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A simulation of an end-of-life reverse supply chain for electric vehicle batteries

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Abstract

The purpose of this study is to investigate the operation of an integrated end-of-life supply chain network in which authorised treatment facilities (ATFs), remanufacturers, and recyclers offer to Electric Vehicle (EV) manufacturers the end of life (EOL) management of batteries within the UK. A simulation model has been constructed in order to measure the process efficiency, labour costs and transport costs of this reverse supply chain network for different resource (capacity) configurations. Although current demand for the management of the end-of-life (EOL) for the batteries is low there is a prediction of a rapid increase in demand as Electric Vehicle sales increase and the EV batteries within these vehicles reach their end of life. It is intended that the simulation will provide an indication of the potential capacity requirements through the supply chain that are required to deal with this future demand.

Keywords: discrete-event simulation; electric vehicle batteries; reverse supply chain

1. Introduction

A reverse supply chain consists of all the parties and processes involved to collect products from a customer to recover value or dispose of them (Guide Jr. & Van Wassenhove, 2002). One of the industries that will be experiencing significant challenges in their reverse supply chains in the coming years due to the rapid growth of electric vehicle (EV) adoption is the automotive industry. Therefore, there is a need to study the end-of-life supply chain of one of the most important electric cars' components, electric vehicle batteries. Electric vehicle batteries are the most critical component of electric vehicles because they account for a significant part of the vehicle's cost.

Electric vehicle batteries require unique management when reaching their end-of-life (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 batteries' production (Moores, 2017). Therefore, the recovery of EV materials could help to 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 *et al.*, 2018). Therefore, the EOL management of batteries contributes to the reduction of the EV carbon footprint. Thirdly, there are several potential risks associated with batteries' handling, and it is necessary to follow careful procedures to minimise the risks (Zeng *et al.*, 2015). Therefore, it is essential to assign this work to professional original equipment manufacturers (OEMs) and third-party logistics (3PL) providers. Lastly, under the European waste batteries directive, EV producers are responsible for the environmental impacts of the batteries used in their vehicles right up until the end-of-lifecycle. (Winslow *et al.*, 2018). In this study a simulation model has been constructed with the aim to not only include manufacturers and recyclers in the reverse supply chain models but also consider other key stakeholders such as remanufacturers, refurbishing companies and second life clients. Another contribution of the model is to consider not just productivity metrics but other key metrics, such as sustainability measures. The article will provide some context to the study in terms of the UK EOL supply chain (section 2) and present a simulation study of the process (section 3). A discussion of the simulation follows in section 4.

2. The UK end-of-life supply chain for electric vehicle batteries

The UK end-of-life supply chain for electric vehicle batteries is in an early stage. The number of EVs and EV batteries reaching their end-of-life is still low, and EV manufacturers have not defined value recovery paths yet. However, some companies are already preparing for future electric vehicle battery returns. Some of the few returning batteries are currently under their warranty period, and these are returned through Dealers. Dealers are sending back these batteries to EV manufacturers, making them pay for high transport and disposal costs. A few EV companies are running pilots with remanufacturing companies to evaluate the possibility to remanufacture and refurbish their batteries. Remanufacturing companies are preparing and looking for opportunities to improve their processes and are looking for collaboration opportunities, especially with UK-based recyclers, to minimise battery exporters' dependence. Remanufacturing companies understand that not all batteries can be remanufactured. Therefore, they need economical and efficient recyclers to pay for their material recovery services.

Electric vehicle batteries are also returning through scrap car recyclers and their Authorised Treatment Facilities (ATF) networks. When EV vehicles reach their end-of-life, EV users may sell their EV to scrap car recycling companies. Some EV manufacturers have partnerships with specific scrap car recycling companies and are sending them their EOL vehicles. Also, EV users can choose their favourite scrap car recycling company to sell their EVs. The scrap car recycling companies have networks of ATFs with operational staff trained to handle EOL vehicle. The ATFs trained to receive EVs remove the batteries from the vehicles following strict procedures and should look for the main dismantling and safety information on the IDIS (International Dismantling Information System). The IDIS is a central repository of manufacturer compiled treatment information for EVs, with information gathered from manufacturers from Europe, Japan, Korea, Malaysia, India, China and the USA.

