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Enhancing Critical Raw Material Usage through Battery Cell Extraction and Reuse

Alex Bunodiere[(a)], Joost R. Duflou[(a, b)]
a) KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, 3001, Leuven, Belgium
b) Member of Flanders Make

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Abstract: This paper proposes a circular economy business model for recycling and remanufacturing Bosch Gen 3 batteries to enhance sustainability and economic viability. The model integrates collection, robotic disassembly, and state-of-health-based categorisation to extract the most valuable, reusable cells and then tests a battery remanufacturing option to maximize profit and critical raw material recovery. Two collection methods are analysed: incentivized returns (Option 1) and battery waste sorting at recycling centres (Option 2). A Monte Carlo simulation evaluates profitability with several uncertainties, including logistics and deposit refunds. Option 1 is more likely to obtain higher-quality cells, but is less likely to be profitable due to the high costs associated with the incentive, while Option 2 is more cost-effective, but yields lower-quality cells. This study highlights opportunities to optimize incentives and recycling value, providing a scalable framework for sustainable battery end-of-life management.

Introduction

The demand for lithium-ion batteries (LIBs) is growing over 30% annually, projected to reach 4.7 TWh and $400 billion by 2030, driven by electrification and energy transitions(J. Fleischmann & Schaufus, 2023). This growth depends on critical raw materials (CRMs) like lithium, cobalt, and nickel, which face supply chain risks and environmental concerns. In the power tool industry, LIBs are valued for their energy density and lifespan, but challenges include securing material supplies, ensuring tool compatibility, and recycling to recover valuable resources. Tackling these issues is essential for sustainable growth and reduced environmental impact (Zeng et al., 2014).

Although consumer drop-off programs are expanding, current recycling practices remain fragmented and inadequate. Batteries are often treated as mixed e-waste, limiting the recovery of valuable materials (Zeng et al., 2014). Recent regulatory changes, such as the European Union's Batteries Regulation, emphasize circular economy principles by setting strict standards for lifecycle sustainability. Effective from August 2023, these regulations mandate reductions in hazardous substances, higher recycling targets, and designs that allow easy battery removal and replacement by 2027. Such measures provide a favourable policy framework for improving battery management systems (Directorate-General for Environment, 2023).

CRM recovery could possibly be facilitated by selective disassembly from LIBs, However, analysis of real-life case studies has concluded that the economic feasibility of product disassembly is strongly linked to the recovery and reuse of functional components from the processed products. Fuji Film's single-use camera remanufacturing model incorporates modular design, automation, and efficient logistics, processing up to 33 million units annually. This system achieved a 62% reduction in CO_2 emissions and demonstrated the economic viability of scalable, sustainable end-of-life management (Duflou et al., 2008).

This paper builds on these principles to propose a circular economy model for Bosch Gen 3 tool batteries (*Power for All Alliance*, 2024), which would fall under category 6, based on the EU waste electrical and electronic equipment (WEEE) category classification (Magalini et al., 2014). The model combines reverse logistics, automated disassembly, state-of-health (SoH) testing, and customer incentives to address inefficiencies in current systems. By focusing on residual value extraction and profitable remanufacturing, the study highlights the potential to optimize CRM recovery and reduce e-waste through a potentially profit business model.

Methodology

Case Study: Bosch PFA Gen 3 Battery

This study focuses on the Bosch Generation 3 (gen 3) 4Ah battery (*Power for All Alliance*, 2024). The gen 3 4Ah battery was selected for its high potential volume and standardized design, ensuring compatibility with 164 tools from 12 different manufacturers' tools under the Power for All Alliance. As the latest generation (gen 3), it offers a single capacity option (4Ah) in one physical size, unlike the gen 2, which had seven capacities across two physical sizes. This streamlined design enhances its suitability for robotic disassembly. While not the highest-volume model at the time of writing, the transition from gen 2 to gen 3 batteries was already underway.

According to Eurostat, 244,048 tonnes of portable batteries were sold in 2022 (Eurostat, 2024)However, this data encompasses all battery types and is reported by weight rather than individual units. To estimate Bosch lithium-ion power tool battery sales, Bosch's European power tool revenue, which totalled €5.6 billion in 2023 (Bosch Power Tools, 2024), can be used as a reference. Assuming an average sales price of €100 per unit, this equates to approximately 56 million power tools sold in 2023. Bosch power tools also report that 10% of its power tool sales occur in Germany, suggesting around 5.6 million units were sold there in 2023. Additionally, market data from the United Kingdom indicates that 81.1% of power tools sold in 2022 were cordless (Protrade, 2023) Applying this proportion to Bosch's estimated German sales suggests that approximately 4.5 million cordless power tools, most of which would contain a LIB.

Figure 2: Flow chart of proposed EOL treatment

While this is a rough estimation and limited to Germany, it highlights the substantial number of Bosch batteries sold annually, supporting the economic feasibility of a circular economy model presented in this paper.

Figure 1 provides an exploded view of the gen 2 battery, highlighting individual components such as the plastic housing, cells, nickel strip and Battery Management System (BMS). A sample battery was manually disassembled, and its components were weighed to estimate their recycling value, which is detailed in the *results* section.

