Exploring reverse supply chain configurations of high voltage Li-ion batteries for heavy e-vehicles under different structural and operational conditions

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Abstract: Electrification of transportation is widely recognized as an enabler of sustainable development thanks to its potential to mitigate current global warming crisis. So far, industry has been focusing on technology deployment and scaling up, paying limited attention to the end-of-life of new vehicles and their components. However, if this emerging technology is to be truly sustainable in the long range, proactive planning and development of product and material recovery solutions is crucial from many perspectives. Reverse supply chain design is subject to deep uncertainties and simulation has been already used in literature as a suitable tool for examining alternative configurations and the key drivers of optimal design. This study aims to investigate the implications of different structural (centralized vs decentralized) and operational (in-house and outsourcing) configurations of the reverse supply chain configuration of high voltage li-ion batteries for heavy e-vehicles. All the stages in the reverse supply chain, i.e. acquisition of returned batteries, inspection, reconditioning (remanufacturing or recycling), warehousing and transportation, repurposing for second-life applications are considered. A Mixed Integer Linear Programming (MILP) model is finally proposed to support strategic and tactical decisions of an OEM (original equipment manufacturer) according to efficiency and circularity objectives. Results provide valuable ground for decision-making regarding the development of reverse supply chain systems of high voltage batteries and demonstrate that such systems can offer economic benefits for vehicle manufacturers.

Keywords: Circular Economy, reverse supply chain; lithium-ion batteries; electric vehicles; mixed integer linear programming

1.Introduction

The automotive industry is experiencing a significant transformation due to electrification of transportation and expected new sustainable technologies of essential components, such as batteries. Due to the ongoing technology deployment and scaling up, there are increasing concerns about the sustainable end-of-life management of batteries (Narins 2017; Richa et al. 2014). Hence, building the Circular Economy of lithium-ion batteries is today in the agenda of academics, policy-makers and business actors. Important factors such as the high economic value of materials inside batteries, material supply security and environmental obligations justify the implementation of Reverse Supply Chain (RSC) systems for batteries.

RSC can be defined as a set of activities and logistics structure for managing the backward flow of products (from customers back to suppliers) in order to retrieve their value (Prahinski & Kocabasoglu 2006; Fleischmann et al. 2000). This value can be recovered either at product/component level, for example through remanufacturing, repurposing, or at the material level through recycling. Although returned batteries are suitable for all recovery options, their destiny at the end of life is subject to structural and operational configuration of RSC, as well as strategic priorities of involved organisations.

Operations within reverse supply chain are more complex than traditional linear production-distribution manufacturing supply chains (Srivastava 2008). Indeed, such system is characterized by new actors (e.g., recyclers), new processes (e.g., collection, inspection, disassembly, recycling, transportation etc.), a wide range of uncertainties connected to reverse supply chain activities, e.g. uncertainties in relation to quality, quantity, diversity, time of returned products, balancing returns with demands (Sasikumar & Kannan 2008a), information asymmetries and incentive misalignment issues (Guide & Van Wassenhove 2009). In addition, RSC development is subject to multitude of other factors, such as economic viability, technological feasibility, legislation etc. (Lapko et al. 2018; Lau & Wang 2009). The complexity of the reverse supply chain and the involved uncertainties create many obstacles for network development and management. There is still no clear understanding how a reverse network should be developed, as companies keep struggling to set up an efficient system.

Therefore, this study aims to investigate the implications of different structural (centralized vs decentralized) and operational (in-house and outsourcing) configurations of the reverse supply chain of high voltage li-ion batteries for heavy e-vehicles. All the stages in the reverse supply chain are considered: acquisition of returned batteries, inspection, reconditioning (remanufacturing, repurposing for second-life applications and recycling), warehousing and transportation. A Mixed Integer Linear Programming (MILP) model is finally proposed to support strategic and tactical decisions of an OEM (original equipment manufacturer) according to efficiency and circularity objectives.

