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Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing

M. Alfaro-Algaba, F. Javier Ramirez*

School of Industrial Engineering, Universidad de Castilla-La Mancha, 02071 Albacete, Spain

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ABSTRACT

The rapidly-growing use of electric vehicles (EVs) worldwide will generate a huge quantity of end-of-life (EoL) products in the coming decades and, in consequence, there will be an accumulation of Waste Electrical and Electronic Equipment (WEEE) to be disposed of. Therefore, actions to favour the recovery of certain components from EVs, such as the electric vehicle battery (EVB), generates an opportunity for research. This paper presents a model for designing the disassembly process of the EVB pack for remanufacturing, obtaining the highest economic profitability from the process with the minimum environmental impact. Based on the disassembly sequence planning (DSP), the model provides the optimal disassembly level and the most suitable decision for the use of the disassembled components: reuse, remanufacturing, recycling or disposal. The lithium-ion (Li-ion) battery from the Audi A3 Sportback e-tron Hybrid is selected as the case study. Different case study scenarios based on the state of health (SOH) of the batteries are proposed. The results demonstrate the feasibility and effectiveness of the model, providing significant insights into the recovery processes of WEEE, particularly Li-ion EVB packs.

1. Introduction

The use of electric vehicles (EVs) around the world has grown considerably in recent years. The support of governments in the form of initiatives to reduce CO_2 emissions and to raise awareness of the use of clean technologies is encouraging this rapid growth. The worldwide sales of EVs are expected to increase from the current 1.1 million to 11 million in 2025, and 30 million in 2030 (Bloomberg Finance L.P., 2018). China will be the leader of this transition with 50% of the global EV market by 2025. Consequently, a huge number of electric vehicles batteries (EVBs) are expected to reach the end-of-life (EoL) stage and will need to be disposed of or recycled in the coming decades. EVs will be one of the main sources of EoL products and Waste Electrical and Electronic Equipment (WEEE) in the near future (Li et al., 2018), with the recovery process of EVBs in the framework of the reverse logistic management of WEEE (Islam and Huda, 2018) being a key problem to address.

The EVB is a key component of the EV. It is the power source of the electric motor and is charged when the vehicle is not in use by means of a charger. There are four principal EVB technologies in use: lead acid, nickel metal hydride, lithium-ion (Li-ion) and sodium nickel chloride (Andwari et al., 2017). The Li-ion battery is the most widely used EVB in the market due to its unquestionable advantages in terms of the use of raw materials for its manufacture, cost, increased cycle life, low weight, and high specific capacity (Yun et al., 2018). Due to high levels of deterioration, used EVBs could be a serious problem in the future if procedures for reusing, remanufacturing or recycling are not established. This could lead EoL batteries to accumulate in large numbers, with a significant environmental impact. Therefore, the recovery of batteries is essential to ensure the growth and sustainability of the EV market. The Li-ion battery was selected as the case study in our research.

Remanufacturing is defined as "the process of returning a used product to at least its Original Equipment Manufacturer's (OEM) performance specification from the customers' perspective, and giving the resultant product warranty that it is at least equal to that of a newly manufactured equivalent" (Matsumoto and Ijomah, 2013). Remanufacturing is considered the most economic and environmental option in the recovery process of EoL products, since the recovered product after remanufacturing is comparable to a new one (Ng and Song, 2015). This process is a significant leverage in achieving the circular economy (CE) paradigm (Geissdoerfer et al., 2017) due to its implications for environmental preservation and economic profits for firms. The use of recovered components generates savings in raw materials, manufacturing costs and energy consumption, leading to a reduction in the environmental impact.

* Corresponding author.
E-mail addresses: marina.alfaro@alu.uclm.es (M. Alfaro-Algaba), franciscoj.ramirez@uclm.es (F.J. Ramirez).

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Disassembly is an inevitable step in the recovery process of EoL products because, before being remanufactured, the product must be disassembled. Due to the high costs associated with the disassembly process, it has emerged as a key topic for research in recent decades as part of achieving successful remanufacturing (Zhou et al., 2018; Lambert, 2003), with different methodologies having been proposed to assist the disassembly process of WEEE, in particular batteries (Schwarz et al., 2018; Wegener et al., 2014). The literature has traditionally focused on complete disassembly although there has recently been growing interest in partial disassembly as it is more economically viable. Furthermore, complete disassembly is, in most cases, unnecessary. Thus, current research is focusing on partial disassembly compared to the traditional complete disassembly approaches (Rickli and Camelio, 2013; Smith et al., 2016).

Based on these interests, our research focuses on the identification of the optimal disassembly level as the solution to achieve the highest profitability from the disassembly process and, at the same time, produce the minimum environmental impact. The present study is intended to fill this gap in the literature. We aim to contribute to the knowledge with a model for designing the optimal disassembly process of EVB packs. The contribution of the work is fourfold as we simultaneously obtain: (1) the disassembly planning, (2) the optimal disassembly level as a trade-off decision between no disassembly and complete disassembly, finding the "stopping point" of the process that achieves the highest profitability; (3) the most efficient decision about the potential use of the disassembled components (reuse, remanufacturing, recycling or disposal); and (4) the minimum environmental impact in both the disassembly process and the recovery procedures for the disassembled components.

The paper is organized as follows. Section 2 reviews the related works. Section 3 is devoted to presenting the methodology and the associated formulation. The case study is then presented in Section 4. The results are shown and discussed in Section 5. Finally, Section 6 concludes the paper and proposes future lines of research.

2. Literature review

2.1. Lithium-ion battery

Li-ion technology is currently considered the most suitable and promising for EVB applications, mainly due to its high energy density, long lifetime, good efficiency in the charging/discharging processes, and light weight (Zhou et al., 2014; Andwari et al., 2017). However, its market price is still high (Andwari et al., 2017), and thus its use in EVs is not accessible for all makes of vehicles attempting to reach the market with competitive prices. In addition, during the manufacturing process of the Li-ion battery, a significant quantity of greenhouse gases (GHG) are emitted into the atmosphere, with subsequent negative environmental implications (Gallagher et al., 2014). This presents another opportunity for research: how to recover the EVB in order to reuse certain components and thus prevent future environmental damage.

The Li-ion battery is usually formed by four main components: anode, cathode, electrolyte and separator. The anode and cathode are manufactured with lithium metal oxide and lithiated graphite, the electrolyte is made of lithium salts and organic solvents, and the separator is a micro-porous membrane allowing the lithium ions to pass through the pores. A variety of Li-ion cathode materials have been developed in recent decades using different chemistries: Lithium Cobalt Oxide ($LiCoO_2$), Nickel Cobalt Aluminum Oxide (NCA), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Polymer ($LiMnO_4$) and Lithium iron phosphate ($LiFePO_4$). Currently, NMC is the most in-demand technology for EVBs, mainly due to its lower self-heating rate and high energy density (Hannan et al., 2018). More detailed information about the technologies, the components of the Li-ion batteries, and the chemical reactions involved in the processes of charge and discharge is presented in Hannan et al. (2018), Andwari et al. (2017), and Li et al. (2015).

Li-ion battery packs are typically composed of a battery module and a battery management system (Yun et al., 2018), with the modules being assembled from battery cells. In order to achieve the energy demands, cells are connected in series and parallel, depending on the required capacity and application.

Li-ion batteries for automotive applications are considered to have reached EoL once the estimation of the battery condition based on the state of charge (SOC), the state of health (SOH) and the state of function (SOF) reflect an irreversible loss in its performance with respect to the ideal status, or the OEM performance specification (Casals et al., 2017; Hannan et al., 2018). This occurs after a certain number of charge-cycles that varies greatly from 1000 to 10,000 cycles, depending on the type of battery and the operating conditions. This is the point at which refurbishment of the EVB is required in order for it to be used for other applications such as auto-consumption in homes, to support renewable energy facilities, as an uninterruptible power source (UPS), or for use as an energy reserve. In this way, the lifetime of the battery can be extended up to 20 years and more than 8000 charge-cycles (Mathew et al., 2017). Subsequently, the battery would reach its EoL and the components must be recycled or disposed of.

