. We use the same 400 districts listed in the data of KBA [20]. Note that the data must be adjusted manually in order to avoid wrong coordinate queries because some districts share the same name.

2. t: Time periods: $t=2030,\dots,2060$.

We investigate the time period from 2030 to 2060. This assumption is based on the plan of European Union to achieve carbon-neutrality in 2050 [21].

3. b_{it}: Total battery inventory in the population region i in time period t.

Total amount and the share of batteries within the population regions are calculated in the following steps. Two types of vehicles contain a large battery: hybrid vehicles and electric vehicles. For convenience, we refer to both groups as e-vehicles.

a. We assume that the battery of a vehicle registered in a district will be recollected from the same district.

b. L: Lifetime of a vehicle battery: $L=10$.

The lifetime of electric vehicle batteries is its estimated average lifetime and is equal to 10 years. For example, the battery of a vehicle sold in 2020 will be brought to the recollection center in 2030.

c. S_1: The aggregated total number of new vehicles for all population regions in time period 1: $S_1=3.607.258$.

d. $k_{(z,\,z+1)}$: Change rate of the aggregated total number of vehicles for all population regions from time z to $z+1$, $z=1,\dots,Z-1$. $k_{(z,\,z+1)}=0$ for $z=2020,\dots,2049$.

We assume that the total number of new vehicle registrations is constant between 2020 and 2050 and equal to 2019 statistics. According to KBA statistics average annual rate of change of new vehicle registrations between 2009 and 2019 is -0.1% and is neglected.

e. p_z: Penetration ratio of e-vehicles in time period z:

We investigate three scenarios for the penetration rates of e-vehicles: optimistic, normal, and pessimistic, as described in Fig. 1.

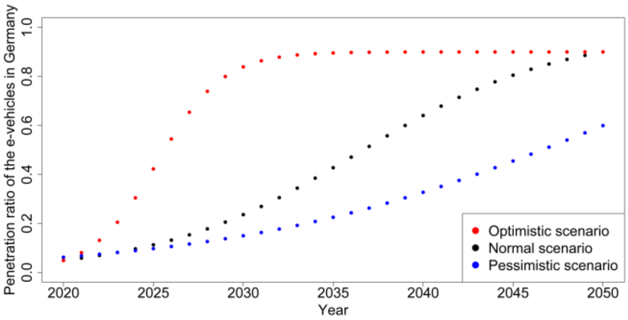


Fig. 1: Penetration ratio of e-vehicles in Germany between 2020-2050 according to the three scenarios investigated.

Some selected penetration ratio values are as follows:

$p_{\text{optimistic }2030}=0.84$, $p_{\text{optimistic }2050}=0.9$,
$p_{\text{normal }2030}=0.24$, $p_{\text{normal }2050}=0.9$,
$p_{\text{pessimistic }2030}=0.15$, $p_{\text{pessimistic }2050}=0.6$.

We assume that the ratio of e-vehicles registered in a district linearly approaches the value of all registered vehicles in that district in 2019 (See Equation 11). The trend for three exemplary districts is shown in Table 1.

Table 1. Possible cases for change in ratio of e-vehicles during 2020-2050.

District	Share of e-vehicles in the district from all e-vehicles registered in Germany in 01.01.2019	Share of vehicles in the district from all vehicles registered in Germany in 01.01.2019	Trend in the share of e-vehicles in the district in 2050 compared to 2020
District 1	4.83%	2.57%	Falling
District 2	0.33%	0.48%	Growing
District 3	0.19%	0.19%	Constant

In the optimistic scenario, we assume that the electric vehicle penetration ratio is 0.84 in 2030, and 0.9 in 2050, which approximates the objectives of the Federal Government.

In the normal scenario, the penetration ratio grows gradually until it reaches the intended value of 0.9 in 2050.

In the pessimistic scenario, in 2050 penetration ratio is 0.6 and we have a gradual increase of penetration ratio. This scenario considers that a different technology will prevail in the future.

f. V_z: The aggregated total number of new e-vehicles for all population regions in time period z. Numbers are rounded up to the nearest integer.

Some selected values are as follows:

$V_{optimistic\ 2020}=174.244$, $V_{optimistic\ 2050}=3.247.189$,
$V_{normal\ 2020}=178.567$, $V_{normal\ 2050}=3.246.668$,
$V_{pessimistic\ 2020}=223.160$, $V_{pessimistic\ 2050}=2.162.086$.

We exclude batteries of e-vehicles registered before 2020, since the first recollection center shall start operation in 2030. Vehicle batteries that will reach their EOL before 2030 should not affect the location decision.