The rest of the paper is organised as follows. Next section provides a review of modelling approaches in the automotive sector, and for battery recovery in particular. Section 3 presents the modelling approach, with key model characteristics and their quantitative formulations in sections 4 and 5. Section 6 discusses the developed model against existing approaches and indicates the next steps of the study.

2.Literature review

The research stream on reverse supply chain design focuses on examination and management of distribution flows from customers to recovery facilities (and back to manufacturing sites). Review studies on RSC network design highlight the necessity to examine supply chain entities and connections between them, summarizing the key issues as: number of facilities and their location, types of recovery activities, allocation of physical flows among facilities, production and capacity planning, balancing forward and reverse operations (Souza 2013; Akçalı et al. 2009; Fleischmann et al. 2000).

We conducted a literature review in order to identify modeling approaches employed in the automotive sector, and for battery recovery in particular. The scope of the review includes academic articles published from 2008 onward (only publications in English). The search was conducted in the Scopus database applying the following key words: "network design" - to include all the articles that deal with the heuristic or mathematical design of networks and thus to avoid results that were less analytical; "closed loop supply chain", "reverse supply chain", "reverse logistics", "product recovery" - to include all the articles with alternative terminology and related scope; "automotive", "car", "vehicle", "battery" - to include only articles addressing specific context. The relevance of materials was evaluated in terms of their relation to network design. After exclusion of studies purely focused on "supplier selection", "routing problems", "general overview on RSC and managerial aspects", or targeting other industries, 31 articles were selected.

Among them, only five articles were focused on modelling of RSC for batteries (Reddy et al. 2019; Li et al. 2018; Demirel et al. 2016; Hoyer et al. 2015; Sasikumar & Haq 2011).. These studies considered remanufacturing, reuse, recycling and disposal as battery end-of-life management options, with overall network structure of 3-4 stages and either static or dynamic planning horizons. Reuse or repurposing of batteries was considered in only one study, in combination with recycling and disposal (Demirel et al. 2016). MILP appears to be a dominant modelling approach, as it allows framing complex supply chain entities through linear relations. In addition, sensitivity analysis is largely employed for dealing with the effects of uncertainties. See Appendix A for the summary.

It should be noted, that existing models are subject to various limitations in relation to involved actors and processes, interactions between forward and reverse flows, considered scenarios and assumption taken. Although models may provide general implications for some relations, they are context dependent. In order to address a specific business problem, the algorithm should be adjusted.

In this paper, we develop a model for an European automotive manufacturer according to its business priorities and interests. However, the decision-making criteria are considered as relevant for any industry.

3.Modelling approach

Before mathematical model development, the model characteristics had been discussed with a European automotive manufacturer. The company takes the lead in RSC development and aims to determine its optimal configuration. The required data was collected through semi-structured interviews and participating in the company's strategic meetings. Model characteristics are presented in the next section, which follows by mathematical model formulation.

The system has been modelled via Mixed Integer Linear Programming (MILP), an optimization approach that allows to find analytically the set of parameters that minimizes a given KPI. This methodology can be applied to a problem whose variables and parameters are linearly dependent. The chosen optimization software is MATLAB™, due to its flexibility and simplicity.

4.Model characteristics

The model considers refurbishment, remanufacturing, repurposing and recycling as end-of-life options. They are accomplished through the following set of key processes: collection of used BP (1), visual inspection of returned BP for damage (2), battery pack (BP) dismantling into battery modules (BM) (3), visual inspection of BM for damage (4), BM testing (5), BM sorting by state of health (SOH) (6), assembling of used BM (7), assembling of new BM (8), testing of assembled BP (9), storing/sending to dealers (or customers) (10), sending damaged parts and scrap to recycling (11). The RSC structure and its key stages are depicted at Figure 1. We distinguish remanufacturing from refurbishment on the basis of BM assembled: remanufactured BP is composed only from new BM, while refurbished BP is composed primary from returned BM (although new BM can be used as well if the amount of returned BM is not sufficient). Also repurposed BP is composed of returned BM, but with remaining capacity below 80% (SOH<80%). However, BM with SOH >=80% also can be utilised in case of spare units available after refurbishment. Remanufacturing and refurbishment operations are performed at the same facility. Damaged modules and scrap produced during remanufacturing, refurbishment and repurposing processes are sent to recycling. The output of recycling (material content) leaves the system. The same is true for repurposed BP sold to other applications. Each process includes storage activities and transportation links in-between.

