



# Location of facilities and network design for reverse logistics of lithium-ion batteries in Sweden

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## Abstract

Estimations of the amount of lithium-ion batteries reaching their end-of-life in 2025 and the amount being recycled indicates large deviations. To enable an efficient recycling process a well-defined and efficient supply chain network for the recovery of discarded lithium-ion batteries must be put in place. This includes analyzing the needs and restrictions of such a network. The aim of this paper is to provide decision support tools, to analyze input, and optimize a future supply chain for discarded lithium-ion batteries. A mixed integer programming model is developed and applied to the Swedish market. The findings show that several aspects will affect a reverse supply chain for discarded lithium-ion batteries, many of which are still uncertain and hard to predict.

**Keywords** Reverse logistics · Facility location · Successive re-optimization · Scenario based optimization · Network design

## 1 Introduction

Production and development of batteries containing lithium increase rapidly (Melin 2019b). The volumes of lithium-ion batteries are expected to increase and exceed the current flow of small non-rechargeable batteries. Such batteries can be found in a variety of products such as power tools, forklifts, trucks, trolleys, hand-held electronics. Due to the consumption of lithium-ion batteries, the demand for lithium is considered to further increase and it is assumed that batteries could account for 66 percent of global lithium production (Swain 2017). The increased demand is mainly driven by a swift growth of battery electric vehicle (BEV) production. The Swedish emission targets state that no later than 2045, Sweden will have net zero emissions compared with 1990. In addition the same targets

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state that the emissions caused by domestic transportation, excluding domestic flights, should be 70 percent lower in 2030 compared with 2010 (Swedish Energy Agency 2019). Incentive-wise, in 2018 the Swedish government introduced the bonus-malus system. This means that environmental adapted vehicles, which emit less than 60 g/km carbon dioxide, are rewarded with a bonus up to 60,000 SEK. On the other hand, the tax for vehicles with a internal combustion engine (ICE) is increased during the three first years of their use (Transportstyrelsen 2018). In a global context, both Great Britain and France have committed to ban the sale of cars with ICEs by 2040 (Gardiner 2017). Volvo has previously announced that starting in 2019 every new model launched will be partly, or completely, battery-powered (Vaughan 2017). This is not to say that the production of ICE powered vehicles will stop completely, but every model will be offered either as fully or partly electrified. Volkswagen has committed to produce around 50 million battery-driven vehicles over the coming years (Gitlin 2018), while General Motors advocates for a national policy in the United States, which would mean that at least 7 percent of sold cars in the US in 2021 have to be battery-powered (Blanco 2018). This percentage has to increase with at least two percent each year leading to 15 percent in 2025 and 25 percent in 2030. The International Energy Agency estimates that there will be 140 million electric vehicles globally by 2030. It is very difficult to say what effect it will have on lithium-ion batteries in terms of weight, but the CEO of the Canadian battery recycling company Li-Cycle argue that it could generate as much as 11 million tonnes (Gardiner 2017). To ensure that future demand can be met, lithium production capacity must increase. If, however, the trend of lithium demand stays at the same level and the recycling rate stays at a low level the scarcity of lithium could be a major problem by 2050 (Weil and Ziemann 2014). When lithium-ion batteries have reached their end-of-life the only sustainable option is that they are to be recycled. However, the recycling process of lithium-ion batteries is not yet fully developed. To enable such a process, it is important to study and analyze the impact of potential needs and restrictions on the design of the supply chain network for end-of-life lithium batteries.

Lithium-ion batteries have made a real impact on mobile phones and laptops, and since 2010 they have dominated the power tool market (Melin 2019a). The first serial manufactured electrical vehicles were introduced to the market in 2010 (Melin 2018). First cars and later on even busses has grown at a high pace and do currently dominate the market of lithium-ion batteries, these volumes continue to grow and circular Energy Storage estimates that more than 3,750,000 tonnes of lithium-ion batteries will be placed on the global market by 2025. There are also discrepancies between the amount of lithium-ion batteries reaching their end of life and the amount of being recycled. Estimations done by Circular Energy Storage (Melin 2018) place the amount of end-of-life batteries at approximately 750,000 tonnes in 2025 while the estimation of recycled batteries for the same time equals approximately 400,000 tonnes. Whereas neither the infrastructure nor the recycling process is fully developed, it is clear that there will be large quantities of discarded lithium-ion batteries needed to be recycled in the future. Currently, there are several ongoing research projects regarding the recycling process of lithium-ion batteries (Melin

2019a). However, to enable an efficient recycling process a well-defined and efficient supply chain network for the recovery of discarded lithium-ion batteries must be put in place. This includes analyzing the needs and restrictions of such a network. The purpose of this paper is therefore to provide necessary input and developed decision support tools that could be of use to analyse and optimize a future supply chain for discarded lithium-ion batteries.

The rest of this paper is structured as follows, in Sect. 2 a brief literature review is given on the subject of reverse logistics and facility location, Sect. 3 provides the context, needs, and restrictions that the supply chain network has to consider. Section 4 presents a developed MIP optimization model which is subsequently applied at the Swedish BEV-market. The final section includes the conclusions drawn by the study.

## 2 Literature review

The term reverse logistics has over the years gained increased attention. Its definition has been changing, and its scope widened as a result of increased scholarly interest in the subject (Agrawal et al. 2015). In its simplest form, it can be described as the opposite flow to a conventional supply chain (Fleischmann et al. 2000). Jayaraman et al. (2003) describe the reverse chain as when a product or component returns to the chain of production after its use. This can be for either repair, re-manufacturing, or recycling. Reverse logistics, therefore, encloses all the activities from used products no longer needed by the user, to products which are reusable in the market (Fleischmann et al. 1997). Its overall objective can be to reduce, substitute, reuse or recycle (Jayaraman et al. 2003). As a traditional supply chain handles the flow from the point of origin to many demand zones, the reverse chain is about bringing together a high number of low volume flows (Fleischmann et al. 2000). There are factors affecting the reverse chain's effectiveness both positively and negatively, described as drivers and barriers respectively (Agrawal et al. 2015). The drivers and barriers differ in character depending on which country and sector the chain is set up for. However, factors such as economic, legislative, environmental, and social have been broadly identified as drivers (Agrawal et al. 2015). Different barriers could be described as customer preference, regulation, resource constraints, and lack of stakeholder commitment (Carter and Ellram 1998). Volume is a major critical factor for the design of any supply chain network, it becomes even more critical in a reverse or recovery supply chain network. There is a high level of uncertainty for product returns and recovery management, since demand may be difficult to forecast. Fleischmann et al. (2000) claims that the availability of used products at the disposer market involves major unknown factors and that the timing and quantity of freed products are determined by the former user, rather than by the requirements of the recoverers. One could argue that this is a broad generalization and not applicable in all situations. Consider the change of battery for an EV; this is heavily dependent on the requirements of the manufacturer or its particular lifetime, it would not be a rational decision to change a fully functional battery. Products like apparel or consumer

electronics on the other hand, where the switching cost is much lower, corresponds better to the arguments of Fleischmann et al. (2000).