Despite the fact that the performance and durability of the battery depends mainly on its charging and discharging (Hannan et al., 2018), cells with lower capacity or uneven degradation are prone to overcharging/discharging the battery (Li et al., 2014), accelerating its EoL. Thus, it is necessary to balance the system and control the state of the single cells in order to prevent the deterioration of the battery pack (Väyrynen and Salminen, 2012).

The battery cell is thus a component of great interest for research in order to analyse the feasibility of its recovery and reuse, or its replacement, after disassembly.

2.2. Disassembly planning

Disassembly is an unavoidable step in the recovery process of a product. Before a part of the product or its components can be reused, remanufactured or recycled, the product must be partially or completely disassembled. Disassembly planning is the procedure of generating a manufacturing plan for removing the components from a whole assembled product (Zhou et al., 2018; Lambert, 2003).

The disassembly process has been widely addressed in the literature. The recent work by Zhou et al. (2018) and the previous study by Lambert (2003) provide extensive surveys on the disassembly theory (disassembly mode, disassembly modelling, and planning methods), and the different approaches to resolving the disassembly problem. The work by "Wegener et al. (2014) develops a planning approach for the disassembly of EVBs and, more recently, the study by Schwarz et al. (2018) proposes the use of a virtual disassembly tool based on a method-time management system to assist battery disassembly.

The disassembly mode is a significant decision in resolving the disassembly problem. According to Zhou et al. (2018), there are two disassembly modes: complete and partial. Complete disassembly is focused on the total dismantling of the product. It involves completely separating the components from the assembled product. The literature reports that complete disassembly is more expensive than partial disassembly, and often unnecessary (Smith et al., 2016). Nonetheless, research has traditionally focused on complete disassembly. The survey by Zhou et al. (2018) provides more than sixty references of published papers about complete disassembly, highlighting the works by Li et al. (2002), Gupta et al. (2004), Kongar and Gupta (2006), Kuo (2013), Jin et al. (2013), Xia et al. (2015), and Xia et al. (2016), as important research on the disassembly processes of WEEE.

Nevertheless, the interest of researchers in partial disassembly has recently increased. Initially, this disassembly mode was used mainly to retrieve a specific component from a product. Once the component was extracted, the disassembly process concluded. Currently, research on partial disassembly includes environmental concerns, in addition to the traditional economic considerations. Feldmann et al. (2001) was the first to suggest the disassembly process should be finished once the process reaches the disassembly level where the economic profit is optimal, or what is commonly called the "stopping point". This solution proposes a balance between 'no disassembly' and 'complete disassembly'. Based on this approach, other authors have contributed significant works on partial disassembly: Smith et al. (2016) proposed a cost-benefit analysis to find the optimized disassembly level using specific rules; Rickli and Camelio (2013) suggested a trade-off between economic profit and environmental impact; Rickli and Camelio (2014) considered the possible uncertainties in the quality of the product to recover in obtaining the partial disassembly sequences; Percoco and Diella (2013) proposed multi-objective making decision techniques to resolve the partial disassembly planning problem; and Wang et al. (2017) considered destructive operations in selective disassembly sequence planning.

3. Methodology

The model presented and formulated in this section proposes the analysis and optimisation of two sub-objectives, economic and environmental, which will be combined in order to obtain the solution that best achieves the maximum economic profit with the minimum environmental impact in the EVB disassembly process.

To carry this out, a cost-benefit analysis is proposed in order to find the best solution that maximises the sum of the two sub-objectives. The objective function F_0 to be optimised can be expressed as follows:

$$F_0 = y_1 + y_2 \tag{1}$$

where:

- y_1 is the economic sub-objective
- y_2 is the environmental sub-objective

The methodology developed is based on the use of the approach proposed by Feldmann et al. (2001) to assess the economic sub-objective, and the Eco-indicator 99 method (Pré Consultants, 2000) to evaluate the environmental impact sub-objective by using a number to express the environmental impact of a material or process based on data from a Life Cycle Assessment (LCA). The objective function deals with finding the optimal disassembly level of the product, also known as "stopping point" (Feldmann et al., 2001) as a balance between the "no disassembly" and the "complete disassembly". In the first case, complete products are disposed of once they reach the EoL state, which generates high disposal costs and a corresponding increase in environmental impacts. In the "complete disassembly" solution, all components are recovered, so they can be reused, remanufactured or recycled according to the state of the components. This solution reduces environmental impacts, but makes the disassembly process unviable from the economic point of view. Thus, our model proposes a partial disassembly process while optimizing the economic and environmental goals.

Fig. 1 shows the model approach, where the maximum value of F_0 corresponds to the "stopping point", or the disassembly level of the process where the objective function is maximised.

3.1. Economic sub-objective analysis

The economic sub-objective is expressed as follows:

$$y_1 = \mathrm{ID} - \mathrm{CD} \tag{2}$$

where:

- *ID* represents the total incomes (gains).
- *CD* represents the total disassembly costs.

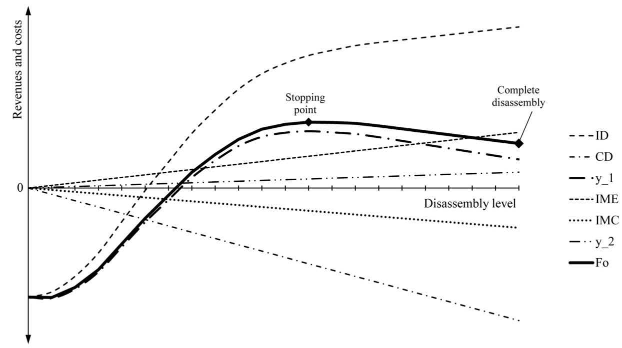


Fig. 1. Model approach (modified from Feldmann et al. (2001)).

The total incomes are assessed by means of the following equation:

$$\mathrm{ID} = \sum_{i=1}^{n}\sum_{j=1}^{2} \mathrm{IRR}_i\, o_{i,j} + \sum_{i=1}^{n} \mathrm{IRC}_i\, o_{i,3} - \sum_{i=1}^{n} \mathrm{CDS}_i\, o_{i,4} \tag{3}$$

where:

- i is an index of each component (from 1 to n).
- j in an index representing the recovery option for the components:
  - ○ $j = 1$ if component i is assigned to be reused.
  - ○ $j = 2$ if component i is assigned to be remanufactured.
  - ○ $j = 3$ if component i is assigned to be recycled.
  - ○ $j = 4$ if component i is assigned to be disposed of.
- IRR_i represents the revenues obtained by reusing or remanufacturing component i, which avoids manufacturing a new one.
- IRC_i represents the revenue obtained by recycling component i, which allows the raw material to be recovered for the same or a different application.
- CDS_i represents the disposal costs of component i to be disposed of.
- $o_{i,j}$ is an indicator representing the recovery option of the component i, equal to 1 if option j is assigned to component i, 0 if otherwise.

On the other hand, total disassembly costs are expressed as follows:

$$\mathrm{CD} = \sum_{i=1}^{n} t_{d,i}\, C_{d,i} + \sum_{i=1}^{n}\sum_{j=1}^{2} \mathrm{Ca}_{i,j}\, o_{i,j} + \sum_{i=1}^{n}\sum_{j=1}^{4} \mathrm{Cg}_{i,j}\, o_{i,j} \tag{4}$$

where:

- $t_{d,i}$ represents the operation time to disassemble component i.
- $C_{d,i}$ represents the cost per unit of time in the disassembly process of component i.
- $Ca_{i,j}$ represents the recovering cost of component i to be reused (j = 1) or remanufactured (j = 2).
- $Cg_{i,j}$ represents the overhead cost of the company, assigned to component i to be disassembled. This depends on recovery option j.

3.2. Environmental sub-objective analysis

The assessment of the environmental sub-objective is carried out by means of the Eco-indicator 99 methodology (Pré Consultants, 2000). This allows us to analyse, on the one hand, the savings in environmental impact as a result of the components being reused or remanufactured rather than having to manufacture them again for new products, and, on the other hand, the environmental impact produced in the disassembly process of the product.