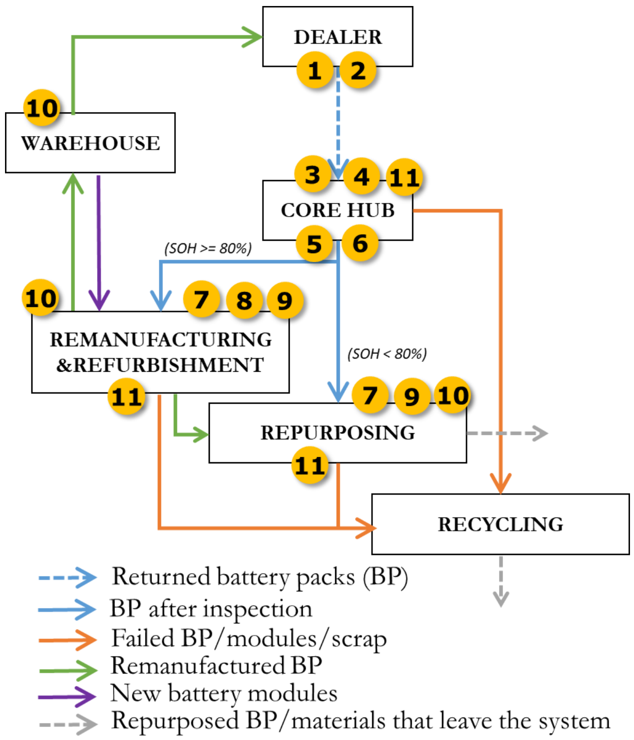

Figure 1: RSC structure

We focus on examination of network configurations based on the degree of centralization and the degree of OEM engagement against two decision categories – motivations: economic viability and circularity.

Fleischmann et al. (2000) defines centralisation through a number of locations at which the same process is performed. We adapt this definition and define a network as **centralised** when pre-processing (inspection, dismantling) and processing (remanufacturing, repurposing, recycling) activities are performed in the same location (or at close geographical proximity); **decentralised** network refers to two possible set ups: a) each process is carried out at single facility but at different geographical locations; b) each process is carried out in parallel at several facilities with different geographical locations (e.g. multiple recovery centres).

Researchers indicate several alternatives for OEM engagement in RSC: self-support (OEM itself manages pre-processing and processing operations), outsourcing (OEM involves existing retailers or third parties) and collaborations (Sasikumar & Kannan 2008b; Lau & Wang 2009; Krikke et al. 2013). In this study we focus only on two distinctive options: **in-house** (self-support) and **outsourcing** of operations, and consider OEM's engagement in remanufacturing/refurbishment and repurposing operations.

The proposed decision support model enables exploring the two dimensions in the continuum, meaning that the optimal configuration can be characterised by **mixed features**: centralisation of some activities, but not the others; carrying out in-house operations of some processes and outsourcing of others. Moreover, the model allows examining **changes of the RSC configuration over time** (multi-period model).

The choice of the configuration options is mainly driven by the offered value-added opportunities. Schenkel et al. (2015) indicates that recovery of returned products can provide OEM economic, environmental, information and customer value. Given the operational perspective of this study, the first two value categories are considered as the most relevant for decision-making. We frame them as economic viability and degree of circularity.

