A Simulation Analysis of Economic and Environmental Factors in the Design of an Electric Vehicle Battery Reverse Supply Chain

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Abstract: This article presents a study of a discrete-event simulation model of a UK reverse supply chain (RSC) for electric vehicle batteries. The purpose of the study is to use the model to run a set of simulated scenarios to explore how different operational strategies affect the RSC design configuration. The performance of the RSC can be measured in terms of its economic impact (such as the value of material recovered and production savings) and environmental impact (such as batteries recovered, remanufactured and repurposed, kg of materials recovered and CO_2 emissions reduction). A key outcome of the study is that supply chain participants found that although they were aware of individual processes within the RSC the insights of the model covering the whole RSC and the metrics generated would enable them to make better informed RSC design decisions.

1 INTRODUCTION

Environmental, legal, social and economic factors have been encouraging manufacturing companies to adopt greener and more sustainable supply chain practices and are accounting for the end-of-life (EoL) of products (Kazemi, Modak and Govindan, 2019). Consequently, businesses are now looking at supply chains more broadly and considering the reverse flow, creating reverse supply chains. A reverse supply chain (RSC) consists of all the parties and processes involved in collecting products from a customer to recover value or dispose of them (Guide Jr. and Van Wassenhove, 2002).

The automotive industry is one of the industries experiencing significant challenges in their reverse supply chains in the coming years due to the rapid growth of electric vehicle (EV) adoption. Global EV sales are expected to increase steadily in the coming years, from 3.1 million in 2020 to 14 million in 2025 (BloombergNEF, 2021). Electric vehicle batteries are the most critical component of electric vehicles because they account for a significant part of the vehicle's cost and are highly relevant for EV development and adoption. Since EV batteries typically last between 8 to 10 years, the EOL supply chain of this component needs to be prepared to handle the increasing volumes of batteries that are going to reach their end-of-life in the following decades.

Electric vehicle batteries require unique management when reaching their EOL for several reasons. Firstly, the EV battery industry may face a shortage or rise in the price of some of the critical raw materials used in battery production (International Energy Agency, 2018; Moores, 2018). Therefore, recovering EV battery materials could help save costs and preserve raw materials. Secondly, lithium-ion, the most common EV battery type, uses metals such as lithium, cobalt, nickel, and graphite that may harm the environment and human health if not disposed of properly (Winslow, Laux and Townsend, 2018; International Energy Agency, 2019). Therefore, the EoL management of batteries contributes to the reduction of the EV carbon footprint. Thirdly, several potential risks are associated with battery handling, and it is necessary to follow careful procedures to minimise the risks (Zeng, Li and Liu, 2015).

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Therefore, assigning this work to professional OEMs (Original Equipment Manufacturers) and third-party logistics 3PL providers is essential. Lastly, under the latest Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries that was released in July 2023 (European Commission, 2023), EV manufacturers are responsible for the environmental impacts of the batteries used in their vehicles right up until the end-of-life cycle. The UK is one of the most influential electric vehicle markets in Europe. The British government is supporting the electrification of the automotive sector in several ways.

The UK and the European Union (EU) have agreed to extend their tariff-free trade in electric vehicles, potentially saving car manufacturers and consumers up to £4.3 billion in additional costs (GOV.UK, 2023b). Moreover, the UK government has been attracting investment in EV battery gigafactories and EV manufacturing. Nissan is investing £3 billion to develop EVS in Sunderland. At the same time, BMW is investing £600 million to build Mini EVs in Oxford (GOV.UK, 2023a). Envision and Tata are investing £450 million and £4 billion in new gigafactories (AESC, 2023; GOV.UK, 2023c).

Despite all the important investments in EV and EV battery manufacturing, the UK end-of-life electric vehicle supply chain is at an early stage. The number of EVs (Electric Vehicles) and EV batteries reaching their end-of-life is still low, and several EV manufacturers have not defined the structure of their EoL reverse supply chains yet.

Several authors have addressed the topic of reverse supply chain design by developing models. Some interesting models were found in the literature (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015). However, most of these papers suggest alternatives to improve the efficiency of the processes rather than to achieve supply chain sustainability. There is also a lack of industry case studies; most of the papers found in the literature present illustrative cases with created data. Some practical simulation models were found in the literature (see Jayant et al., 2014; Yanikara & Kuhl, 2015) but they are generally limited to a quantitative analysis without a thoughtful understanding of the industry context and other factors that influence design decisions such as industry stage, suppliers' resources and capabilities or legislations. Furthermore, the models studied mainly include manufacturers and recyclers in their reverse supply chain models but do not consider other key stakeholders such as remanufacturers, refurbishing companies and second-life repurposing companies. The relevance of building appropriate relationships between them to build successful and sustainable supply chains is also overlooked.