The Eco-indicator (Pré Consultants, 2000) is a numerical index that ex- presses the overall environmental impact caused by a manufacturing process or the manufacturing of raw material, and measured in "milli-point" (mPt). The higher the number, the greater is the impact produced.

Therefore, the environmental sub-objective function is defined as the one that maximises the reduction in the environmental impact in the overall process, taking into account the savings produced by the components that need not be manufactured again for new products, and the environmental impact caused by the disassembly process. This function is defined as follows:

$$y_2 = \text{IME} - \text{IMC} \tag{5}$$

where:

- *IME* is the environmental impact avoided due to the components being reused, remanufactured, or recycled.
- *IMC* is the environmental impact caused in the disassembly process of the product.

IME is assessed by means of the following expression:

$$\text{IME} = \sum_{i=1}^{n}\sum_{j=1}^{3} o_{i,j}\cdot \text{ie}_{i,j} \tag{6}$$

where:

- $ie_{i,1,2}$ represents the environmental impact avoided by reusing or remanufacturing component *i*, and expressed as follows:

$$\text{ie}_{i,1,2} = \left[\text{EI}_{1,i} + \text{EI}_{2,i} + \left(\frac{\text{EI}_{3,i} + \text{EI}_{4,i}}{2}\right)\right]\cdot f_c \tag{7}$$

  where:
  - ○ $EI_{1,i}$ is the Eco-indicator of the environmental impact caused by the production of new raw material [mPt·kg]
  - ○ $EI_{2,i}$ is the Eco-indicator of the environmental impact caused by the manufacturing process of component *i* [mPt·ud]
  - ○ $EI_{3,i}$ is the Eco-indicator of the environmental impact caused by the recycling process of component *i* [mPt·kg]
  - ○ $EI_{4,i}$ is the Eco-indicator of the environmental impact caused by the disposal process (landfill) of component *i* [mPt·kg]
  - ○ f_c is a factor used to convert the environmental impact in mili-points (mPt) into monetary units (€), and assessed as follows:

$$f_c = \frac{P_{\text{ha}}\cdot r_{\text{habs/ha}}}{\text{IA}_{\text{hab·year}}} \tag{8}$$

    where:
    - ○ P_{ha} represents the estimated price of one hectare (ha) of land
    - ○ $r_{hab/ha}$ represents the ratio of hectares per capita (hab) in the country analysed
    - ○ $IA_{hab\cdot year}$ represents the estimated environmental impact of an inhabitant per year ($10^6\frac{\text{mPt}}{\text{hab}}$)
- $ie_{i,3}$ represents the environmental impact avoided by recycling component *i*:

$$\text{ie}_{i,3} = (\text{EI}_{1,i} + \text{EI}_{4,i})\cdot f_c \tag{9}$$

On the other hand, *IMC* is assessed as follows:

$$\text{IMC} = \sum_{i=1}^{n}\sum_{j=1}^{4} o_{i,j}\cdot \text{ic}_{i,j} \tag{10}$$

where:

- $ic_{i,j}$ represents the environmental impact caused by component *i* in the recovering process according to option *j*.

4. Case study

The Audi A3 Sportback e-tron Hybrid Li-ion Battery Pack was selected as the case study in our research in order to verify the reliability and effectiveness of the proposed model. After the description of the EVB pack and its components, the disassembly process of the battery is detailed. Calculation assumptions are then defined and the case study scenarios are proposed.

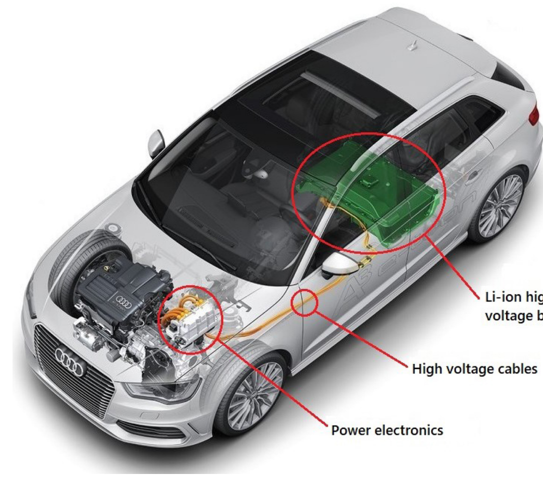


Fig. 2. Electric power system of the Audi A3 Sportback e-tron hybrid. © 2019 by AUDI AG. With permission. All rights reserved. Source: Audi (2018c).

4.1. Description of the Audi A3 Sportback e-tron hybrid Li-ion battery pack

The electric power system of the Audi A3 Sportback e-tron hybrid consists of three principal parts, as shown in Fig. 2: the Li-ion high voltage battery, as the storage system; the power electronics, to convert the direct current (DC) into alternating current (AC); and the high voltage cables to connect them.

The Li-ion high voltage battery (hereinafter the EVB) is our case study. It essentially comprises a pack of 8 modules with 12 cells in each one (96 cells in total), the Battery Management Controller (BMC), the Battery Junction Box (BJB) and the cooling system. Figs. 3 and 4, show detailed pictures of the battery, where the components and fasteners are identified, while Table 1 lists the components and fasteners of the EVB, and their quantities per battery.

4.2. Disassembly process of the EVB pack

Disassembly is an unavoidable step in the recovery process of EoL

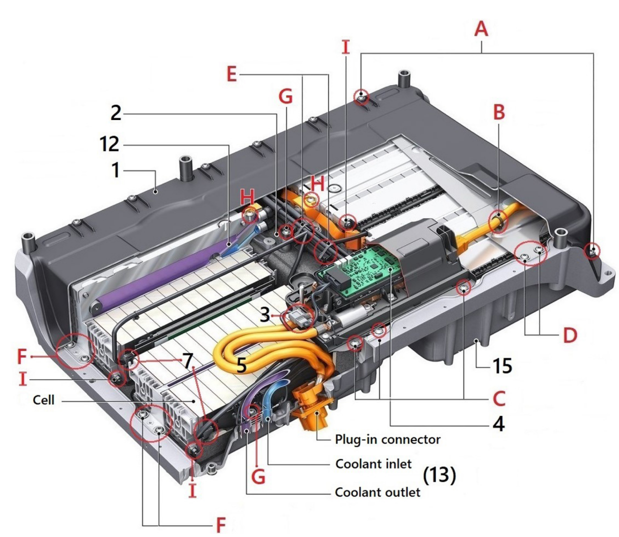
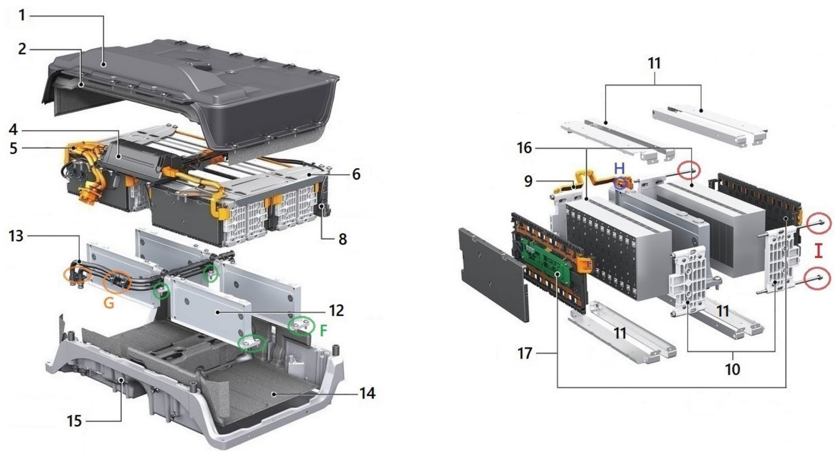


Fig. 3. Li-ion battery of the Audi A3 Sportback e-tron Hybrid. © 2019 by AUDI AG. With permission. All rights reserved. Modified from: Audi (2018a).



(a) Exploded view of the battery   (b) Exploded view of the module pack

Fig. 4. Exploded views of the Li-ion battery of the Audi A3 Sportback e-tron Hybrid. © 2019 by AUDI AG. With permission. All rights reserved. Modified from: Audi (2018b).

Table 1
Main components and fasteners of the Audi A3 Sportback e-tron Hybrid Li-ion battery.