Economic viability takes into consideration cost structure of recovery processes (cost of establishing new facilities, their capacity expansion, operating costs in case of in-house operations, or cost of outsourced operation), warehousing and transportation. It will be discussed in terms of two main indicators: NPV (net present value) and PBT (payback time).

We consider the **degree of circularity** in terms of the content of batteries (amount of BM) reintroduced back in the system through refurbishment and repurposing. We do not consider remanufacturing, because new BM are employed in the process. Among the circularity indicators proposed at the product/component level (c.f. Morana et al., 2019), we build on the Product-Level Circularity Metric (PLCM) defined as a ratio from the economic value from recirculated flows over the economic value of all flows (Linder et al., 2017) and further adapt it to the considered system. In particular, we calculate degree of circularity as a multiplication of a proportion of batteries processed (either in refurbishment or repurposing) and their respective health factor, which represents battery's remaining service life (it reflects the value remaining in BM).

5.Formulation of the mathematical model

The following assumptions were considered:

- Different battery types are considered cumulatively (no differentiation, average values are assigned).
- Flow of batteries and modules is assigned by the routing coefficients.

- Time is represented as discrete: the model evolves along 12 time steps (one-time step = one year), each associated with a set of parameters and depending on the previous steps.
- Processing times are considered negligible in the model (compared to the length of a time step);
- Operations taking place at the dealers are not considered as differential.
- Cost parameters are considered constant during the whole simulation.
- Establishing costs are linear functions of the established capacity; expansion costs are linear functions of the expanded capacity; fixed costs are a linear function of the established capacity; variable processing costs are linear functions of the quantity of batteries processed.
- The maximum floor expansion space is supposed to be 150 m2 for the existing plants and 1500 m2 for the new ones.
- The selling price of the remanufactured, refurbished and repurposed batteries are calculated as the product between the associated Health Factor and the new battery price.
- The Health factor associated to remanufactured batteries is higher than the one associated to refurbished batteries that is respectively higher than the Health Factor of repurposed batteries.
- The process flow for remanufacturing, refurbishing and repurposing activities is the same.
- The cost of a new battery module has been considered as the 70% of the new battery pack cost expressed in Eur/KWh.
- The outsourcing costs has been calculated adding the third-party company profit margin to the corresponding in-house cost.
- Transportation costs are calculated considering a fixed trip cost coefficient, depending on the average truck load (number of loaded batteries), and a variable trip cost coefficient, depending on the travelled distance.
- No stock is considered in the model
- Remanufactured, repurposed and refurbished batteries are sources of revenue, while recycling is not source of revenue but only of costs.
- Investments for new facilities include all relevant cost items, depending on the process they perform.
- The costs of outsourced remanufacturing, refurbishing and repurposing activities are only made of the variable component.
- Capacity of the facilities refers to the maximum cumulative processing capacity of a single time step.
- Single life cycle of batteries is considered (remanufactured batteries do not enter back the system).

The nomenclature of the variables and parameters is reported in Appendix B.

Objective function

Maximize:

$$NPV = \sum_t \frac{Rev_t - TC_t - Rcpc_t - EstC_t - FixC_t - ExpC_t - VarC_t - OutC_t}{(1+r)^t}$$

Revenues at time *t*

$$Rev_t = \sum_m I_{mt} \cdot RPpr + \sum_p \sum_i \beta_{pit} \cdot RFpr \cdot RF\_WH + \sum_p \sum_i \beta_{pit} \cdot RMpr \cdot RM\_WH$$