Modelling a future sustainable EoL reverse supply chain poses a number of challenges. In the case of the EV battery industry, its UK EoL reverse supply chain is still in a developing stage, and no defined supply chain is currently operating and so the EoL process flows for EV batteries are not clearly defined. The technology for recycling, recovery and remanufacturing is still under development. The service providers and companies that offer EoL services are at the moment handling low volumes of batteries, and markets for the recovered products and materials are still being explored. Moreover, the legislation around the EoL treatment of EV batteries is subject to change. Also, current legislation is mainly focused on recycling as opposed to alternative options for batteries such as remanufacturing and repurposing.

This research draws on the preliminary information collected from managers and directors from companies that have experience providing EoL services to the automotive industry and have worked or have run pilots with EV batteries. This study presents a potential UK EoL supply chain for electric vehicle batteries that includes a dealer service centre, a specialised authorised treatment facility (ATF) network across the UK, a remanufacturing company, a repurposing company and a recycling company. These selected companies are key players in the EoL supply chain for EV batteries since they are responsible for collecting the EV batteries from EV users and offer different recovery alternatives to extend the life of EV batteries, components, and materials. All the companies involved in this research are UK-based. Even though this study focuses on the UK context, the methodology can be used to study other contexts, and the model can be easily adapted. The objectives of the study are the following:

- To model a UK EoL RSC for EV batteries that can be used to represent future design configurations.
- To run a set of simulated scenarios to explore how different sustainability strategies affect the RSC design configuration and assess the economic impact (such as the value of material recovered and production savings) and environmental impact (such as batteries recovered, remanufactured and repurposed, kg of materials recovered and CO2 emissions reduction).

2 THE SIMULATION STUDY

The main stages in the simulation study are now presented with results from a scenario that assesses the effect on the RSC design of batteries destined for recycling, remanufacturing and repurposing operations.

2.1 Data Collection/Process Mapping

The initial data of the current process was collected through semi-structured interviews and questionnaires. While the future RSC for EV batteries model was abstracted and refined using facilitated modelling (Robinson et al., 2014) sessions with managers and directors from a scrap car recycling company that manages an important ATF network, remanufacturing company, repurposing company and a lithium-ion battery recycler. Meanwhile questionnaires were used to collect specific data about the process characteristics such as processing times, processing sequences and workforce schedules. The participants of the facilitated interventions were:

- Client_AC: Environmental Planning Manager – Automotive company
- Client_RG: Technology and Innovation Manager – Recycling group
- Client_EC: Company Director – Engineering company
- Client_CF: Head of Forecasting – Consultancy Firm specialised in lithium-ion battery and electric vehicle supply chain.
- Client_CF2: Battery specialist and Senior Engineer from Circular Economy team – Consultancy Firm specialised in circular economy projects.

The main processes that have been mapped and included in the UK EOL supply chain for electric vehicle batteries of this study are the following (Figure 1):

- Batteries still under the warranty period are collected by the dealer service centres, otherwise batteries are collected through the ATFs.
- After the batteries are removed from the EVs, they are sent to the Testing Facility where the battery packs pass through an initial testing.
- Then, the batteries are disassembled to module level, and tested to decide the EOL route.
- The modules in good condition are sent to the remanufacturing plant for remanufacturing. After the remanufacturing process is completed the new batteries are tested and packed.
- The modules that did not pass the module testing are disassembled to cell level.
- The battery cells then pass through a grading process to measure their performance.
- The cells in good conditions that can be used to build up new second-life batteries are sent to the repurposing plant to be assembled, tested and packed.
- The cells that did not pass the grading are sent to a recycling plant where they are scrapped with any valuable material recovered.