A supply chain integrates several interrelated activities through a network (Christopher 1999). Supply chain network design (SCND) can be considered as the first, and to some extent most important step, for either decreasing the total cost or increasing the total profit of a supply chain (Simchi-Levi et al. 2004). It is further one of the most crucial problems regarding planning in supply chain management (Govindan et al. 2017). The goal of this process is to engineer an efficient network structure to increase the chains total value (Farahani et al. 2014). Facility location addresses the challenges of where to locate or position new facilities to optimize at least one given objective. It could therefore be seen as a critical part of supply chain network design (Melo et al. 2009). The objective could be to either minimize costs, travel distance, or waiting times, or to maximize profit, revenues, or service levels. There could also be the combination of two or more such objectives (Farahani et al. 2010). As facility location has a decisive role in supply chain network design and planning. Melo et al. (2009) argue that the importance of its role will grow further as the need for more comprehensive models, which simultaneously can cope with many aspects, will increase. It is, therefore, necessary for sophisticated models to determine the best structure of a supply chain. As these decisions require large capital investments and are expected to be in operations for a long time, they could be seen as the core of strategical decisions (Klose and Drexl 2005; Melo et al. 2009). SCND is, however, a difficult task. In contrast to tactical or operational decisions which can be re-optimized on relatively short notice, facility locations are fixed and cannot be changed easily, due to underlying changes of the conditions for the supply chain (Daskin et al. 2005). These underlying changes of the conditions during the lifetime of the facility may turn a good location today into a bad in the future (Melo et al. 2009). Daskin et al. (2005) argue that regardless of how well tactical and operational decisions are optimized in response to changes in the supply chain, in case of an inefficient location for a facility redundant costs will arise during its lifetime. When making these decisions it is therefore important to recognize all intrinsic uncertainties linked to future conditions.

### 3 Problem description

The life span of a lithium-ion battery can be measured in two ways: overall age and cycle stability (BCG 2010). Cycle stability can be described as the number of times the battery has been discharged and then fully re-charged before losing 20 percent of its initial capacity. The 20 per cent are motivated by the fact that automakers are considering batteries from electrical vehicles not useful for traction when they have reached 80 percent of their initial capacity (Casals et al. 2019). Overall age, on the other hand, refers to the number of years the battery can be expected to function properly.

Furthermore, the life span of a lithium-ion batteries for BEVs is mainly affected by four factors (Futter 2019). These are calendar aging, state of health (SOH), operating temperature, and charging speed. The first factor, calendar

aging, is the natural aging of the battery, even if the battery is not used it will still lose capacity over time. The SOH can be described as the remaining capacity of the battery. This is measured as a percentage where zero percent equals an empty battery while 100 percent equals a full. The third factor affecting the expected lifespan is the operating temperature. The temperature in which all batteries achieve an optimum service life is if they are used at 20 degrees Celsius (Battery-University 2019). The performance of lithium-ion batteries is decreased if the operating temperature is higher or lower. Lastly, the charge level does affect the performance of the battery as well. Lithium-ion batteries charge to 4.20V/cell but for every reduction of 0.10V/cell in charge, voltage is believed to double the cycle life (Battery-University 2019). However, with a lower charge voltage, the storing capacity of the battery is reduced. The optimal charge voltage is believed to be 3.92V/cell in which all related stresses are eliminated. Reducing it further may not lead to more benefits but might induce other symptoms. To estimate a precise lifetime for lithium-ion batteries is a difficult task, not to say impossible, since it can be described as a function of the factors mentioned above. Some batteries will probably fail within the first years while others will function for a long time after the warranty expired. Even if a battery pack seems dead or not usable, the individual cells may. These cells can be pulled and reused, either in a new battery pack or in some other application. This means that when such batteries have reached their end-of-life in their current application, they still have 80 percent useful capacity in other applications. Retired cells could provide considerable benefits through secondary use such as energy storage from solar panels and wind turbines (Lai et al. 2019). They could also be used to acquire power from a regular grid connection when prices are low. This adds another dimension to the problem and difficulties in the estimations of the actual amount of lithium-ion batteries needed to be recycled for a given period. Even if we could predict the lifetime of batteries with a given certainty, there would still be uncertainty around the proportion of batteries which can be recycled and which can be reused.

Over recent years, a growing interest in recycling of lithium-ion batteries has emerged (Richa et al. 2014; Kumar 2011; Swain 2017). And even if the complete process is not yet fully developed, there are some processes and activities that have to be performed, both from a legal perspective and a metallurgical processing perspective. When a battery is removed from its application due to various reasons, it has to be tested and its quality evaluated. Based on the findings it is determined if it is suitable for re-use, where no additional treatment is needed, or if it is applicable for second use, i.e. have to go through a re-manufacturing process before being used in another application. If none of the previous options are possible the batteries need to be prepared for recycling, which means dismantled, discharged, and short-circuited in order for them to be considered safe to handle. From a legal standpoint lithium-ion batteries which are not encapsulated in a vehicle or any other application are considered dangerous goods (MSB 2019a). This means that there are restrictions regarding the transportation of discarded and unassembled lithium-ion batteries. According to regulations by the Swedish Civil Contingencies Agency (MSB 2019b) it is not allowed to transport more than 333 kilograms of lithium-ion batteries per transportation unit. A transport unit is defined as "Motorized vehicle without trailer,

or a combination consisting of a motorized vehicle with trailer”. Some exceptions are allowed, for example, if the batteries are transported for testing. Further regulations do apply, such as how the batteries should be packed for transportation and how they should be stored. If a battery is damaged and imposes increased risk, a permit from the Swedish Civil Contingencies Agency must be issued to transport the damaged battery.

As the objective of a reverse supply chain can be either to reduce, reuse, substitute, or recycle, in the case of spent lithium-ion batteries it is to recycle or to reuse. A big part of the batteries recovered will be recycled but some batteries might be subject to reuse, either to power other vehicles or in other applications. In the literature (Fleischmann et al. 2001; Jayaraman et al. 1999; Agrawal et al. 2015; Guide and Wassenhove 2003), recovery networks have been described as including several groups of activities such as collection, inspection/separation, re-processing, disposal, and re-distribution. The need for product acquisition, as described by Agrawal et al. (2015) and Guide and Wassenhove (2003) is motivated to determine which batteries need to enter the recovery network. Collection activities have to be carried out between various acquisition points and transportation of the battery packs to the inspection sites. Activities performed in inspection sites can include condition test, to determine if the battery packs are suited for reuse or second use, dismantling, short-circuited, and prepared for further transportation. It is in this step that the flows are being separated, one flow is directed to where battery packs suited for second use are being sent, there being reprocessed before being re-distributed to customers for other applications. The second flow constitutes those battery packs which need to be recycled. These are transported to recycling facilities where raw materials are extracted. Figure 1 gives a holistic view of how the supply chain should be designed to ensure that all necessary activities are performed.