4. Total number of operating recollection centers in time period t is R_t.
$R_t=1$ for $t=2030,...,2039$,
$R_t=2$ for $t=2040,...,2049$,
$R_t=3$ for $t=2050,...,2060$.

We assume that first recollection center will start operation in 2030, after the average lifetime of a LIB from the starting period, 2020. We assume that next center will open after a decade.

5. d_{ij}: Travel duration from the population region i to the recollection center in location j, $i=1,...,I$, $j=1,...,J$.

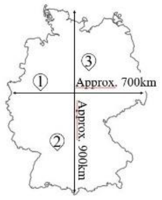
The minimum of the maximum durations from all districts to one district is approximately 5.581 hours. Note that, only one recollection center operates from 2030 to 2039 and it must be reached from any district within this time. We set D_{max} = 6 hours to ensure feasibility of the model.

We perform statistical calculations and generate graphs in R [22]. We use Python 3.7 [23] API of Gurobi 9.0 [24] to solve the model. We use computer with Intel(R)Core(TM)i5-6400 CPU@ 2.70 GHz processor and 8 gigabytes RAM. We obtain travel duration information from Open Route Service API [25].

In this case study, we use a fine-grained spatial distribution of batteries to determine three recollection centers for e-vehicle batteries. The average solution times of the models with 400 districts and 31 time periods is five hours. Nevertheless, in practice it shall not be a discouraging factor since recollection center location is a long-term strategic decision.

The results of the models for all three scenarios are same and are listed in Table 2.

Table 2. Results of the mathematical model for the three scenarios.

		Recollection center to be opened in		
	Scenario	2030	2040	2050
	Optimistic, Normal, Pessimistic	Soest, Nordrhein-Westfalen	Hohenlohekreis, Baden-Württemberg	Helmstedt, Niedersachsen

The first recollection center is opened relatively in the middle of Germany in the north-south direction. This is expected since we have a time limit for transportation between districts and recollection centers. The location of the first center is closer to the western border of the country because of higher population density and vehicle registrations compared to the eastern region.

Mainly this density also affects the location of the second center, as in the southern part of Germany the population density and vehicle registration are also high. Only afterwards, the third center opens in northern part of Germany, to reduce the transportation time there.

An important finding is that the determination of the location may not strongly depend on the local increase of the LIB within the country. Other parameters, such as the distribution across the country, seem to have a greater leverage effect. The sensitivity of the results to the distributional differences must be examined in more detail.

6. Conclusion and outlook

Electric vehicles shall become mainstream, thus the number of EOL vehicle batteries will increase. They have a potential to form a circular value chain. One possible scenario is battery repurposing, which needs specialized facilities. Batteries must be recollected and transported to these facilities. There is a need to develop tools that can guide decision makers to establish recollection centers.

In this paper, we develop a tool to determine locations for recollection centers based on a facility location model. The goal is to minimize the total transport durations of batteries, to ensure a quick and therefore safer transportation.

The strength of the model is that both total and local growth of vehicles can be adapted. Therefore, we test and discuss the model for three scenarios, based on parameters calculated for Germany from 2020 to 2050.

The location decision is robust to spatial and temporal distribution of batteries. The simulation shows that these parameters have a small influence on the sensitivity of the results. In future investigations, influence of other parameters, such as the capacity of the facilities, will be examined.

The model can be extended to reflect the requirements on a real recollection center. The current calculation assumes an infinite capacity of the recollection centers. If the efficient capacity of a recollection center is predictable, the required number of the centers and their locations could be calculated by the model.

Another future research topic is the influence of battery lifetime. We assume a constant lifetime of ten years. However, the development of the LIB is still characterized by a rapid technological advancement and the lifetime may change in future. Using the model, the influence of the lifetime can be analyzed.

The model can be also used for other settings. In the conducted calculation, we assume that no recollection infrastructure exists. Yet, existing facilities for battery recycling already recollect batteries. The model can be used to expand the existing network after updating the variables and constraints. Another setting is when decision makers consider several objectives. A multi-objective optimization version of the model can be used to generate Pareto optimal solutions. Decision makers will select one of these solutions according to their compromise criteria.

E-mobility is at the start of the implementation phase. Thus, there is a great opportunity to form circular economy value chains in e-mobility, such as for EOL batteries, even if the available data is limited. One challenge is the organization of the recollection of batteries. To find efficient solutions for recollection, different scenarios – including the facility location – with parameter variations should be calculated and analyzed. As the information availability and quality will change in time, the model should be continuously updated to reflect the real situation.

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