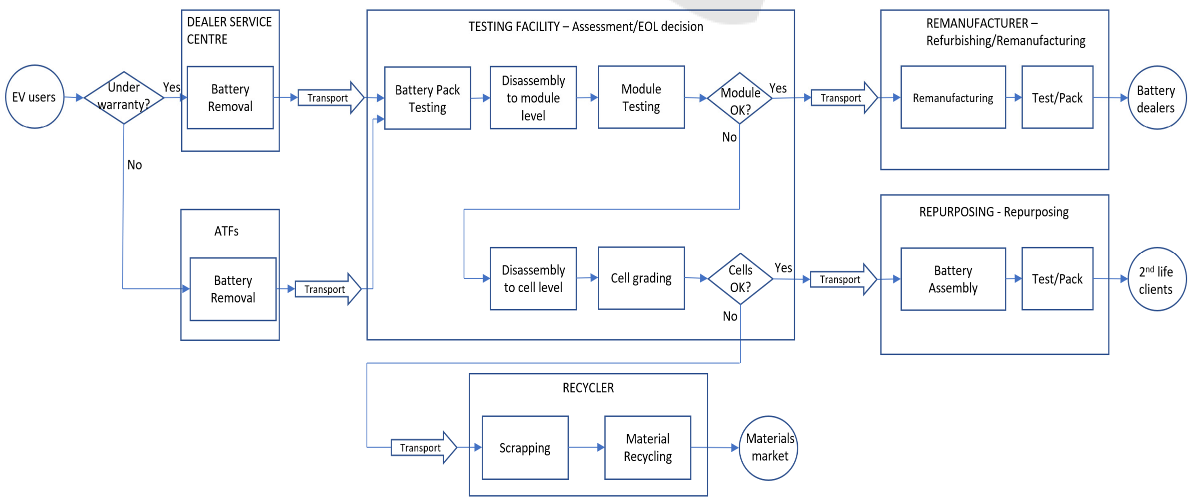

Figure 1: EOL EV batteries process map.

2.2 Modelling Input Data

The demand level for battery processing has been estimated based on secondary data from the Department for Transport in the UK (Department of Transport, 2022) and from an 8-10 years estimated lifetime of EV battery (Gruber et al., 2011). The processing times were estimated based on information provided by the industry participants in the study based in the recycling, remanufacturing and repurposing sector.

2.3 Building the Model

The discrete-event simulation model of the EOL RSC for EV batteries was built using the Arena Simulation Software v16.2 (Rockwell Automation, 2023). The software allowed the building up of a simplified RSC network following the process map in Figure 1.

2.4 Validation

In this case study as the simulation model is representing a potential EOL RSC that does not exist, the validation was supported using the facilitated modelling intervention sessions (Robinson et al., 2014) with industry experts. The three aspects of validation proposed by Pegden, Shannon and Sadowski (1995) are used: conceptual validity, operational validity and believability.

2.4.1 Conceptual Validity

Conceptual validity ensures that the model built represents a credible approximation to the real-world system. To confirm the conceptual validity of this simulation model and increase its credibility, facilitated sessions were conducted with potential users of the simulation model. Individual facilitated sessions were arranged with potential users of the simulation model (Client_AC, Client_RG, Client_EC, Client_CF, Client_CF2) for the validation stage. In these meetings the conceptual model, simplification and assumptions of the EOL RSC for EV batteries of this study were shared with the participants. Some of the key elements of the conceptual model were explained and discussed. The participants shared new insights about the current situation of the EOL RSC of EV batteries in UK and mainland Europe.

Client_AC, Client_RG. Client_EC, Client_CF and Client_CF2 made some observations suggesting changes in the activities shown in the process map. For instance, the activity "Battery pack testing" was added to the process map since Client_RG suggested that new technology has been developed that allow testing before battery pack disassembling. Client_RG stated that even though disassembling often takes place in an ATF or a recycler it would be better to leave that activity to technical experts in a specialised testing facility. An additional dismantling process to the cell block has been added to the model based on Client CG and Client CF2 feedback. According to on Client CG and Client CF2, the process of dismantling to cell level for repurposing is different from dismantling for recycling because the dismantling for recycling can be destructive and as a consequence take less time.

2.4.2 Operational Validity

The operational validity can be usually confirmed by comparing the results obtained in the model with the real-world performance (Greasley, 2023). In this case study, as the simulation model represents a potential EOL RSC that does not exist, the validation was conducted by conducting a sensitivity analysis of the simulation model subsystems. Banks et al. (2005) suggest some alternatives to validate the DES model behaviour for systems with no operational or limited historical data. The alternatives suggested by Banks et al. (2005) are parameter sensitivity test and structural sensitivity test.