Transportation costs at time *t*

$$TC_t = VTC_t + FTC_t + RCTC_t$$

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Variable trasportation costs at time t

$$VTC_t = \frac{Tvar}{BPtrip \cdot BPsize} \Big(\sum_i \sum_j x_{ijt} \cdot DL\_CH\_dist_{ij} + \sum_p \sum_i \beta_{pit} \cdot WH\_DL\_dist_{pi} + \sum_k \sum_p \Omega_{kpt} \cdot RM\_WH\_dist_{kp} + \sum_p \sum_k \alpha_{pkt} \cdot WH\_RM\_dist_{pk} + \sum_j \sum_k z_{pkt} \cdot CH\_RM\_dist_{jk} + \sum_j \sum_m y_{pkt} \cdot CH\_RP\_dist_{jm} + \sum_j \sum_l \theta_{jlt} \cdot CH\_RC\_dist_{jl} + \sum_k \sum_l w_{klt} \cdot RM\_RC\_dist_{kl} + \sum_k \sum_m \gamma_{kmt} \cdot RM\_RP\_dist_{km} + \sum_m \sum_l \delta_{mlt} \cdot RP\_RC\_dist_{ml} \Big)$$

Fixed transportation costs at time t

$$FTC_t = \frac{Tfix}{BPtrip \cdot BPsize} \Big(\sum_i \sum_j x_{ijt} + \sum_p \sum_i \beta_{pit} + \sum_k \sum_p \Omega_{kpt} + \sum_p \sum_k \alpha_{pkt} + \sum_j \sum_k z_{pkt} + \sum_j \sum_m y_{pkt} + \sum_j \sum_l \theta_{jlt} + \sum_k \sum_l w_{klt} + \sum_k \sum_m \gamma_{kmt} + \sum_m \sum_l \delta_{mlt} \Big)$$

Transportation costs towards recycling centres at time *t*

$$RCTC_t = BP\_wh \cdot \Big(+ \sum_j \sum_l \theta_{jlt} \cdot Tbp_l \cdot CH\_RCbp + \sum_j \sum_l \theta_{jlt} \cdot Tbm_l \cdot CH\_RCbm + \sum_k \sum_l w_{klt} \cdot Tbm_l + \sum_m \sum_l \delta_{mlt} \cdot Tbm_l \Big)$$

Transportation costs towards recycling centres at time *t*

$$RCTC_t = BP\_wh \cdot \Big(+ \sum_j \sum_l \theta_{jlt} \cdot Tbp_l \cdot CH\_RCbp + \sum_j \sum_l \theta_{jlt} \cdot Tbm_l \cdot CH\_RCbm + \sum_k \sum_l w_{klt} \cdot Tbm_l + \sum_m \sum_l \delta_{mlt} \cdot Tbm_l \Big)$$

Recycling processing costs at time t

$$RCPC_t = BP\_wh \cdot \left(\sum_j \sum_l \theta_{jlt} \cdot Rbp_l \cdot CH\_RCbp + \sum_j \sum_l \theta_{jlt} \cdot Rbm_l \cdot CH\_RCbm + \sum_k \sum_l w_{klt} \cdot Rbm_l + \sum_m \sum_l \delta_{mlt} \cdot Rbm_l \right)$$

Establishing costs at time t

(t_{est} is the year in which the plant is established)

$$EstC_t = \sum_j CH\_estab\_cost(CHcap_{j,t_{est}}) + (1 - RMcoeff)\sum_k RM\_estab\_cost(RMcap_{k,t_{est}}) + (1 - RPcoeff)\sum_m RP\_estab\_cost(RPcap_{m,t_{est}}) + \sum_p WH\_estab\_cost(WHcap_{p,t_{est}})$$

Expansion costs at time t

$$ExpC_t = \sum_j CH\_exp\_cost(CHexp_{jt}) + (1 - RMcoeff)\sum_k RM\_exp\_cost(RMexp_{kt}) + (1 - RPcoeff)\sum_m RP\_exp\_cost(RPexp_{mt}) + \sum_p WH\_exp\_cost(WHexp_{pt})$$

Fixed costs at time t

$$FixC_t = \sum_j CHfix(CHcap_{jt}) + (1 - RMcoeff)\sum_k RMfix(RMcap_{kt}) + (1 - RPcoeff)\sum_m RPfix(RPcap_{mt}) + \sum_p WHfix(WHcap_{pt})$$