As this study seeks to develop a strategic optimization model for discarded lithium-ion batteries which need to be recycled, the focus will be on the

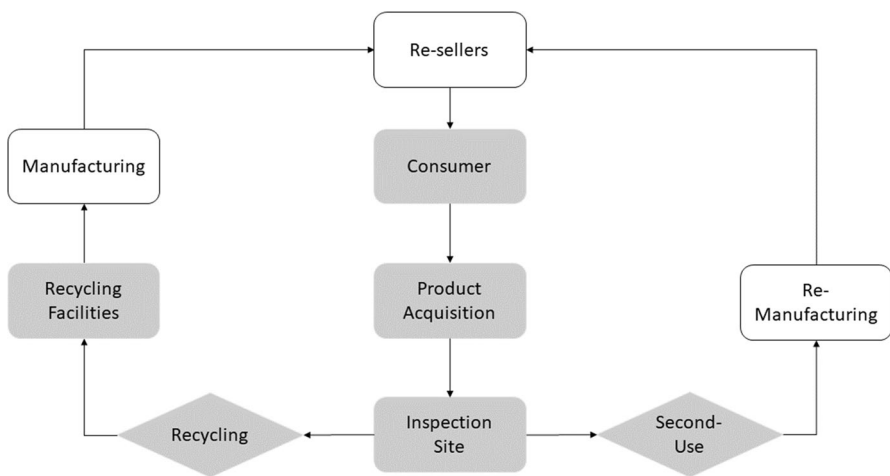


Fig. 1 Illustration of the supply chain

activities marked by grey color in Fig. 1. Considering the network structure, it can be described as a simple network structure where no consideration to the special characteristics of lithium-ion batteries has been taken. However, what differs a reverse supply chain for spent lithium-ion batteries from other used products are the stages of preparation before processing, legal restrictions, and the high degree of uncertainty regarding the amount of discarded batteries. The possibility of applying stochastic optimization (Birge and Louveaux 2011) has been considered. However, such an approach would require that probabilities be assigned to the amount of batteries for recycling, although lithium-ion batteries have not been on the market long enough time to determine such probabilities. In addition, the amount of discarded batteries is assumed to grow considerably from year to year which makes it desirable to optimize the supply chain for each period while at the same time consider the entire time horizon in a holistic approach.

## 4 Optimization model

As the optimization model is used for strategic purposes, i.e., to decide where to locate different inspection sites and recycling facilities, the formulation of the problem takes in to consideration the following cost elements:

- Collection costs, i.e., the costs of collecting discarded batteries at car workshops and transporting them to the inspection sites.
- Transportation costs from inspection sites to recycling facilities or through inter-modal terminals.
- Handling costs at inter-modal terminals, and
- The cost of capital for establishing various facilities.

The model can be described as a unlinked discrete multi-period problem without considering any inventories. The periods are representing various years. As demands are aggregated to these periods, the demand for each zone and each period must be ensured.

To fully describe the model mathematically, the following notation will be used:

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### Indices

$i \in \{1, \dots, I\}$ :	Set of demand zones.
$p \in \{2010, \dots, P\}$ :	Set of time periods, years.
$j \in \{1, \dots, J(p)\}$ :	Set of potential inspection sites.
$r \in \{1, \dots, R(p)\}$ :	Set of potential recycling facilities.
$k \in \{1, \dots, K\}$ :	Set of transportation modes.
$t \in \{1, \dots, T\}$ :	Set of available inter-modal terminals.

### Parameters

$d_{ip}$ :	Demand in kilograms per demand zone $i$ and year $p$ .
$c_{jikp}^1$ :	Collection cost from demand zone $i$ to inspection site $j$ with transportation mode $k$ in year $p$ .

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$C_k^2$ :	Transportation cost per kilogram and kilometer using transportation mode $k$ .
$C_{jip}^3$ :	Minimum cost of collection from demand zone $i$ to inspection site $j$ in year $p$ .
$A_{jt}^1$ :	Distance in kilometer between inspection site $j$ and inter-modal terminal $t$ .
$A_{jr}^2$ :	Distance in kilometer between inspection site $j$ and recycling facility $r$ .
$A_{tr}^3$ :	Distance in kilometers between inter-modal terminal $t$ and recycling facility $r$ .
$h_t$ :	Handling cost per kilogram at inter-modal terminal $t$ .
$k_j^1$ :	Yearly production capacity in kilograms for inspection site $j$ .
$k_r^2$ :	Yearly production capacity in kilograms for recycling facility $r$ .
$F_j^1$ :	Fixed cost for establishing inspection site $j$ .
$F_r^2$ :	Fixed cost for establishing recycling facility $r$ .
$DPR$ :	Years of depreciation.
$IR$ :	Internal rate, percentage on the initial investment.
$I_{max}$ :	Maximum number of inspection sites allowed.
$R_{max}$ :	Maximum number of recycling facilities allowed.
<i>Decision variables</i>	
$X_{ji}$ :	Proportion of the demand for demand zone $i$ in which is met by inspection site $j$ .
$Y_{jik}$ :	Kilograms transported from inspection site $j$ to inter-modal terminal $t$ using transportation mode $k$ .
$Z_{trk}$ :	Kilograms transported from inter-modal terminal $t$ to recycling facility $r$ using transportation mode $k$ .
$S_{jrk}$ :	Kilograms transported from inspection site $j$ directly to recycling facility $r$ using transportation mode $k$ .
$P_j = \begin{cases} 1, & \text{if inspection site } j \text{ is being used} \\ 0, & \text{otherwise.} \end{cases}$	
$Q_r = \begin{cases} 1, & \text{if recycling facility } r \text{ is being used} \\ 0, & \text{otherwise.} \end{cases}$	