Ref.	Denomination	Qty.
1	Upper housing shell	1
2	Upper insulator	1
3	Plug-in cable between BJB and CMCs–BMC	1
4	Battery Junction Box (BJB)	1
5	High Voltage cables and connectors	1
6	Top transverse cover	2
7	Plug-in cable CMCs–BMC	1
8	Battery Management Controller (BMC)	1
9	Module connector	4
10	Side module junction	16
11	Top and bottom fastener of module	32
12	Cooling plate	4
13	Cooling pipe	2
14	Lower insulation	1
15	Lower housing shell (aluminium)	1
16	Module	8
17	Cell Management Controller (CMC)	8
A	Top housing shell screw	18
B	High voltage cable anchor	6
C	Junction box screw	6
D	Top transverse covers screw	8
E	Anchor of CMCs–BMC wire	6
F	Screw connecting cooling plates-modules with lower housing	16
G	Screw connecting cooling pipes with lower housing	7
H	Modules connectors screws	12
I	Screw connecting the modules	16

products. In the case of EVBs, the main goal of disassembly is the extraction of the modules as they are the most valuable components in the EVB and, potentially, could be reused. Prior to disassembly, the condition of the modules should be analysed, since, if they are in good condition, they could be reused in other batteries or be sold in the secondary market as stationary storage in households or renewable energy, and also as batteries for forklifts. If the modules are in poor condition, however, and their expected lifetime is low, the most valuable materials could be recycled or, in the worst case, incinerated.

The disassembly process of the EVB under study is conducted according to the precedence diagram shown in Fig. 5, where the components and fasteners are identified as described in Table 1. Besides, Table 2 shows the disassembly level according to the disassembly sequence of the product. The process is carried out in different steps, which are described as follows:

i. Unscrew the screws of the upper housing (A).
ii. Remove the upper housing (1) and the insulator (2).
iii. Cut anchorages of high voltage cables (B) and unscrew the screws that connect the BJB to the casing (C).
iv. Disconnect the plugging cable between BJB and CMCs-BMC (3), and remove the BJB (4) together with the cables attached thereto (5).
v. Unscrew the screws (D) and remove the two upper transverse covers (6).
vi. Disconnect and remove all plugging wires connecting the CMCs with BMC (7), and cut their anchors (E).
vii. Unscrew and remove the BMC (8).
viii. Unscrew the screws that join the cooling plates and modules to the lower housing (F) and screws that join the cooling pipes to the lower housing (G).
ix. Unscrew the screws (H), and remove the module connectors (9).
x. Unscrew the screws connecting modules (I) and remove side plastic links (10) and the upper and lower fasteners of the modules (11).
xi. Remove the 4 cooling plates (12), the pipes through which coolant flows (13), the lower insulator (14), and the lower housing shell (15).
xii. Remove the modules (16) together with their CMCs (17).

4.3. Calculation assumptions

In order to perform the calculations, the following further assumptions were considered in the present work:

i. It is assumed that the reused or remanufactured components will be sold in the second-hand market (e.g. as spare parts) and the recycled components as raw materials, obtaining benefits in all the cases.
ii. The revenues obtained from the reuse or remanufacture of the components are considered according to the retail prices in Spain for 2018 and the information from manufacturers.
iii. The revenues obtained from recycling of components are assumed according to the information from recycling companies in Spain and the price of recycled materials in 2018 (SMP, 2018; Recimex, 2018), as shown in Table 3.
iv. The disposal costs of the components are considered as 25% of the revenues from reuse or remanufacturing (IRR), according to the information from disposal companies in Spain.
v. Conditioning costs to reuse the components are assumed as 10% of

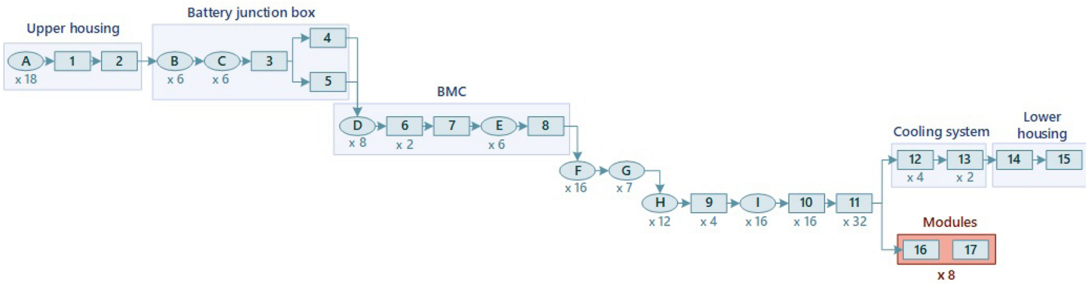


Fig. 5. Precedence diagram for disassembly of the Li-ion EVB.

Table 2
Disassembly level according to disassembly sequence.

Disassembly sequence	Disassembly level (%)	Disassembly sequence	Disassembly level (%)
A	3.13	9	53.13
1	6.25	I	56.25
2	9.38	10	59.38
B	12.50	11	62.50
C	15.63	12	65.63
3	18.75	13	68.75
4	21.88	14	71.88
5	25.00	15	75.00
D	28.13	16-17 (1)	78.13
6	31.25	16-17 (2)	81.25
7	34.38	16-17 (3)	84.38
E	37.50	16-17 (4)	87.50
8	40.62	16-17 (5)	90.63
F	43.75	16-17 (6)	93.75
G	46.88	16-17 (7)	96.88
H	50.00	16-17 (8)	100.00

Table 3
Price of recycled materials.

Material	Cost (€/kg)
Steel	0.8
Stainless steel	2
Aluminium	1
Copper wire	4
Acrylonitrile butadiene styrene (ABS)	0.6
Polypropylene (PP)	0.3
Polyethylene high-density (PEHD)	0.3
Rubber	0.4

IRR, corresponding mainly to cleaning and inspection.

vi. Conditioning costs to remanufacture the components are assumed as 50% of IRR, based on the information from remanufacturing companies in Spain.

vii. The study considers that two workers are required to complete the process. The employer salary is assumed as 1471.8 €/month, equal to double of the minimum inter-professional salary in Spain at the end of 2018 (Ministry of Labour and Social Security, 2018).

viii. In terms of the assessment of the company overhead costs (including indirect costs), Table 4 reports the yearly overheads and general costs of the company considered in the present work. Based on the information provided by a Spanish battery remanufacturing company, the model assigns a portion of these costs to each component being disassembled, and depending on the choice of recovery option: 0.2 for reuse, 0.5 for remanufacturing, 0.2 for recycling and 0.1 for disposal. The overhead cost per battery and year is obtained by dividing the total annual overhead costs of the company by the number of batteries yearly disassembled.

ix. It is assumed that each operator works 220 days a year, 7.5 h per

Table 4
Overheads and general costs of the company.

Concept	Yearly cost (€)
Indirect labour	123,800
Transportation and handling	11,520
Amortisation of machinery and tools	56,280
Supply of water, electricity and gas	22,800
Maintenance of machinery and facilities	9600
Cleaning and safety	10,500
Marketing	5800
Insurances	18,500
Renting of facilities	38,700
Taxes	22,500
TOTAL	320,000

day,

x. Based on the information from remanufacturing companies, it is assumed that the average time to disassembly the battery is 30 min.

xi. It is assumed that the cost of a second hand battery to be disassembled is 170 € (losses at first), based on Casals et al. (2016).

xii. Spanish law considers batteries are dangerous goods, so they must be transported under special conditions. EVBs must be transported in two containers, of which at least one has to be sealed and fire resistant (Casals et al., 2016). A cost of 960 € is assumed for each special truck. The total cost of transporting all the batteries to be recovered yearly are included as "Transportation and handling" in Table 4.

xiii. The number of batteries received in the disassembly plant is considered to be 500 units per year.

xiv. The time required for the first test and discharge of the battery is not taken into account.

xv. For the calculation of the f_c, factor used to convert mili-points (mPt) to monetary units (€), the procedure described in Smith et al. (2016) is followed. In our case, it is considered that the price of land in Spain is equal to 3197 €/ha (Ministerio de Agricultura, Pesca y Alimentación, 2018), and the ratio of hectares per capita is 1.087. Based on this, f_c is 0.003261 €/mPt.