Variable costs at time t

$$VarC_t = \sum_j CHvar(\sum_i X_{ijt}) + (1 - RMcoeff)\sum_k RMvar\left(\sum_p \Omega_{kpt}\right) + (1 - RPcoeff)\sum_m RPfix(I_{mt}) + \sum_p WHvar\left(\sum_i \beta_{pit}\right) + (warranty \cdot RM\_WH \cdot RMrev)\sum_p \sum_i \beta_{pit} + (warranty \cdot RF\_WH \cdot RFrev)\sum_p \sum_i \beta_{pit} + (warranty \cdot RPrev)\sum_m I_{mt}$$

Outsourcing costs at time t

$$OutC_t = RMcoeff \cdot RM\_WH \cdot RMout \cdot \sum_p \sum_i \beta_{pit} + RMcoeff \cdot RF\_WH \cdot RFout \cdot \sum_p \sum_i \beta_{pit} + RPcoeff \cdot RPout \sum_m I_{mt}$$

Constraints

- Flow consistency between all the RSC stages
- Flow consistency at each RSC stage (in and out)
- Capacity at each processing and storing stage

Degree of Circularity Index (DCI)

$$DCI = HF\_RF * RFrec + HF\_RP * RPrec$$

6. Numerical case study

A numerical case study was implemented based on the data provided by an European automotive manufacturer together with information from publicly available reports on battery processing. Due to the limited space, we report only the results of calculations.

We examined the RSC configuration through 24 scenarios based on priorities and interests of the case company. In particular, the following variations in RSC set-ups were considered:

- allocation of processes between RSC stages: Option A = processes 5 and 6 are located at the core hub; Option B = processes 5 and 6 are performed at recovery facilities (2 options in total);
- allocation of returned battery flows among recovery processes and customer demand for battery replacement: FL1 = 10% to recycling; 10% to repurposing, 80% to remanufacturing/refurbishment; customer demand for replacement: 70% remanufactured BP, 30% refurbished BP; FL2 = same as FL1, except that customer demand is the opposite: 30% remanufactured BP, 70% refurbished BP; FL3 = same demand as in FL2, but flow distribution is: 10% to recycling; 20% to repurposing, 70% to remanufacturing/ refurbishment (3 options in total);
- operational set up of remanufacturing/ refurbishment and repurposing: in-house vs outsourcing (4 options in total).

The results of 24 scenarios are reported in Appendix C.

From the economic perspective (NPV and PBT), it is possible to make the following conclusions. FL1 is a least preferable allocation of flows due to costs related to acquisition of new BM for performing remanufacturing (the dominant recovery option in this flow allocation type). FL2 is more preferable over FL3. For example, scenario S24 (FL3) has 15% lower NPV comparing to S23 (FL2). The difference between flow allocation type FL2 and FL3 can be explained by additional costs related to the purchase of extra BM needed for refurbishment process, as there is no sufficient amount of returned BM to meet customer demand under FL3, because more returned batteries are directed to repurposing. Another reason is the change in transportation costs related to changes in flows: e.g. more batteries are transported from core hubs to repurposing facilities, and there is no flow from remanufacturing/ refurbishment facility to repurposing facility in FL3.

Process allocation type B is more preferable over type A under the same flow allocation type for all operational set up except for in-house operation of all recovery processes and for scenarios with FL1. The difference in NPV varies considerably: 1% in S17 vs S14; 9% in S23 vs S20 with an increase of PBT by 1 year; 30% in S1 vs S4. The differences between process allocation types A and B appear to be a result of different allocation of capacity of core hubs and its extension over time; this, in turn, affects distribution of flows between other facilities in RSC (the dominant flows across all facilities remain the same in both scenarios). However, the mentioned variations over years result in the same final RSC configurations for both process allocation types (under the same flow allocation type for all operational set up).