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### 4.1 Objective function

To reduce the number of variables and shorten the run time of the model the parameter  $C_{jip}^3$  has been used, which is the minimum cost of collection for the different transport modes. That is, costs of all transport modes are calculated, but only the transport mode which represents the minimum cost will be used in the optimization. If one wishes to use a specific mode of transport, or include all modes, this is still possible. By multiplying each of these parameters with the fraction of the demand in each demand zone  $i$  ensured by inspection site  $j$ ,  $X_{ji}$ , the total collection cost for the network is obtained, resulting in the following term of the objective function:

$$\sum_j \sum_i C_{jip}^3 * X_{ji}. \tag{1}$$

The transportation cost from inspection sites to recycling facilities, or from inspection sites to recycling facilities through inter-modal terminals depends on the amount (in kilograms) sent between the nodes and the distance (in kilometers). Depending



on the transport mode, the cost per kilometer is affected. These costs are assumed to be linear in the weight and distance, resulting in the contribution of the following term to the objective function:

$$\sum_t \sum_r \sum_k Z_{trk} * A_{tr}^3 * c_k^2. \tag{2}$$

In those cases where the batteries are sent through a inter-modal terminal, a handling cost per kilogram is added to the term leading to the following contribution to the objective function:

$$\sum_j \sum_t \sum_k Y_{jtk} * (A_{jt}^1 * c_k^2 + h_t) + \sum_j \sum_r \sum_k S_{jrk} * A_{jr}^2 * c_k^2. \tag{3}$$

The last type of costs that are covered by the objective function are the costs of capital. These have been assumed to consist of two factors: a yearly depreciation cost, and the internal rate for the total investment. If any type of facility is used, the corresponding binary variable, either  $P_j$  or  $Q_r$ , is multiplied by these factors resulting in the following terms respectively:

$$\sum_j P_j * \left( \frac{F_j^1}{DPR} + F_j^1 * IR_j^1 \right), \tag{4}$$

and

$$\sum_r Q_r * \left( \frac{F_r^2}{DPR} + F_r^2 * IR_r^2 \right). \tag{5}$$

### 4.2 Constraints

All demand in each demand zone must be ensured in full:

$$\sum_j X_{ji} = 1, \quad \forall i. \tag{6}$$

For each inspection site, there needs to be a balance between incoming batteries and out-flowing materials. All incoming batteries must either be transported directly to recycling facilities after treatment or to recycling facilities through inter-modal terminals. The first term represents the flow of incoming batteries, as this is composed by the fraction of the demand in all demand zones supplied by the particular inspection site, multiplied with the actual demand of the corresponding region. Since this network only handles the lithium-ion batteries and the materials recovered from those, the in-flow amount has been multiplied by 0.5 to represent the proportion of the materials of the battery packs for which there are already defined flows, such as plastics. The left-hand side of Eq. (7) below represents the sum of kilograms sent from each inspection site to all recycling facilities or inter-modal terminals.

Equation (8) below ensures that the number of kilograms sent to each inter-modal terminal from all inspection sites is the same as that sent from each inter-modal terminal to all recycling facilities.

$$\sum_i X_{ji} * d_{ip} * 0.5 = \sum_t \sum_k Y_{jtk} + \sum_r \sum_k S_{jrk}, \quad \forall j. \tag{7}$$

$$\sum_j \sum_k Y_{jtk} = \sum_r \sum_k Z_{trk}, \quad \forall t. \tag{8}$$

Furthermore, the in-flow of battery packs or processed battery packs at any facility must be less or equal to the capacity of the corresponding facility. Equation (9) below ensures that the capacity at each inspection site is not exceeded, while Eq. (10) below ensures the same for each recycling facility.

$$\sum_i X_{ji} * d_{ip} \leq k_j^1, \quad \forall j. \tag{9}$$

$$\sum_t \sum_k Z_{trk} + \sum_j \sum_k S_{jrk} \leq k_r^2, \quad \forall r. \tag{10}$$

To ensure structural constraints Eqs. (11)–(13) below have been added. Equation (11) ensures that if a link exists between an inspection site and a recycling facility, that particular recycling facility must be open. Equation (12) ensures the same thing, but in those cases where a link exists between an inter-modal terminal and a recycling facility. Equation (13) ensures that each inspection site is opened if a link to it exists.

$$\sum_j \sum_k S_{jrk} \leq k_r^2 * Q_r, \quad \forall r. \tag{11}$$

$$\sum_t \sum_k Z_{trk} \leq k_r^2 * Q_r, \quad \forall r. \tag{12}$$

$$X_{ji} \leq P_j, \quad \forall i, j. \tag{13}$$

Finally, two more constraints have been added: Eqs. (14) and (15) below are concerned with those cases where it would be desirable to restrict the number of allowed inspection sites or recycling facilities:

$$\sum_j P_j \leq I_{max}, \tag{14}$$

and

$$\sum_r Q_r \leq R_{max}. \tag{15}$$

### 4.3 MIP formulation

The optimization model is thus stated as follows,  $\forall p$ :

$$\begin{aligned} \text{Min } W(p) = & \sum_j \sum_i C_{jip}^3 * X_{ji} + \sum_j \sum_t \sum_k Y_{jtk} * (A_{jt}^1 * c_k^2 + h_t) \\ & + \sum_t \sum_r \sum_k Z_{trk} * A_{tr}^3 * c_k^2 + \sum_j \sum_r \sum_k S_{jrk} * A_{jr}^2 * c_k^2 \\ & + \sum_j P_j * \left( \frac{F_j^1}{DPR} + F_j^1 * IR_j^1 \right) + \sum_r Q_r * \left( \frac{F_r^2}{DPR} + F_r^2 * IR_r^2 \right). \end{aligned} \tag{16}$$

Subject to:

$$\sum_j X_{ji} = 1, \quad \forall i. \tag{17}$$

$$\sum_i X_{ji} * d_{ip} * 0.5 = \sum_t \sum_k Y_{jtk} + \sum_r \sum_k S_{jrk}, \quad \forall j. \tag{18}$$

$$\sum_j \sum_k Y_{jtk} = \sum_r \sum_k Z_{trk}, \quad \forall t. \tag{19}$$

$$\sum_i X_{ji} * d_{ip} \leq k_j^1, \quad \forall j. \tag{20}$$

$$\sum_t \sum_k Z_{trk} + \sum_j \sum_k S_{jrk} \leq k_r^2, \quad \forall r. \tag{21}$$

$$\sum_j \sum_k S_{jrk} \leq k_r^2 * Q_r, \quad \forall r. \tag{22}$$

$$\sum_t \sum_k Z_{trk} \leq k_r^2 * Q_r, \quad \forall r. \tag{23}$$

$$X_{ji} \leq P_j, \quad \forall i, j. \tag{24}$$

$$\sum_j P_j \leq I_{max} \tag{25}$$

$$\sum_r Q_r \leq R_{max} \tag{26}$$

The sets  $J(p)$  and  $R(p)$  are affected by the solution of the previous period. To answer both the questions of how the final supply chain should be designed as well as how it should be successively developed, the model is run starting with the last period of the time horizon. To exemplify, assume that the final year is 2045 so that  $T = 2045$  and that  $P_j \in J(t)$  are the decision variables for opened inspection sites and  $Q_r \in R(t)$  for recycling facilities where  $t \in \{1, 2, \dots, T\}$ . In the first run, concerned with the final period, all possible locations are available and the solution determines the number and the locations of facilities needed to satisfy the highest demand. These locations,  $P_j(2045)$  and  $Q_r(2045)$  which are opened in 2045 are the only locations which are available as candidates in 2044 and earlier periods as necessary. This can further be described mathematically as follows:

$$j \in J(T) = \{1, 2, \dots, n\}$$

$$j \in J(t-1) = J(t) \setminus \{j \mid P_j(t) = 0\}$$

and,

$$r \in R(T) = \{1, 2, \dots, m\}$$

$$r \in R(t-1) = R(t) \setminus \{r \mid Q_r(t) = 0\}.$$

## 5 Case study

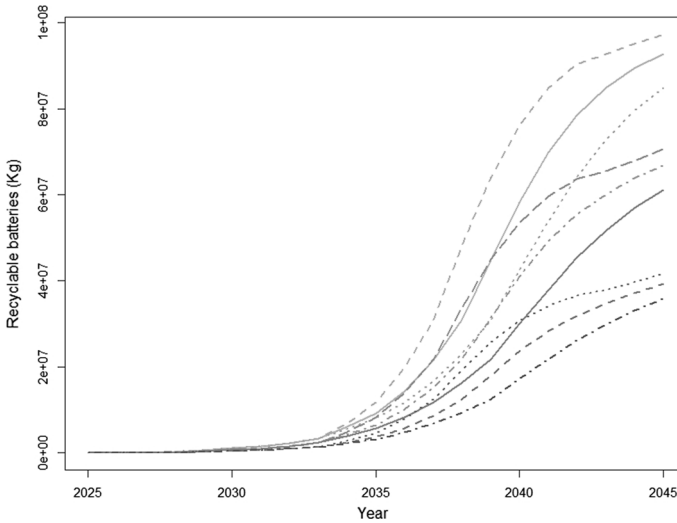
The amount of newly registered electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) in the Swedish market has increased rapidly over the last years. An overwhelming majority of these vehicles carry a lithium-based battery. Data from Statistics Sweden (2019) shows that in 2018, 13.67 percent of all newly registered cars are powered by a battery of some sort. Although the amount of newly registered cars decreased from 2017 to 2018 the amount of newly registered EVs, HEVs and PHEVs increased by 28.2 percent. At the same time, global automakers have made aggressive plans to electrify their vehicles over the coming years. Bloomberg (n.d.) predicts that battery-powered models will increase from 155 models globally in 2017 to approximately 290 in 2022. Furthermore, their forecast anticipates that by 2040, 55 percent of sold cars globally will be electrically powered as well as they will represent 33 percent of the global car fleet. Berggren and Kågeson (2017) state that to fulfil the European Union's target of carbon dioxide emissions by 2050, a vast part of the car fleet has to be fossil-free by that time. Based on their assumption that at least 80 percent of the car fleet has to be partly or fully electrified by 2050, battery driven vehicles will have to represent 50 percent of the new car sales by 2030. As of 2017, the proportion of battery-powered vehicles in Sweden was 2.4 percent of the total car fleet (Statistic Sweden, 2019), which means that these cars have to increase at a high pace the coming years, until they reach a slowdown phase. When this slowdown phase will occur is difficult to determine. The amount of accessible discarded lithium-ion batteries in the future is therefore unsure. Previous studies

(Berggren and Kågeson 2017) have tried to estimate this amount by different approaches, such as what the sales of BEVs should be for the European Union to reach their carbon dioxide emission objective. While others (Power Circle n.d.) have assumed fairly similar size of the total car fleet and increased the fraction of BEVs at a certain pace. The difficulty in estimating the future amount is mainly derived from two uncertain parameters; the number of newly registered BEVs, and the battery's expected lifespan. The first parameter is over time affected by several aspects, such as how the price of other fuels develops over time, the infrastructure and how it evolves, the access to charging points, and technical specifications of the vehicles as range, opportunity cost, or legislative incentives.

Due to uncertain future volumes, actual sales data from Statistic Sweden has been used for the years between 2010 to 2018. To forecast the sales of new BEVs from 2019 to 2030 the predicted market shares of these have been collected from the database ELIS V2.0.3 (Elbilsstatistik n.d.) and used as a "base-case". From this "base-case" both an optimistic and a pessimistic scenario has been derived. In the optimistic case, the market shares develop at a 20 percent higher pace, while in the pessimistic case these develop 20 percent slower. To estimate the number of sold BEVs in each year the respective market share has been multiplied with 366,000, which is the average of the last five years.

To determine when the battery has lost 20 percent or more of its original capacity and thus becomes non-usable for traction is not an easy task. This depends on multiple factors which in turn can change over the time that the vehicle is being used. In terms of overall age, batteries in controlled environments can be functional for up to 20 years (American-Chemical-Society, 2013). On the other hand, the average lifetime for Swedish personal vehicles are 17 years and most manufacturers offer a warranty of around 8 to 10 years for BEV batteries. The technological development contributes to more efficient batteries and better battery management systems which in turn is considered to prolong the life span of chargeable electric vehicle batteries in the future.

Based on these difficulties to estimate the life span of the batteries in vehicles, we assumed that each battery will be functional within the vehicle for 15 years. As technological development is contributing to prolonging the expected life span of lithium-ion batteries, 15 years is considered to be a reasonable benchmark for batteries used in BEVs. Eventually, there is one more factor affecting the generated demand of discarded lithium-ion batteries that have to be recycled: the proportion of batteries reused in other applications. The extent of which is, for various reasons, not possible to determine. Therefore, different scenarios have been used to deal with this uncertainty as well. The first scenario is if no reuse takes place, the second scenario is if 30 percent will be reused, and the third scenario is if 60 percent will be reused. At some point the reused batteries need to be recycled as well, and since previous studies (Casals et al. 2019) have placed the expected lifetime of reused lithium-ion batteries between 6 to 30 years, depending on second-use application, the fraction of which is assumed being reused have been extended by 10 years. Figure 2 shows how the different scenarios develop over the time horizon based on the assumptions made regarding sales and the proportion being reused.



**Fig. 2** Scenarios of demand development

## 5.1 Results

The weight for each battery has been determined by dividing the mean battery capacity of the top ten vehicles in each category by an assumed energy density of  $150\text{W/kg}$ . This yields an approximate weight (in kilograms) per battery. Considering the scenarios mentioned above and based on data from Statistic Sweden (2019) as well as ELIS V2.0.3 (Elbilsstatistik n.d.) calculations, the amount of discarded lithium-ion batteries which needs to be recycled lies between 200 and 700 kilotonnes accumulated until 2045. For the purpose of running the optimization model this amount has been distributed over the Swedish municipalities according to each municipality's fraction in Sweden's total BEV fleet as of February 2019.