For this study the operational validity was confirmed by performing a sensitivity analysis of the process durations and adapting chance decisions points. The sensitivity analysis was conducted to identify if the simulation model built behaves as expected and ensure that the input data used, and model representation are appropriate for the study needs.

2.4.3 Believability

The third aspect of validation is believability. The believability consists of ensuring that the module outputs are credible for the simulation users (Greasley, 2023). To ensure believability, individual interviews were arranged with managers and directors from a car manufacturer and companies involved on the EOL management of EV batteries. The simulation project objectives, the capabilities of the simulation model and assumptions were explained to the participants. To support the explanation and further discussion of the simulation model the structured walkthrough and animation inspection were used. For the structured walkthrough the Arena model flowchart was shown to the participants to ensure that the model was a close representation of a potential EOL RSC for EV batteries. The animation of the simulation model running in slow speed was also shared live with the industry experts to ask for their feedback. The animation also included some performance metrics such as Labour Cost, utilisation of resources. Client_AC, Client_RG, Client_EC, Client_CF and Client_CF2 validated that the metrics Labour cost, and capacity of the system were relevant metrics to assess the performance of the model proposed. Client_EC suggested that for its company future projects they are planning to have different companies operating under the same roof doing the disassemble, SOH assessment, remanufacturing, repurposing, recycling. Client_CF also suggested to choose a specific battery chemistry to make a more detailed estimation of the specific raw material recovered through recycling.

In addition, some changes were made in the processing times, and number of resources of bottleneck processes during the interviews to show in a visual way how the queues and performance metrics changed accordingly. Some processing times were validated while others updated according to the feedback and justifications of Client_AC, Client_EC, Client_RG, Client_CF. Finally, the simulation model animation display was used to obtain insights about performance metrics that the industry experts were interested in knowing from the simulation model.

2.5 Experimentation

A selection of battery routing scenarios were built based on the discussions that had taken place in the facilitated modelling sessions. When participants were asked about the potential routes that batteries would follow, they mentioned that the proportion of batteries sent for recycling, remanufacturing and repurposing will depend on several factors such as country legislations, battery technology/chemistry innovation and aftermarket. Participants Client_CF and Client_CF suggested experiments with extreme scenarios that consider a minimum of 50% recycling. From these discussions a group of scenarios was derived that consider a variation in the proportion of batteries routed for remanufacturing, repurposing and recycling (table 1):

- **Baseline:** it is the initial baseline scenario. This group of scenarios considers that 50% of the batteries are sent for recycling 25% for remanufacturing and 25% for repurposing.
- **Type C1:** this scenario considers that all the batteries (100%) that enter the system go for recycling, which was achieved by sending collected batteries for disassembling to the cell level and then sending all of them for recycling.
- **Type C2:** the second type C scenario considers that 50% of the batteries are sent for recycling and 50% for remanufacturing. This was achieved by sending 50% of the collected batteries for an initial disassembling and then sending them for recycling. The remaining 50% of the batteries were sent for initial disassembling, module testing, and remanufacturing.
- **Type C3:** the last scenario considers that 50% of the batteries are sent for recycling and 50% for repurposing. In this scenario, 50% of the collected batteries were sent for initial disassembling and then for recycling. At the same time, the remaining 50% of the batteries were sent for disassembling, testing and repurposing.

For each of the scenarios, the resources were balanced across each stage of the reverse supply chain, considering a maximum of 80% of utilisation.

The results show the impact of selecting different EoL strategies. For instance, the results of Type C1 scenario that considers 100% of batteries going direct to recycling gives £36,500k as an average profit on sales of recycled material and an average reduction of 45,625 CO_2 emission (kg CO_2-eq).

In Type C2 scenario the profits for recycled material and CO_2 emissions reductions went down by 50%; however, the remanufactured batteries allowed savings of £10,949k and a reduction of emissions of 43,247 (kg CO_2-eq).

In the case of scenario Type C3, sending 50% of the batteries for recycling and 50% for repurposing generated a £109,450k savings due to repurposing and a CO_2 emission reduction of 69,172 (kg CO_2-eq).

Table 1: Type C scenario conditions.

	Battery routing scenarios			
EoL Route	**Baseline**	**Type C1**	**Type C2**	**Type C3**
Recycling	50%	100%	50%	50%
Remanufacturing	25%	-	50%	-
Repurposing	25%	-	-	50%

Table 2: Scenarios - Economic and environmental impact.