Table A.1 in Appendix A summarises the revenues and costs associated with each component to be disassembled, considering the different recovery options.

Table A.2 in Appendix A summarises the values of the environmental impact analysis associated with the components to be disassembled, for the recovery options considered.

4.4. Case study scenarios

In order to test the model designed and obtain the corresponding results for the selected case study, three operative scenarios were considered assuming that the condition of the batteries would be different depending on the use to which they were subjected, and the remaining lifetime of the modules and cells. These scenarios are defined as follows:

- REU scenario. It considers the condition of the battery is good and most of the components can be reused.
- REM scenario. It considers the condition of the battery is less good, but most of the components must be recovered by remanufacturing operations.
- REC scenario. It considers the batteries are in poor condition, so most of the components must be recycled.

Additionally, some exceptions were considered for modules, CMCs, and other components, as follows:

i. In the case of modules, the remanufacturing option is not considered. Therefore, the modules that cannot be reused will be recycled or disposed of.
ii. Similarly, the remanufacturing option is not considered for electrical wires, so this material will be recycled or disposed of.
iii. Screws (steel) and anchors (polypropylene) will be recycled in all the scenarios considered.
iv. The refrigeration pipes (rubber) and insulating (expanded polyethylene) will be disposed of in all the scenarios considered.
v. Cell management controller (CMC), item n° 17, is considered as a component linked to the module, so the same recovery options are considered for modules and CMCs.

Table 5 presents the value of the recovery option indicator of each component in the considered scenarios.

5. Results and discussion

After defining the optimisation model and having presented the case study and the proposed scenarios, this section provides the results. Simulations were performed using a PC with an Intel Core i7 (3.4 GHz) processor and the operating system Windows 10 Enterprise, and were programmed and run using Microsoft Office Excel 2016 and MATLAB R2018a. A total of 27 simulations were carried out.

Table 5
Recovery option indicator ($o_{i,j}$) in the considered scenarios.

Item	REU				REM				REC			
n°	$o_{i,1}$	$o_{i,2}$	$o_{i,3}$	$o_{i,4}$	$o_{i,1}$	$o_{i,2}$	$o_{i,3}$	$o_{i,4}$	$o_{i,1}$	$o_{i,2}$	$o_{i,3}$	$o_{i,4}$
1	1	0	0	0	0	1	0	0	0	0	1	0
2	0	0	0	1	0	0	0	1	0	0	0	1
3	1	0	0	0	1	0	0	0	0	0	1	0
4	1	0	0	0	0	1	0	0	0	0	1	0
5	1	0	0	0	1	0	0	0	0	0	1	0
6	1	0	0	0	0	1	0	0	0	0	1	0
7	1	0	0	0	1	0	0	0	0	0	1	0
8	1	0	0	0	0	1	0	0	0	0	1	0
9	1	0	0	0	1	0	0	0	0	0	1	0
10	1	0	0	0	0	1	0	0	0	0	1	0
11	1	0	0	0	0	1	0	0	0	0	1	0
12	1	0	0	0	0	1	0	0	0	0	1	0
13	0	0	0	1	0	0	0	1	0	0	0	1
14	0	0	0	1	0	0	0	1	0	0	0	1
15	1	0	0	0	0	1	0	0	0	0	1	0
16–17 (×8)	1	0	0	1	1	0	0	1	0	0	1	1
A	0	0	1	0	0	0	1	0	0	0	1	0
B	0	0	1	0	0	0	1	0	0	0	1	0
C	0	0	1	0	0	0	1	0	0	0	1	0
D	0	0	1	0	0	0	1	0	0	0	1	0
E	0	0	1	0	0	0	1	0	0	0	1	0
F	0	0	1	0	0	0	1	0	0	0	1	0
G	0	0	1	0	0	0	1	0	0	0	1	0
H	0	0	1	0	0	0	1	0	0	0	1	0
I	0	0	1	0	0	0	1	0	0	0	1	0

Due to the large quantity of results that the model provides for the case studied, only the most significant outcomes will be presented in order to demonstrate its feasibility and effectiveness. First, in Section 5.1, the results of three simulations based on the REU approach are considered in order to show how the model presents the evolution of the main variables along the disassembly process. Second, in Section 5.2, the most significant results for the three study scenarios defined in Section 4.4 are then presented.

5.1. Simulation results

The results of three representative simulations based on the REU approach are presented, as follows:

- Simulation 1. This simulation considers the least desirable scenario at both economic and environmental level. It assumes that none of the modules of the EVB are useful to be reused, and the 8 modules must be disposed of.
- Simulation 2. It presents an intermediate case, in which half of the modules (4 over 8) are ready to be reused and the remainder of the modules must be disposed of.
- Simulation 3. This simulation presents the most desirable recovery option for the EVB. Based on the REU approach, in which most of the components are ready to be reused, it supposes, in addition, that the 8 modules are in very good condition and could also be reused.

5.1.1. Simulation 1. Disposal of 8 modules

Fig. 6 shows the results of Simulation 1. In this case, it is assumed that the 8 modules are disposed of. The recycling option for modules is not considered in this simulation. The figure presents five charts that correspond to the evolution of the most significant parameters (Y axis) as function of the disassembly level (X axis): the objective function (F_0), the economic sub-objective (y_1), the environmental impact sub-objective (y_2), the total incomes (ID) and the total disassembly costs (CD). From the analysis of this figure, the results reveal the following:

- With regard to the objective function (F_0), the optimal value is equal to 37.38 € and is obtained after item 8 (the Battery Management Controller, BMC) has been removed. This corresponds to a disassembly level of 40.62%. Thus, this simulation proposes a "partial disassembly". In the event that complete disassembly is implemented, the final value of F_0 is equal to -626.83 €, which entails a loss for the company.
- From the analysis of the chart that corresponds to the economic sub-objective (y_1), the graph shows that losses will be obtained for any level of disassembly, obtaining the minimum loss after item 8 has been removed (disassembly level of 40.62%). In the event of complete disassembly being carried out, the economic loss will be equal to -486.35 €.
- Analysing the environmental impact sub-objective (y_2), the favourable evolution of this parameter along the disassembly process can be observed, obtaining a maximum value of 121.18 € after item 15 (Lower housing shell) has been removed, which corresponds to a disassembly level of 75.00%. It is also worth noting that the fitness value of this sub-objective remains positive until items 16–17(3) (third module) have been removed, corresponding to a disassembly level of 84.38%. In the event of performing complete disassembly, the value of y_2 will reach -140.47 €.

5.1.2. Simulation 2. Reuse of 4 modules and disposal of the others

The results of this simulation are presented in Fig. 7. It assumes that 4 modules will be reused and the other 4 will be disposed of. The recycling of modules is not considered in this simulation. The analysis of this figure reveals the following findings:

- Regarding the objective function (F_0), the optimal value obtained is

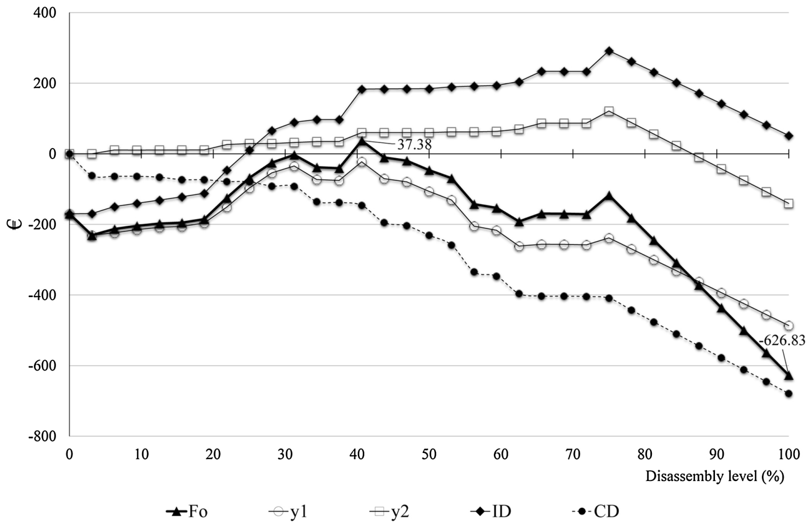


Fig. 6. Model results. Simulation 1.