The costs of the collection have been calculated using the method by Samuelsson (2016) for the estimation of distribution costs. However, some modifications have been made, for example the delivery frequency to each demand zone. The total annual number of stops in a demand zone is then calculated by multiplying the corresponding delivery frequency with the number of car workshops in each demand zone. If there is no demand in any zone for a specific year the cost of collection is set to zero for that specific year and demand zone. These calculations have been carried out for each year and each scenario as described earlier. The value of global parameters used is described in Table 1. The actual road distances between municipalities have been calculated using the Openrouteservices API (Openrouteservice, 2019) using Python. These are used both to calculate the cost of collection as well as the cost of transportation.

Each municipality was initially considered be a potential location for both inspection sites and recycling facilities. However, to shorten the run time of the model, potential locations for inspection sites and recycling facilities were

**Table 1** Global parameters used for estimating collection cost

	Big truck	Small truck	Super small truck
Load capacity (kg)	38,000	18,000	333
Average speed within a demandzone (km/h)	25	25	30
Average speed fom facility to demand zone (km/h)	65	75	85
Estimated stop time for each point (min)	12	12	12
Total allowed time on a route (h)	10	10	10
Cost per hour (SEK)	1100	800	500
Cost per Km (SEK)	20	16	12.5
Cost per Kg and Km (linear cost, SEK)	0.00105	0.00169	0.0648

aggregated to the level of region. This way, instead of having to solve a problem of 580 binary variables, the problem now only includes 42 binary variables. To obtain a credible result of the model, the data used was as far as possible retrieved from Statistic Sweden (Sweden 2019). For those parameters where valid data could not be obtained from Statistic Sweden, these were provided by businesses operating within that specific field. Table 2 summarizes the data sets, while Table 3 lists the values of parameters that have not been calculated or extracted from the open sources mentioned previously.

As the final year, 2045, corresponds to the highest demand, it is interesting to see how many of the two kinds of different facilities are needed to satisfy that demand. In addition to their locations and to the supply chain configuration, it is also desirable to obtain the cost of maintaining the supply chain that particular year. Table 4 lists the number of facilities and the cost of maintaining the supply

**Table 2** Summary of data sets

Number of demand zones	290
Number of time periods	20
Number of potential Inspection sites	21
Number of potential Recycling facilities	21
Number of available transportation modes	3
Number of available inter-modal terminals	35

**Table 3** Parameters used

Parameter	Description	Value
$h_t$	Handling cost per kilogram at inter-modal terminal $t$	0.5 SEK
$k_j^1$	Yearly production capacity in kilograms for inspection site $j$	7500 tonnes
$k_r^2$	Yearly production capacity in kilograms for recycling facility $r$	5000 tonnes
$F_j^1$	Fixed cost for establishing inspection site $j$	50 millions SEK
$F_r^2$	Fixed cost for establishing recycling facility $r$	2.5 billions SEK
$DPR$	Years of depreciation	30
$IR$	Internal rate	5%

**Table 4** Summary of results and scenarios

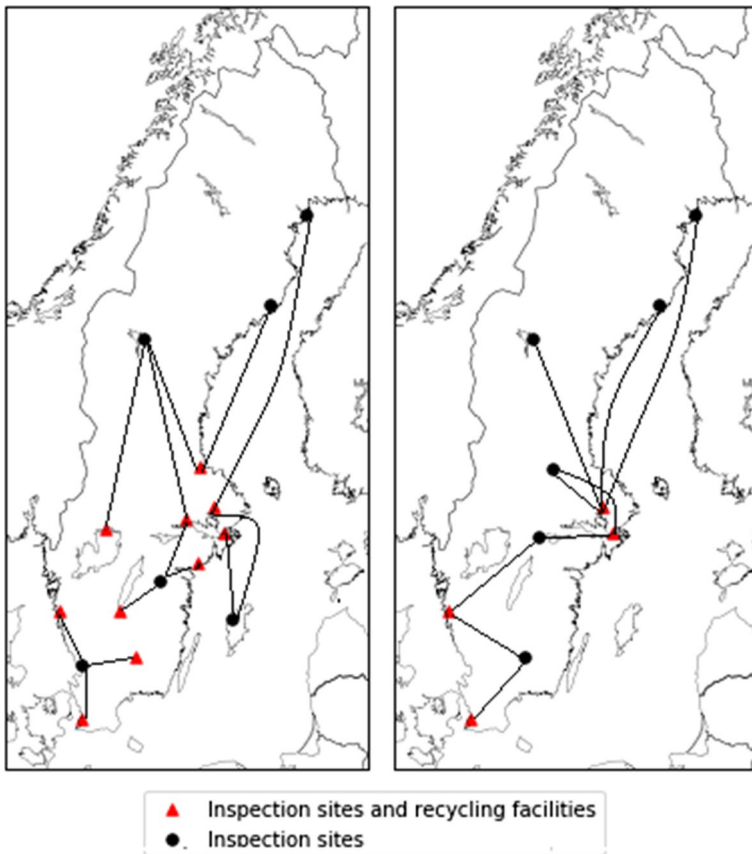
	Yearly cost (billion SEK)	Number of inspection sites	Number of recycling facilities
<i>No re-use</i>			
S1: Optimistic demand	2.30	16	10
S2: Base demand	2.29	16	10
S3: Pessimistic demand	2.07	15	9
<i>30 percent re-use</i>			
S4: Optimistic demand	1.84	13	8
S5: Base demand	1.62	12	7
S6: Pessimistic demand	1.61	12	7
<i>60 percent re-use</i>			
S7: Optimistic demand	1.17	10	5
S8: Base demand	0.968	10	4
S9: Pessimistic demand	0.964	10	4

chain for each scenario of the sales progress and the proportion of batteries being reused in 2045.

Table 4 shows that the cost of maintaining the supply chain is more than twice as large in the scenario which generates the highest volume of discarded lithium-ion batteries, S1, compared to the scenario that generates the lowest volume of discarded batteries, S9. This is so because S1 requires more inspection sites and more than twice as many recycling facilities. However, the progression of the sales does not have the same effect as the factor of the proportion of batteries being re-used before recycled on the cost, or the level of centralization and number of facilities of the network. Figure 3 visualizes the locations of the inspection sites and recycling facilities. In the figure, the locations of the facilities for the year 2045 and scenarios S1 and S9 have been plotted on a map projection of Sweden, while Table 5 describes how the number of facilities should be established for the time horizon in descending order starting from year 2045 and for scenarios S1 and S9.