When removed some ATFs are then reselling the batteries into the market whilst other ATFs are requesting scrap car recycling companies to handle the batteries, and they are sending them to Approved Battery Exporter (ABE) with the authorisation to export automotive batteries. At the moment, there are no established recycling facilities processing electric vehicle batteries in the UK. For this reason, most of the electric vehicle batteries that need to be recycled are exported to mainland Europe adding high logistic costs.

However, the UK scenario is changing, and there is a growing interest in establishing UK based recycling facilities. Some UK-based recyclers are about to open new facilities specialised in recycling lithium-ion batteries from electronic devices and electric vehicles. Even though these companies have not started to operate, they are confident about the UK's supply and market opportunities. After recovering the batteries materials, recyclers would sell the recovered material to different companies depending on the material type.

The map of the UK EOL supply chain for electric vehicle batteries may be seen in Figure 1. This supply chain represents the current and potential routes that batteries could follow at their end of life.

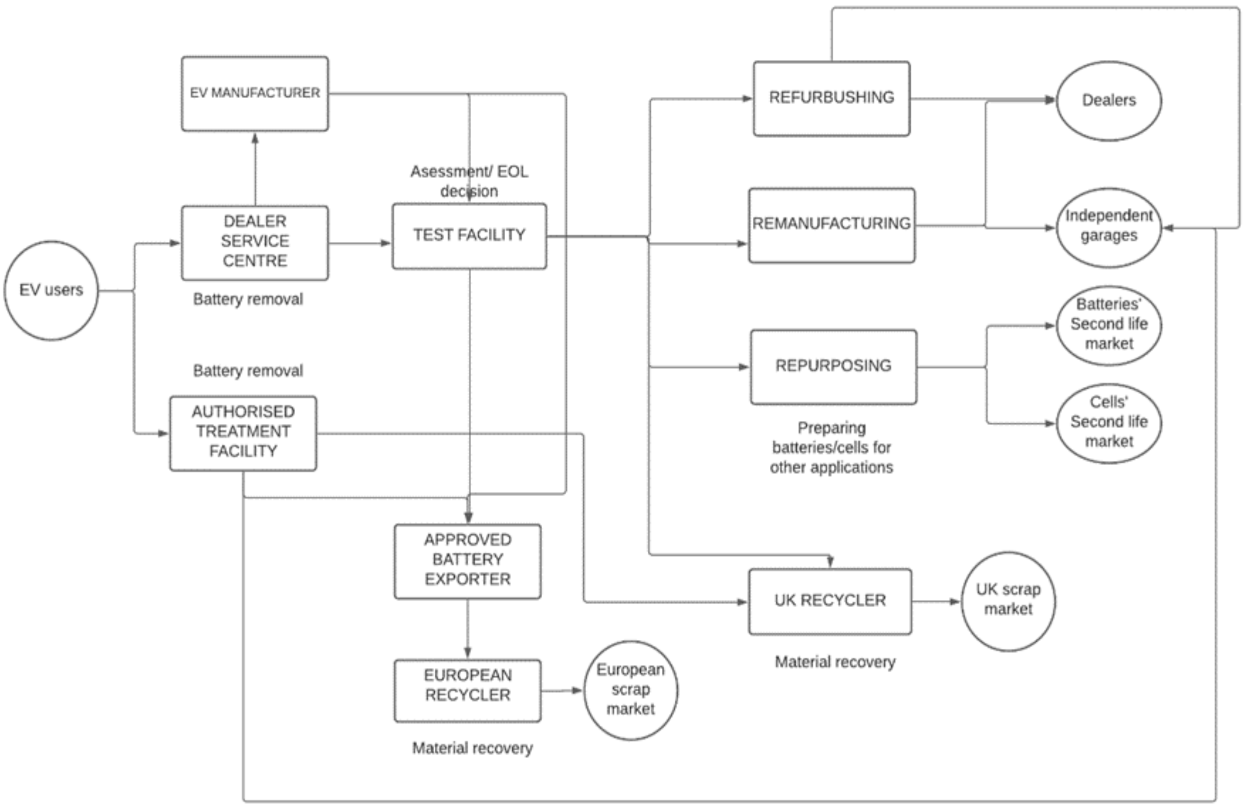

Figure 1. The UK EOL supply chain for electric vehicle batteries

3. The Simulation Study

The proposed simulation model was developed using Arena 11.0 simulation package (Kelton et al., 2015) and includes the main supply chain participants involved in the reverse logistic processes such as the companies in charge of collection, OEM under study and clients of the new batteries produced (e.g. distributors, retailers, factory, outlet). The model developed by Jayant, Gupta and Garg (2014) calculates cycle time, transfer time and cost, service level and resource utilization. The results of the study suggest a significant improvement in the reverse logistics network performance and the product supply planning (Jayant, Gupta and Garg, 2014). Likewise, Yanikara and Kuhl (2015) proposed a general simulation framework to assess various reverse logistic configurations and identify the best option according to productivity and sustainability metrics. A discrete event simulation modelling approach was chosen by the authors since it allows the design of a highly flexible model to represent a variety of system configurations. Moreover, the model proposed provides an assessment of the performance of such network configurations not only in terms of productivity but also in terms of sustainability metrics which according to Govindan, Soleimani and Kannan (2015) has not been included much in the literature. The productivity and sustainability metrics used in this study are transport cost, collection/sorting/processing cost, inventory cost, disposal cost, time in system, value of recovery and emissions.