588.73 €, which corresponds to a disassembly level of 87.5%, and is obtained after items 16–17(4) (the fourth module of the battery) have been removed. Again, the simulation proposes a "partial disassembly", and in the event that a complete disassembly is preferred, a value of F_0 equal to 331.81 € will be obtained. Therefore, in this simulation in both partial and complete disassembly, the objective function yields positive values.

- Analysing the evolution of the economic sub-objective (y_1), the results show that profits are not obtained until items 16–17(3) (the third module) are removed, which corresponds to a disassembly level of 84.38%. The maximum economic profit is obtained after those items have been disassembled. Moreover, if complete disassembly is performed, y_1 reaches a value equal to 333.81 €.
- Concerning the environmental impact sub-objective (y_2), once again the results show a positive evolution of this parameter along the disassembly process. A maximum value of y_2 equal to 401.89 € is obtained after items 16–17(4) (fourth module) have been removed (disassembly level of 87.50%). In addition, in the event of complete disassembly, the value of y_2 reaches 100.27 €.

5.1.3. Simulation 3. Reuse of the 8 modules

Finally, the third simulation considers that all modules are in very good condition and, therefore, the modules can be reused. The results are presented in Fig. 8 and reveal the following:

- The evolution in the objective function (F_0) shows this is the most appropriate and profitable case. The optimal value of F_0 coincides with the stopping point of the process, equal to 1294.45 € and obtained after all the modules have been removed, which corresponds to a complete disassembly process (100% disassembly level).
- Analysing the chart corresponding to the economic sub-objective (y_1), the results reveal that the process yields losses up to the removal of items n° 16–17(3) (third module), corresponding to a disassembly level of 84.38%. From then, the graph shows a favourable evolution of the economic sub-objective until the end of the disassembly process.
- From the analysis of the environmental impact sub-objective (y_2), the favourable evolution of this function along the disassembly process can once again be observed, obtaining the maximum fitness value after the last module has been removed, which corresponds to a value of 682.62 €.

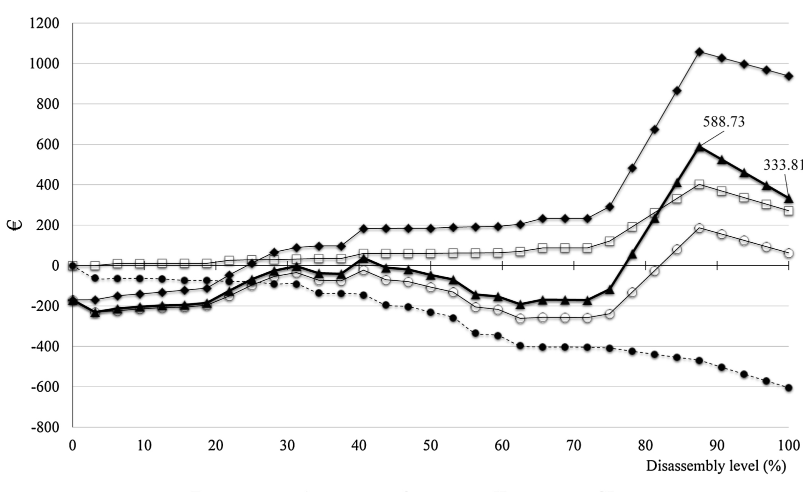


Fig. 7. Model results. Simulation 2.

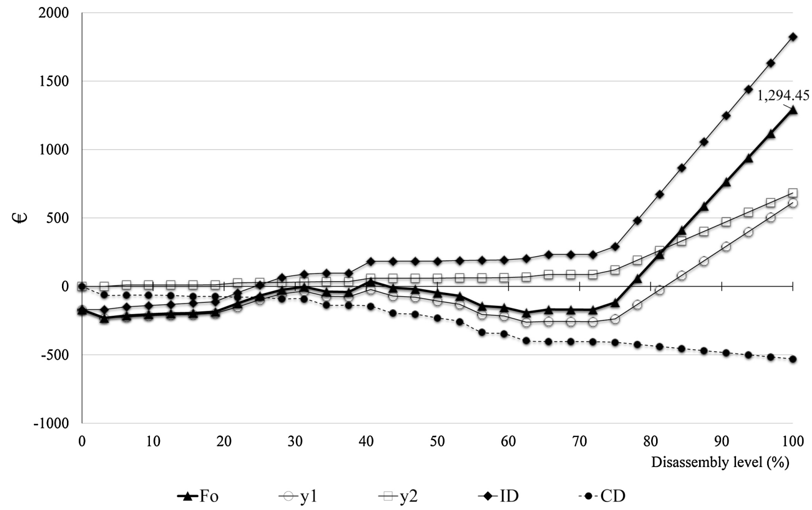


Fig. 8. Model results. Simulation 3.

Drawing on the results of the three simulations considered and presented in Figs. 6–8, some observations can be made in terms of the modules and the disassembly sequence. First, as the modules are the components with greatest added value, the results reveal that the profits are highly dependent on the state of the modules and consequently the chance to reuse them. Second, the results corroborate the importance of the disassembly sequence. As the modules are disassembled at the end of the process, it is not until the process achieves high degrees of disassembly levels (beyond 75%) that the results are significant in terms of the economic profits generated and the environmental impact avoided. This presents an unquestionable advantage from the environmental point of view due to most of the EVB components having to be disassembled prior to the modules. Therefore, the chances to reuse less valuable components are higher than if the modules are disassembled at the beginning of the process. In contrast, from the economic point of view, the profits are lower than in the case in which the modules are disassembled at the beginning of the process, in which case the "stopping point" would be in the early stages of the process depending on the number of modules suitable for reuse.

5.2. Results of the case study scenarios

Based on the case study scenarios defined in Section 4.4, additional simulations were performed in order to obtain a more complete analysis of the results and the corresponding findings that can be obtained in the consideration of the all possible conditions of the batteries and their components prior to disassembly.

5.2.1. REU scenario

This scenario considers that most of the components of the EVB are in good condition, and only the SOH of the modules could be lower than that required to maintain the original performance of the battery. In this case, with the exception of items 2 (upper insulator), 13 (cooling pipe), and 14 (lower insulation), which will be disposed of, and fasteners A to I, which will be recycled, all the other components of the EVB will be reused. In the case of the modules, this scenario assumes that the items 16 and 17 (the core of the module and the CMC) could be reused or disposed of, depending on their SOH (see Table 5).

Table 6 summarises the results of the simulations performed as a function of the number of modules that could be in a good condition, allowing for the possibility of these components being reused without additional recovery operations except for cleaning and testing. From the analysis of these results certain findings can be highlighted, as follows:

Table 6
REU scenario. Overall results.

N° modules	Partial disassembly		Complete disassembly
	F_0 (€)	DS level (%)	F_0 (€)
0	37.37	40.62	−626.83
1	59.44	78.12	−386.67
2	235.87	81.25	−146.51
3	412.3	84.37	93.65
4	588.73	87.50	333.81
5	765.16	90.62	573.97
6	941.59	93.75	814.13
7	1118.02	96.87	1054.29
8	1294.45	100.00	1294.45

- In the event of a partial disassembly being carried out, the results show the values of the objective function F_0 are positive whatever the number of modules being reused, with the fitness value ranging from 37.37 €, if 8 modules are disposed of, to 1294.45 € if all modules are reused.
- If a complete disassembly is proposed, the results of the fitness function reveal that the process is unviable if fewer than 3 modules are reused, with values of F_0 ranging from −626.83 €, if none of the modules are reused, to −146.51 € if two modules are in a good SOH to be reused.
- In the event that 3 or more modules are in a good condition to be reused, the fitness function values are positive, from 93.65 € for 3 modules being reused, to 1294.45 € if all the 8 modules are reused.

5.2.2. REM scenario

The REM scenario takes into consideration that some components of the EVB could be remanufactured in order to return them to their OEM, with a guarantee that the component is equivalent to a new one. Table 5 shows this scenario, considering the following: items 1, 4, 6, 8, 10, 11,

Table 7
REM scenario. Overall results.