In Fig. 3 those locations where both inspection sites and recycling facilities should be located are marked as red triangles while those locations where only inspection sites should be located are marked as black circles. As can be seen, the locations in which recycling facilities are placed in scenario S9 are also present in S1. The locations of the inspection sites may however differ and locations which are only inspection sites in S9 may also be recycling facilities in S1. It is important to keep in mind the assumption that demand is distributed over the demand zones in the same way regardless of the scenario. What differs between the scenarios is the aggregated demand which in turn is affected by the ratio between EVs and PHEVs. In the optimistic scenarios, the market shares of PHEVs decrease at a higher pace when price parity is reached, while in the pessimistic cases the market shares of PHEVs decreases at a slower pace. As can be seen, this factor affects both the number of inspection sites and recycling facilities as well





**Fig. 3** Locations of facilities for scenario 1 (left) and scenario 9 (right)

as their locations. Table 5 describes how these two scenarios are developed and in which pace, year for year starting from 2045 in descending order.

An additional factor to keep in mind is that between the years 2025 and 2034 the demand for S1–S3 is based on actual sales figures for the period 2010–2018 regarding EVs and PHEVs. For the other scenarios, demand is represented by the actual sales number multiplied with the fraction anticipated to be re-used. It is first in the year 2035 that demand is first affected by the forecast and thus diverges further.

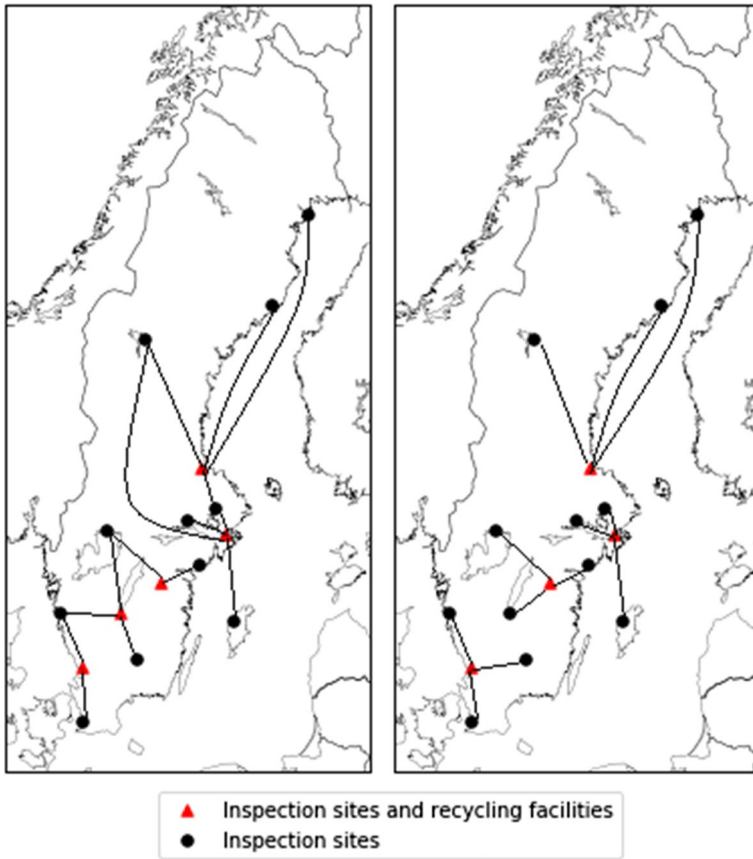
If the initial capacity for each recycling facility is set to 5000 tonnes per year, the number of recycling facilities produced by the solution in order to cover all demand is 10 for Scenario S1. To see how the model response to a change of recycling capacities, two additional analysis were performed for scenario S1. In the first analysis, the capacity was increased to 10,000 tonnes per year and in the second when capacity was increased to 15,000 tonnes per year for each recycling facility. None of the other parameters were changed. The results are presented in Fig. 4 and Table 6.

**Table 5** Facility development during the time frame

Year	Scenario 1			Scenario 9		
	Number of I.F	Number of R.F	Demand in tonnes	Number of I.F	Number of R.F	Demand in tonnes
2045	16	10	97,356	10	4	35,855
2044	16	10	94,995	10	4	33,147
2043	16	10	92,634	10	3	29,910
2042	15	10	90,273	9	3	26,151
2041	15	9	84,765	9	3	21,852
2040	14	8	76,062	8	2	17,267
2039	13	7	64,022	7	2	12,545
2038	11	5	48,127	7	1	9308
2037	10	4	31,018	7	1	6726
2036	9	2	19,807	7	1	4719
2035	8	2	11,766	6	1	3248
2034	7	1	6824	5	1	2249
2033	5	1	3418	5	1	1367
2032	5	1	2259	4	1	903
2031	5	1	1506	4	1	602
2030	4	1	1189	4	1	475
2029	4	1	575	3	1	230
2028	4	1	198	3	1	79
2027	4	1	116	3	1	46
2026	4	1	51	3	1	20
2025	2	1	3	2	1	1

## 6 Conclusions

Several aspects will affect the reverse supply chain for discarded lithium-ion batteries in Sweden, many of which are still uncertain and hard to predict with confidence. As a way of dealing with this uncertainty, different scenarios has been applied. This study contributes first and foremost with necessary input that will assist the process of designing and optimizing a reverse supply chain for discarded lithium-ion batteries. The developed model can become more specific with small changes and can, therefore, be suited for more tactical decisions. It can also serve as a strategic model for other purposes where parameters are unsure. The approach of calculating the fixed cost for establishing facilities, as a sum of a yearly depreciation cost and an internal rate of the initial investment, allows for facility location problems to incorporate a successive re-optimization of the location of facilities based on the period with the highest demand. The approach can further be used in any location or allocation problems which have the characteristics of fluctuating demand from period to period, or when the demand is assumed to slowly progress until it has reached a steady state. The robustness of the model



**Fig. 4** Locations with increased recycling capacity, 10,000 tonnes (left) and 15,000 tonnes (right) per year and facility

**Table 6** Results in year 2045 when recycling capacity is increased

	Recycling capacity in tonnes		
	5000	10,000	15,000
Number of recycling facilities	10	5	4
Number of inspection sites	16	16	16
Total cost in year 2045 (billion SEK)	2.30	1.26	1.054
Collection cost (billion SEK)	0.148	0.148	0.148
Transportation cost (million SEK)	2.93	5.30	5.65

has however not been tested. Further studies should therefore try to convert the model to a linked multi period mixed integer problem in order to determine the robustness of the successive re-optimization model.