The configuration proposed by the model have both decentralised and centralised characteristics. As it is reported in Appendix C, the model assigned various levels of centralisation over location 1 for core hub, remanufacturing/ refurbishment, repurposing and warehousing facilities across different scenarios. However, each operation is also performed in alternative facilities (a characteristics of decentralisation).

The model indicates scenario S23 as the best solution, as it offers the highest NPV with the shortest PBT period. It is characterised by process allocation type B, FL2, and full outsourcing of EOL operation. If we consider the same PBT (9 years), the next best scenarios would be S14 and S17. Comparing to S23, they offer a very different operational set-up: in-house operation of remanufacturing/refurbishment and outsourcing of repurposing. The opposite operational set-up, outsourcing of remanufacturing/refurbishment and in-house operation of repurposing (S11 and S8), is characterised by much lower NPV by and 2 extra years of PBT comparing to S23. The middle way would be performing recovery operations fully in-house (S2 and S5), with lower NPV, but with only one extra year of PBT comparing to S23.Full outsourcing of recovery operations (e.g. S23 and S20) appears to be more preferable comparing to their in-house management (e.g. S2 and S5). However, if the mixed operational set-up is considered, the model highlights that it is more economically attractive to bring in-house remanufacturing/refurbishment comparing to repurposing (e.g. S17 vs S11).

Comparing to outsourcing, in-house operations require high initial investments for establishing new facilities, capacity expansion; operating costs, which lead to lower economic performance. However, they may offer a stronger competitive advantage if the company prioritises not only economic indicators, but also other aspects such as security of components supply, better control of the employed recovery technologies and output of processes.

The model also provides implications for the degree of circularity. It is primary affected by allocation of flows among recovery facilities. All considered types of flows assume that 83% of returned battery modules are re-introduce back in the industrial system via different distribution of flows between refurbishment and repurposing. We obtain the following values of circularity: FL1 (30% refurbishment; 53% repurposing) = 0.505; FL2 (70% refurbishment; 13% repurposing) = 0.625; FL3 (68% refurbishment; 15% repurposing) = 0.619. Refurbishment process has the highest circularity index, as it (re)assembles BM with high health factor. Therefore, from the perspective of value embedded in batteries, it is better not to send batteries suitable for refurbishment to repurposing. It appears that the same is true also from the economic perspective (FL2 is preferable over FL3 and FL1). The degree of circularity index provides additional information for a decision-maker for choosing the dominant end-of-life recovery process or a mix of processes.

Therefore, it is possible to imply that for the examined case study, it is preferable to choose RSC configuration with flow allocation FL2, process allocation type B and outsourcing of recovery options.

7.Discussion and conclusions

As shown in Appendix A, the developed model offers a new approach for examining different configuration options of RSC for Li-ion batteries. Previous models were framed around specific structural (centralized or decentralized) and operational (in-house or outsourcing) configurations, but did not examine alternative options against each other. The chosen modelling approach enables the optimization of the RSC configuration under multiple operational and structural conditions. In particular, given the expected demand, it is aband decentralisation, and level of OEM engagement that minimize investment and operations costs. Moreover, the proposed model considers multiple processes and the related facilities, offering the most effective investment strategy given the changes in battery volume over 12-year-period, while taking into consideration also the chance to outsource portions of the RSC.

Although the economic factors are commonly addressed and the optimisation usually aims to maximise profit or minimise costs, environmental performance has been addressed only in one other paper in the form of emissions. We introduce the Degree of Circularity Index as an additional decision parameter, which should provide an alternative perspective when choosing the preferred RSC configuration.

However, the model is subject to some limitations. Due to the introduced simplifications, this approach gives only a general idea of the best system structure: time step length choice, deterministic demand and battery flows, centralization of the dealers per country, approximation of the transportation cost, and the impossibility to observe system dynamism over time are the main limits directly linked to the chosen modelling approach.

Current results represent the first step of a broader on-going study that entails the use of the model to design the RSC of a European automotive manufacturer based on a mix of company-specific and generic data.

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