N°modules	Partial disassembly		Complete disassembly
	F_0 (€)	DS level (%)	F_0 (€)
0	−11.45	40.62	−696.94
1	−11.45	40.62	−507.67
2	63.98	81.25	−318.4
3	189.53	84.37	−129.12
4	315.07	87.50	60.15
5	440.62	90.62	249.43
6	566.16	93.75	438.7
7	691.71	96.87	627.98
8	817.25	100.00	817.25

12 and 15 are remanufactured; items 3, 5, 7 and 9 (cables and connectors) are ready to be reused; items A to I are recycled; and items 2, 13, and 14 have to be disposed of. In the case of the modules, this scenario assumes again that modules could be reused or disposed of, depending on their SOH.

The results are summarised in Table 7. As in the previous scenario analysed, the simulations were performed considering the quantity of modules that could be reused, from 0 to 8. The analysis of this table reveals the following findings:

- If a partial disassembly is considered, the process is unviable if none or only one of the modules is ready to be reused. In these two cases, the value of F_0 is equal to −11.45 € for a disassembly level equal to 40.62%. The partial disassembly process is feasible in the event that 2 or more modules could be reused, with F_0 results ranging from 63.98 € (81.25% of disassembly level) if 2 modules are reused, to 817.25 € (100% of disassembly) if all modules are ready to be reused.
- Considering the complete disassembly process, the results reveal that the process is unviable unless 4 or more modules are in good SOH to be reused, with the values ranging from −696.94 € (0 modules) to −129.12 € (3 modules), which involves losses for the company, and from 60.15 € (4 modules) to 817.25 € (8 modules), for a feasible process.

5.2.3. REC scenario

This scenario assumes that all components of the EVB are recycled with the exception of items 2, 13, and 14, which are disposed of. The results are shown in Table 8, where the number of modules under consideration to be recycled ranges from 0 to 8. From this table, several findings can be highlighted:

Table 8
REC scenario. Overall results.

N° modules	Partial disassembly		Complete disassembly
	F_0 (€)	DS level (%)	F_0 (€)
0	−33.43	40.62	−764.54
1	−33.43	40.62	−633.13
2	−33.43	40.62	−501.72
3	−33.43	40.62	−370.3
4	16.03	87.50	−238.89
5	83.71	90.62	−107.48
6	151.39	93.75	23.93
7	219.07	96.87	155.34
8	286.76	100.00	286.76

- In the consideration of partial disassembly, the process is not feasible if fewer than 4 modules are ready to be recycled. In this area of losses, the fitness value is equal to −33.43 € for the disassembly levels of 40.62%. In contrast, the process is feasible if 4 or more modules are ready to be recycled, with the values of F_0 ranging from 16.03 € (4 modules) to 286.76 € (8 modules).
- In the event that a complete disassembly process could be considered, the process is unviable if fewer than 6 modules are ready to be recycled, obtaining considerable losses ranging from −764.54 € if none of the modules are recycled to −107.48 € in the case of 5 modules being recycled. If 6, 7 or 8 modules are in the required SOH to be recycled, the results reveal positive values of the F_0 fitness function.

Having presented the results based on the proposed scenarios and having highlighted some findings, it is worth noting the effectiveness of the model and its decision-making ability in managing the recovery process of EoL components from EVB. In addition, from a more general perspective, patterns can be deduced and managerial implications can be suggested, as summarised below.

According to the results presented in Tables 6–8, the most favourable recovery option for the EVB under study is reuse, from both the economic and environmental point of view. That is, the REU scenario is that which generates the greatest benefits if the condition of the batteries allows most of the components to be reused, as the scenario proposes.

From the results of the partial disassembly mode for all scenarios, it is worth underlining the significance of the BMC in achieving the stopping point of the process, reaching a disassembly level 40.62% and a net profit of 37.38 € in the REU scenario if none of the modules are ready to be reused, and the same disassembly level with −11.45 € in the REM scenario if none or only one module is available for reuse, or −33.43 € in the REC scenario if fewer than 4 modules are ready to be recycled.

Analysing the results as a function of the disassembly mode, it should be noted that partial disassembly is more desirable than complete disassembly in most cases, particularly if not many modules are ready to be reused or recycled. In the REU scenario, partial disassembly provides profits in all cases, as opposed to complete disassembly, for which 3 or more modules must be reused to obtain gains. If the REM scenario is analysed, partial disassembly provides positive results from a minimum of 2 modules to be reused, in contrast to complete disassembly, a process that requires 4 or more modules for reuse. In the case of the REC scenario, 4 or more modules to be recycled are necessary to obtain profits in the event of partial disassembly, or 6 or more if a complete disassembly is performed.

In addition, our research contributes with several managerial implications. First, this work can provide firms with a tool to improve their practices in recovery of EoL products, particularly batteries, although the work could be applied to other products to be recovered. Second, the model provides firms with a methodology to optimise their environmental practices, based on Ecoindicator 99, allowing them to quantitatively evaluate the environmental impacts and savings of all materials and associated processes (disassembly, recycling, disposal, …). It is a robust tool that helps place environmental practices at the same level as traditional economic issues. Third, the model provides firms with a tool to manage the recycling quotas of discarded batteries as the environmental performance of the process can be accurately measured, helping firms comply with governmental legislation in terms of recyclability issues.

Finally, it is important to highlight the key factors in the success of this research. First, the practical approach of the model, which was inspired by companies' need to manage these types of recovery practices. The methodology considers all the economic and environmental factors involved in the recovery process of EoL products. Second, the case study is based on an EVB currently in use and with a great penetration in the automotive market. Therefore, this research anticipates a recovery process that will undoubtedly be required in the near future. Third, the case study is supported by real data supplied by remanufacturing and recycling companies that currently operate in the European market, contributing in this way with a more realistic information data pack on which to make the calculations and provide the results.

6. Conclusions and future works

This paper presents a model for the techno-economic and environmental planning of the disassembly process of Li-ion EVBs for remanufacturing. The model takes into consideration all the factors affecting both the disassembly process variables and the recovery procedures parameters when different options of the disassembled components are considered: reuse, remanufacturing, recycling or disposal. The work contributes to the state of the art with a model to optimise the recovery of EoL Li-ion batteries. In so doing, we also obtain the disassembly sequence planning, the optimal level of the disassembly process achieving the maximum profit while minimising the environmental impact, and the decision on the final recovery option of the disassembled components, all of which results in a trade-off decision allowing a partial disassembly solution to be selected as the most appropriate choice for the management of this type of WEEE.

The model was tested using a real case study based on the Audi A3 Sportback e-tron Hybrid Li-ion Battery Pack, providing significant results that demonstrate its feasibility and effectiveness. Three case study scenarios based on different conditions of SOH of the batteries were considered, assuming that most of the components of the batteries could be respectively reused, remanufactured or recycled. The results provide valuable information concerning the optimal disassembly level of the battery for the scenarios considered depending on the number of modules that could be ready to be reused or recycled.

Future research could focus on various areas. First, on the analysis of the disassembly process considering the use of robots, or other solutions based on human-robot collaboration, in a more automatic framework where costs and environmental indicators could be even further optimised. Second, the model could be improved considering the disassembly process up to cell level. This would require the definition of solutions and procedures for remanufacturing and recycling cells. In addition, the re-planning of the disassembly process for decision-making depending on the quality parameters of the components and the process uncertainties could be interesting for a more strategical design of the disassembly sequence operations in real time.

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Appendix A. Data and results

Table A.1
Revenues and costs associated with the components (€).