Impact metrics (Average)	Baseline	Type C1	Type C2	Type C3
Profit on sales of *recycled* material (£k)	18,820	36,500	18,252	18,260
CO_2 emission reduction (kg CO_2-eqv)	22,823	45,625	22,815	22,825
Savings due to *remanufacturing* (£k)	5,447	-	10,949	-
CO_2 emission reduction (kg CO_2-eqv)	21,515	-	43,247	-
Savings due to *repurposing* (£k)	54,656	-	-	109,450
CO_2 emission reduction (kg CO_2-eqv)	34,543	-	-	69,172

Table 2 shows a summary of the economic and environmental impact of each of the experiments.

3 DISCUSSION

This research proposes a simulation modelling approach used in an industry case study that complements previous RSC modelling that has mostly used linear and non-linear modelling (see, for example, Jindal & Sangwan, 2014; Ghorbani et al., 2014; Das & Dutta, 2015, Jayant et al., 2014; Yanikara & Kuhl, 2015).

As Simchi-Levi (2014) and Sodhi and Tang (2014) suggest, the models that come from a real industry context are more valid and generalisable in practice. Therefore, this research studies RSC design issues in a real and challenging industry context of a developing industry of a high-technology complex product, namely the EV battery industry.

As the study participants suggested, there is no certainty about the proportion of batteries that would follow the recycling, remanufacturing and repurposing routes. The EoL routes for batteries and the future volume of batteries will be highly dependent on the UK battery legislation and market conditions. If legislation promotes recycling then it is likely that the percentage of batteries that follow the recycling route would increase. Whereas if the legislation would set up remanufacturing or repurposing targets, the proportions of batteries following such routes may increase. Moreover, any further changes in the UK government's phasing out of petrol car use, such as presented by the British government in September 2023 (Reuters, 2023), could affect the number of EVs entering the market and the number of EoL EV batteries returning from the market. In addition, the proportion of batteries sent to remanufacturing and repurposing will depend on the market available for such products. If the technology and chemistry continue evolving at a fast pace, by the time the batteries return from the market, the OEMs may require different batteries. In the case of repurposed batteries, the market for them is still in its infancy.

The participants stated that they have been studying and assessing the different EoL processes in isolation but have not seen a model of the whole RSC for EV batteries before. Having a visual flexible model able to represent a future supply chain that does not exists would allow them to assess a range of potential RSC configurations that follow different processes, routes and volumes was considered important for the study participants. In this case the model proved to be useful to assess the impact of different RSC configurations that follow different sustainability strategies in terms of throughput, resources required, capacity (number of batteries processes, tonnes of material recycled, remanufactured batteries, repurposed batteries) and sustainability impact of changes (economic savings, CO_2 impact). The study participants agreed that the metrics shown in the simulation model study would allow them to conduct more accurate cost-benefit analysis to make well-informed RSC design decisions.

This paper contributes to the RSC literature, but it is not without limitations. Conducting a case study in a particular industry limits the option to generalise the results and findings. Future research could benefit from including participants from different industries to validate if the research methodology can be used in different industry contexts and generalise the results.

Another characteristic of the UK EV battery industry is that it has few EoL service providers and competitors. Hence, despite engaging with key stakeholders with industry experience and management expertise, future research would benefit from including more industry participants from the EV battery industry. For future research, the number of participants could be increased to gain insights from other OEMs, remanufacturers, recyclers and ATFs in the sector with different perspectives on the problem under study.

Furthermore, future research could improve the simulation model and adapt the model to take into consideration the number and location of decentralised facilities and the corresponding transport implications (i.e. transport time, cost and CO_2 impact).

4 CONCLUSION

This paper presents a discrete-event simulation tool that practitioners may use to model a future reverse supply chain that does not exist and has limited historical data. Managers and practitioners can use the model proposed to measure the impact of changes in processes, routes and volumes in terms of throughput, capacity (number of batteries processes, tonnes of material recycled, remanufactured batteries, repurposed batteries) and sustainability impact of changes (economic savings, CO_2 impact). The insights of the model and the valuable metrics in terms of capacity planning and economic and environmental metrics were considered valuable by the industry experts who participated in this study to assess what-if scenarios and make informed RSC design decisions.

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