This case study presents the UK EOL supply chain for electric vehicle batteries that includes a specialised ATF network across the UK; a UK based Remanufacturer, and a UK based Recycler. For this study, it is considered that these companies have a partnership to provide a complete end-of-life management solution to one electric vehicle manufacturer. The main processes that have been mapped at the UK EOL supply chain for electric vehicle batteries of this study are the following: the collection of batteries from dealers and removal and collection of batteries from ATFs, the battery assessment at a central test facility, the preparation of the batteries for their correspondent EOL route and posterior recycling, remanufacturing, and refurbishing.

The objectives of this study are to model an integrated end-of-life supply chain network in which UK ATF network, Remanufacturers, and Recyclers offer to EV manufacturers the end-of-life management of batteries through remanufacturing and recycling within the UK. The model will measure the process efficiency, labour costs and transport cost on a collaborative reverse supply chain network for different resource (capacity) configurations.

The data for this study was collected through interviews and questionnaires to managers and directors from a Remanufacturing company, a scrap car recycling company that manages an important ATF network, and a lithium-ion battery recycler. The purpose of the interviews was to understand the businesses and the correspondent processes involved in the EOL management of electric vehicle batteries. Meanwhile, the questionnaires were used to collect specific data about the processes such as processing times, sequences, workforce schedules, as well as the processing and transport cost ratios.

Before building up the simulation model of the integrated end-of-life supply chain network for electric vehicle batteries, it is essential to create a process map that represents the sequence of steps in the process to be analysed. The integrated end-of-life electric vehicle batteries supply chain network of this study was built using the Arena discrete-event simulation software (Kelton et al., 2015) following the process map in Figure 2. The entities of the model are the electric vehicle batteries, while the resources that were included in the system model were the operators that work at the Dealer centre, ATF, test facility, remanufacturing company and recycler.