Ref.	IRR_i	IRC_i	CDS_i	$C_{d,i}$	$Ca_{i,1}$	$Ca_{i,2}$	$Cg_{i,1}$	$Cg_{i,2}$	$Cg_{i,3}$	$Cg_{i,4}$
1	8.40	4.20	2.10	0.02	0.84	4.20	1.02	2.54	1.02	0.51
2	0.30	0.15	0.08	0.02	0.03	0.15	0.07	0.18	0.07	0.04
3	0.40	0.20	0.10	0.01	0.04	0.20	0.01	0.02	0.01	0.00
4	40.00	20.00	10.00	0.01	4.00	20.00	0.58	1.45	0.58	0.29
5	4.80	2.40	1.20	0.01	0.48	2.40	0.09	0.22	0.09	0.04
6	2.00	1.00	0.50	0.04	0.20	1.00	0.15	0.36	0.15	0.07
7	4.80	2.40	1.20	0.35	0.48	2.40	0.09	0.22	0.09	0.04
8	60.00	30.00	15.00	0.03	6.00	30.00	0.87	2.18	0.87	0.44
9	3.20	1.60	0.80	0.28	0.32	1.60	0.06	0.15	0.06	0.03
10	0.58	0.29	0.14	0.19	0.06	0.29	0.14	0.35	0.14	0.07
11	4.48	2.24	1.12	0.38	0.45	2.24	0.33	0.81	0.33	0.16
12	12.00	6.00	3.00	0.12	1.20	6.00	0.87	2.18	0.87	0.44
13	0.80	0.40	0.20	0.02	0.08	0.40	0.15	0.36	0.15	0.07
14	0.30	0.15	0.08	0.06	0.03	0.15	0.07	0.18	0.07	0.04
15	24.00	12.00	6.00	0.02	2.40	12.00	1.74	4.36	1.74	0.87
16-17	90.00	60.00	22.50	0.03	9.00	45.00	1.45	3.63	1.45	0.73
A	1.44	0.72	0.36	0.43	0.14	0.72	0.05	0.13	0.05	0.03
B	0.19	0.10	0.05	0.09	0.02	0.10	0.01	0.02	0.01	0.00
C	0.48	0.24	0.12	0.14	0.05	0.24	0.02	0.04	0.02	0.01
D	0.64	0.32	0.16	0.19	0.06	0.32	0.02	0.06	0.02	0.01
E	0.03	0.02	0.01	0.09	0.00	0.02	0.01	0.02	0.01	0.00
F	1.28	0.64	0.32	0.38	0.13	0.64	0.05	0.12	0.05	0.02
G	0.56	0.28	0.14	0.17	0.06	0.28	0.02	0.05	0.02	0.01
H	0.48	0.24	0.12	0.28	0.05	0.24	0.02	0.04	0.02	0.01
I	3.52	1.76	0.88	0.47	0.35	1.76	0.13	0.32	0.13	0.06

Table A.2
Environmental impact parameters associated with the components ($EI_{i,j}$ are measured in mPt; $ie_{i,j}$ and $ic_{i,j}$ are measured in €).

Ref.	$EI_{1,i}$	$EI_{2,i}$	$EI_{3,i}$	$EI_{4,i}$	$ie_{i,1,2}$	$ie_{i,3}$	$ic_{i,1}$	$ic_{i,2}$	$ic_{i,3}$	$ic_{i,4}$
1	2800.00	147.00	602.00	28.70	10.639	9.224	0.048	0.072	1.963	0.094
2	165.00	10.50	43.00	1.95	0.646	0.544	0.003	0.005	0.140	0.006
3	70.00	1.50	1.20	0.07	0.235	0.228	0.000	0.001	0.004	0.000
4	2700.80	1718.20	576.80	220.28	15.710	9.526	0.560	0.840	1.881	0.718
5	840.00	18.00	14.40	0.84	2.823	2.742	0.006	0.009	0.047	0.003
6	780.00	72.00	60.00	1.40	2.878	2.548	0.023	0.035	0.196	0.005
7	840.00	18.00	14.40	0.84	2.823	2.742	0.006	0.009	0.047	0.003
8	4859.40	2597.40	812.40	328.80	26.177	16.919	0.847	1.271	2.649	1.072
9	560.00	12.00	9.60	0.56	1.882	1.828	0.004	0.006	0.031	0.002
10	316.80	20.16	82.56	3.36	1.239	1.044	0.007	0.010	0.269	0.011
11	1747.20	161.28	134.40	3.14	6.448	5.708	0.053	0.079	0.438	0.010
12	4680.00	432.00	360.00	8.40	17.271	15.289	0.141	0.211	1.174	0.027
13	360.00	21.00	86.00	4.10	1.389	1.187	0.007	0.010	0.280	0.013
14	165.00	10.50	43.00	1.95	0.646	0.544	0.003	0.005	0.140	0.006
15	9360.00	864.00	720.00	16.80	34.542	30.578	0.282	0.423	2.348	0.055
16-17	6031.34	4322.55	13,168.83	10,029.83	71.589	52.375	1.410	2.114	42.944	32.707
A	30.96	36.00	8.64	0.50	0.233	0.103	0.012	0.018	0.028	0.002
B	15.84	1.01	4.13	0.17	0.062	0.052	0.000	0.000	0.013	0.001
C	10.32	12.00	2.88	0.17	0.078	0.034	0.004	0.006	0.009	0.001
D	13.76	16.00	3.84	0.22	0.104	0.046	0.005	0.008	0.013	0.001
E	17.82	1.13	4.64	0.19	0.070	0.059	0.000	0.001	0.015	0.001
F	27.52	32.00	7.68	0.45	0.207	0.091	0.010	0.016	0.025	0.001
G	12.04	14.00	3.36	0.20	0.091	0.040	0.005	0.007	0.011	0.001
H	10.32	12.48	2.88	0.17	0.079	0.034	0.004	0.006	0.009	0.001
I	75.68	88.32	21.12	1.23	0.571	0.25	0.03	0.04	0.07	0.00

Appendix B. Acronyms and nomenclature

Notations and related descriptions for acronyms, parameters and subscripts are presented in Tables B1–B.3.

Table B.1
Acronyms

AC	Alternating current
BJB	Battery junction box
BMC	Battery management controller
CE	Circular economy
CMC	Cell management controller
DC	Direct current
DIS	Disposal
DSP	Disassembly sequence planning
EoL	End of life
EV	Electric vehicle
EVB	Electric vehicle battery
GHG	Greenhouse gases
LCA	Life Cycle Assessment
Li-ion	Lithium-ion
mPt	Milli-point
NCA	Nickel Cobalt Aluminum Oxide
OEM	Original equipment manufacturer's
PHEV	Plug-in Hybrid electric vehicles
REC	Recycling
REM	Remanufacturing
REU	Reuse
SOC	State of charge
SOF	State of function
SOH	State of health
UPS	Uninterrupted power supply
WEEE	Waste from electrical and electronic equipment

Table B.2
Parameters

F_0	Objective function
y_1	Economic sub-objective
y_2	Environmental sub-objective
ID	Total incomes
CD	Total disassembly costs
IRR_i	Revenue obtained from component i to be reused or remanufactured
$o_{i,j}$	Indicator of the recovery mode: 1 if mode j is assigned to component i
IRC_i	Revenue obtained from component i to be recycled
CDS_i	Disposal cost of component i
$t_{d,i}$	Operation time to disassemble component i
$Ca_{i,j}$	Recovering cost of component i in mode j
$Cg_{i,j}$	Total overhead costs assigned to component i in mode j
IME	Environmental impact avoided
IMC	Environmental impact caused
$ie_{i,1,2}$	Environmental impact avoided by reuse or remanufacture of component i
$ie_{i,3}$	Environmental impact avoided by recycling component i
$EI_{1,i}$	Eco-indicator value by producing the raw material for component i
$EI_{2,i}$	Eco-indicator value concerning the manufacturing process of component i
$EI_{3,i}$	Eco-indicator value of the recycling process of component i
$EI_{4,i}$	Eco-indicator value of the disposal process of component i
f_c	Indicator to convert mili-points (mPt) into monetary units (€)
P_{ha}	Estimated price of one hectare (ha)
$r_{hab/ha}$	Ratio of hectares per capita
$IA_{hab/ha}$	Estimated environmental impact of an inhabitant per year
$ic_{i,j}$	Environmental impact caused by component i in mode j

Table B.3
Subscripts

i	Indicator of component
j	Indicator of recovery mode
1	Component i is assigned to be reused
2	Component i is assigned to be remanufactured
3	Component i is assigned to be recycled
4	Component i is assigned to be disposed of

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