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## References

- Agrawal S, Singh RK, Murtaza Q (2015) A literature review and perspectives in reverse logistics. *Resour Conserv Recycl* 97:76–92
- Battery-University (2019) Bu-502: discharging at high and low temperatures. Retrieved March 18, 2019, from <https://batteryuniversity.com/index.php/learn/article/dischargingathighandlowtemperatures>
- Battery-University (2019) Bu-808: how to prolong lithium-based batteries. Retrieved March 19, 2019, from <https://batteryuniversity.com/learn/article/howtoprolonglithiumbasedbatteries>
- BCG (2010). Batteries for electric cars challenges, opportunities, and the outlook to 2020. Boston Consulting Group
- Berggren C, Kågeson P (2017) Speeding up european electro-mobility: how to electrify half of new car sales by 2030. Report for transport and environment
- Birge JR, Louveaux F (2011) Introduction to stochastic programming. Springer, Berlin
- Blanco S (2018) GM calls for national electric vehicle policy, says EVS should be 25
- Bloomberg N (n.d.) Electric vehicle outlook 2018—bloomberg new energy finance. Retrieved March 12, 2019, from <https://about.bnef.com/electric-vehicle-outlook/>
- Carter CR, Ellram LM (1998) Reverse logistics: a review of the literature and framework for future investigation. *J Bus Logist* 19(1):85
- Casals LC, Barbero M, Corchero C (2019) Reused second life batteries for aggregated demand response services. *J Clean Prod* 212:99–108
- Christopher M (1999) Logistics and supply chain management: strategies for reducing cost and improving service. Financial Times: Pitman Publishing, London
- Daskin MS, Snyder LV, Berger RT (2005) Facility location in supply chain design. In: *Logistics systems: design and optimization*. Springer, Berlin, pp 39–65
- Elbilsstatistik (n.d.) Retrieved October 16, 2019. <https://www.elbilsstatistik.se/>
- Farahani RZ, Rezapour S, Drezner T, Fallah S (2014) Competitive supply chain network design: an overview of classifications, models, solution techniques and applications. *Omega* 45:92–118
- Farahani RZ, SteadieSeifi M, Asgari N (2010) Multiple criteria facility location problems: a survey. *Appl Math Model* 34(7):1689–1709
- Fleischmann M, Beullens P, Bloemhof-Ruwaard JM, Van Wassenhove LN (2001) The impact of product recovery on logistics network design. *Prod. Oper. Manag.* 10(2):156–173
- Fleischmann M, Bloemhof-Ruwaard JM, Dekker R, Van der Laan E, Van Nunen JA, Van Wassenhove LN (1997) Quantitative models for reverse logistics: a review. *Eur J Oper Res* 103(1):1–17
- Fleischmann M, Krikke HR, Dekker R, Flapper SDP (2000) A characterisation of logistics networks for product recovery. *Omega* 28(6):653–666
- Futter C (2019) Personal communication, Einride AB, p 17

- Gardiner J (2017) The rise of electric cars could leave us with a big battery waste problem. Retrieved from <https://www.theguardian.com/sustainable-business/2017/aug/10/electric-cars-big-battery-waste-problem-lithium-recycling>
- Gitlin JM (2018) Volkswagen plans to make 50 million electric cars, CEO says. Retrieved March 20, 2019, from <https://arstechnica.com/cars/2018/11/volkswagen-plans-to-make-50-million-electric-cars-ceo-says/>
- Govindan K, Fattahi M, Keyvanshokoo E (2017) Supply chain network design under uncertainty: a comprehensive review and future research directions. *Eur J Oper Res* 263(1):108–141
- Guide VDR, Wassenhove LN (2003) Business aspects of closed-loop supply chains. Carnegie Mellon University Press, Pittsburgh
- Jayaraman V, Guide VDR Jr, Srivastava R (1999) A closed-loop logistics model for remanufacturing. *J Oper Res Soc* 50(5):497–508
- Jayaraman V, Patterson RA, Rolland E (2003) The design of reverse distribution networks: models and solution procedures. *Eur J Oper Res* 150(1):128–149
- Klose A, Drexl A (2005) Facility location models for distribution system design. *Eur J Oper Res* 162(1):4–29
- Kumar A (2011) The lithium battery recycling challenge. *Waste Manag World* 12(4)
- Lai X, Qiao D, Zheng Y, Ouyang M, Han X, Zhou L (2019) A rapid screening and regrouping approach based on neural networks for large-scale retired lithium-ion cells in second-use applications. *J Clean Prod* 213:776–791
- Melin HE (2018) The lithium-ion battery end-of-life market 2018–2025
- Melin HE (2019a) State-of-the-art in reuse and recycling of lithium-ion batteries: a research review. Commissioned by The Swedish Energy Agency
- Melin HE (2019b) The lithium-ion battery end-of-life market: a baseline study
- Melo MT, Nickel S, Saldanha-Da-Gama F (2009) Facility location and supply chain management: a review. *Eur J Oper Res* 196(2):401–412
- MSB (2019) Litiumbatterier. Retrieved February 6, 2020, from <https://www.msb.se/sv/arnesomraden/skydd-mot-olyckor-och-farliga-amnen/farligt-gods/litiumbatterier/>
- MSB (2019) Transport av farligt gods. Retrieved October 27, 2019, from <https://www.msb.se/sv/regler/gallande-regler/transport-av-farligt-gods/>
- Openrouteservice (2019) Openrouteservice. Retrieved May 27, 2019, from <https://openrouteservice.org/category/api/>
- Power Circle (n.d.) Elis elbilsstatistik. Retrieved November 18, 2019. <http://powercircle.org/projekt/elis-elbilsstatistik/>
- Richa K, Babbitt CW, Gaustad G, Wang X (2014) A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour Conserv Recycl* 83:63–76
- Samuelsson B (2016) Estimating distribution costs in a supply chain network optimisation tool, a case study. *Oper Res* 16(3):469–499
- Simchi-Levi D, Kaminsky P, Simchi-Levi E (2004) Managing the supply chain: definitive guide. Tata McGraw-Hill Education
- Sweden Statistic (2019) Statistikdatabasen. Retrieved May 27, 2019, from <http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/?rxid=dda96411-b532-4971-a55a-2c6f0d07c07f>
- Swain B (2017) Recovery and recycling of lithium: a review. *Separation Purif Technol* 172:388–403
- Swedish Energy Agency (2019) Sveriges energi- och klimatmål. Retrieved November 25, 2019, from <https://www.energimyndigheten.se/klimat-miljo/sveriges-energi-och-klimatmal/>
- Transportstyrelsen, (2018) Bonus malus-system för personbilar, lätta lastbilar och lätta bussar. Retrieved November 25, 2019, from <https://www.transportstyrelsen.se/sv/vagtrafik/Fordon/bonus-malus/>
- Weil M., Ziemann S (2014). Recycling of traction batteries as a challenge and chance for future lithium availability. *Lithium-Ion Batteries*. Elsevier. 18, pp 509–528