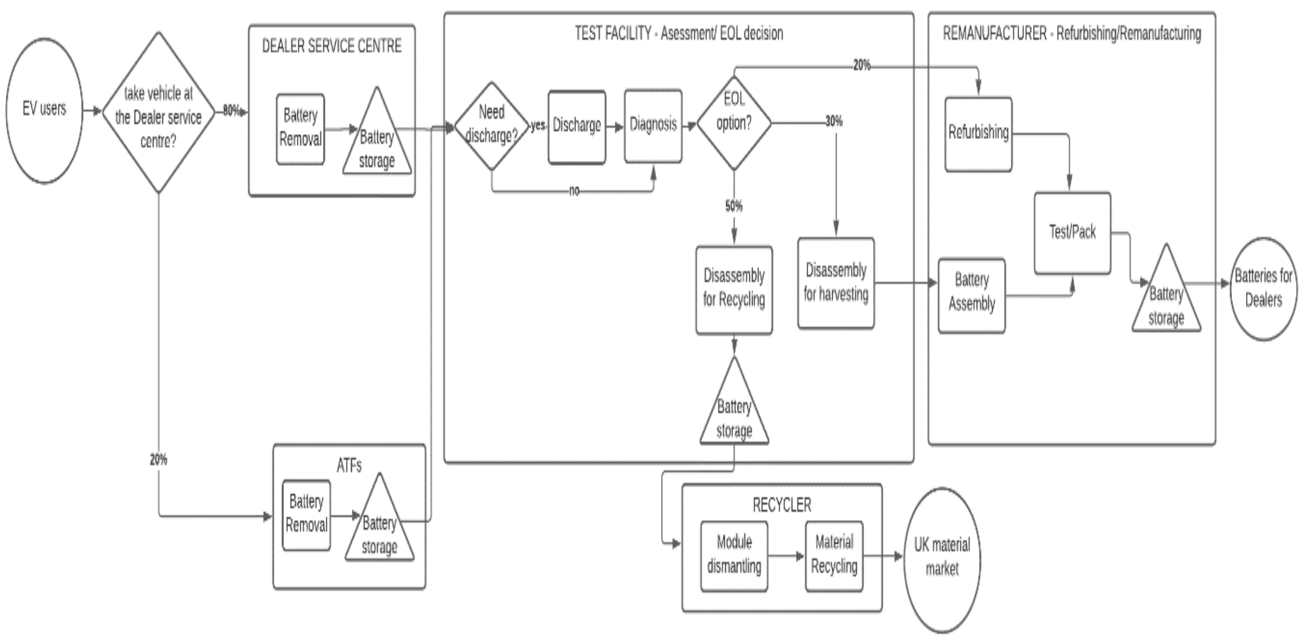

Figure 2. EOL EV batteries process map

This model considers the following assumptions:

- The entities that flow through the system are batteries. In the case of entities that use as a unit of analysis modules, cells or tons of material, these have been transformed to a battery equivalent.
- The model considers only one dealer service centre, one ATF, one test facility, one remanufacturing company and one material recycler. Each of them has a specific number of multitasking resources (operators) that can help with any process at their facilities.
- The lorries that transport batteries between facilities wait to have full-loaded shipments (12 batteries) to collect the batteries.
- The model considers that each of the companies works one shift, five days a week.

4. Discussion

In this study, three different end-of-life electric vehicle batteries supply chain network configurations are compared to illustrate the use of the simulation-based tool. The supply chain network model consists of a single product type that is returned through a Dealer centre and an ATF

The simulation compares the utilisation of resources, queue waiting time, labour cost and transport cost of the three alternative scenarios when making changes to the number of resources and processing time of activities.

Not having enough information on how to handle, disassemble, measure the state of health (SOH) of batteries and recover their value represent a significant problem for the companies working in the EOL management industry. Even though the IDIS initiative has helped ATFs with the battery removal process, there is still valuable information about the internal components of batteries that is not shared by battery designers and could help to improve the EOL processes and make them more efficient.

In the long term, the storage of batteries and the space required to process them could represent a substantial reverse logistic cost that should be monitored. Working with electric vehicle batteries may cost much more than working with engines or gearboxes because of the safety considerations and suppression systems' technology needed. The reverse supply chain for lithium-ion batteries is complex. For this reason, the interviewed companies recognise that building long-term business relationships between remanufacturers, material recyclers, and scrap car recyclers is necessary to succeed. These companies need each other to secure batteries and components supply. They recognise that the processes for the end-of-life of batteries such as discharge, dismantling, remanufacturing, and material recycling requires unique expertise. For this reason, there is a need for collaboration to make the most out of the capabilities of each of them and offer a full end-of-life management service to EV manufacturers. Collaborative relationships go beyond the regular commercial relationship (Matopoulos *et al.*, 2007) and deliver more powerful advantages than those that could be achieved when companies work individually (Panahifar *et al.*, 2018).

Currently the model simulates one battery type. Dealing with different types of batteries makes the EOL management of batteries more complicated because operators need to follow different procedures and use different tools for each type of battery. In this case further work is planned to extend the simulation model to represent a reverse supply chain network processing different battery types.

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