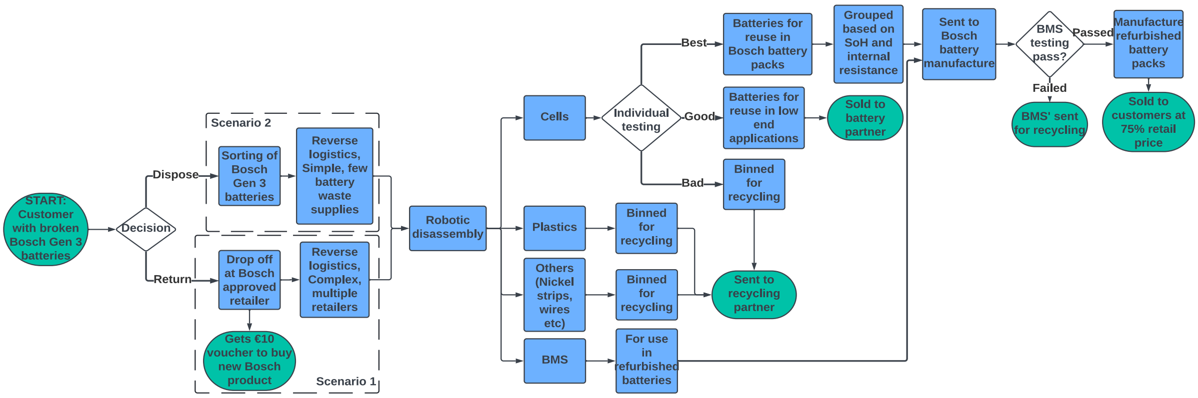

Figure 1: Flow chart of proposed EOL treatment

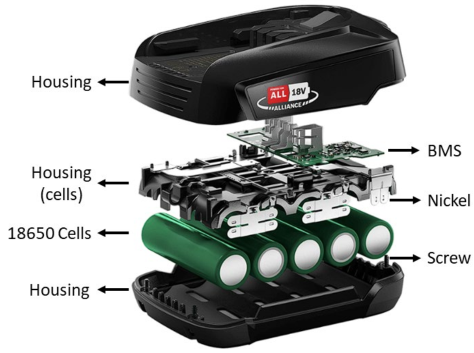

Figure 3: Bosch gen 2 battery exploded view (Power for All Alliance, 2024)

This battery employs 21700 lithium-ion cells (the number refers to the width (21mm) and length (70mm) of the cell), which are optimal for remanufacturing and recycling efforts due to their higher energy density than more traditional 18650 cells used in gen 2 batteries. The proposed battery remanufacturing model (shown in *Figure 2* below) developed for this paper, covers the battery from failure at the customer, through collection/incentivised return, to robotic disassembly and eventual remanufacturing into a new battery.

Battery collection/deposit refund

End-of-life management for these batteries typically follows three pathways: landfill disposal, incineration, or recycling, often accompanied by a hoarding tendency, where users store broken batteries at home for extended periods (Mudgal et al., 2011). When choosing recycling customers typically dispose of their broken tool battery at either an e-waste collection centre or in a dedicated battery disposal container, from where it is collected and sent to a specialised battery recycling centre (Bebat, 2024).

While specific recycling data on tool LIBs is unavailable, estimates from battery and accumulator recycling data (Eurostat, 2025) indicate that approximately 46% of batteries sold in the EU were collected for recycling in 2022. However, this calculation is flawed, as it relies on a three-year reference period—significantly shorter than the typical lifespan of LIBs, as highlighted by BeBat, the Belgian battery collection agency.

"*…there has been strong growth in recent years in the market for lithium rechargeable batteries...It is clear that the current method of calculating the collection rate is no longer adequate…"* (Bebat, 2023)

Additionally, the data does not distinguish between individual cells and battery packs, such as the Bosch gen 3 tool batteries, which are generally more likely to be recycled due to their larger size and structured disposal pathways (Mudgal et al., 2011). To increase this conservative 46% collection rate and capture the battery before it is shredded, this model introduces one novel approach, namely providing a financial incentive for the customer to return the battery to a retailer hereby referred to as option 1. A second approach is also explored where the batteries are separated at the battery treatment facility referred to as option 2. These two methods of collection are compared in the *results* section.

1. Option 1: Incentivised return

To encourage the return of Gen 3 batteries, the model would offer customers a Bosch voucher upon returning their battery to an approved dealer. A voucher value of €10 was determined as an appropriate amount, based on the recommended retail price of the Gen 3 battery of €126 at the time of writing (Bosch, 2024).

The voucher program costs are discounted in the model to an effective cost of (€2 – €4). The cost of a €10 voucher to a company is less than its face value and depends on factors like the cost of goods sold (COGS), redemption rate, administrative expenses, and potential additional sales. For example, if COGS is €5 and only 60% of vouchers are redeemed, the cost per voucher is €3. This option also requires robust logistics to collect and consolidate batteries nationwide for processing, since batteries could be returned at any Bosch dealer, and would have to make its way to a central point. These reverse logistics costs, due to dispersed retailers, are estimated to range from (€0.50 – €2) per battery pack, with a mode of €1. This wide range reflects uncertainties in transportation and handling expenses.

2. Option 2: Battery waste sorting

This approach utilizes the existing battery collection system, where batteries are deposited into collection boxes and transported to centralized recycling centres. At these centres, a new sorting process would be added where only gen 3 batteries are sorted from other types before being sent to a robotic disassembly plant via reverse logistics. The amount paid per battery pack to the battery recycling centre is €1, this value was estimated, based on the costs incurred by the battery recycler to collect the batteries together with an additional fee for the sorting. The reverse logistics costs are lower than Option 1 (€0.30–€0.80) due to simpler processes in the logistics chain, being a point-to-point flow.

Both option 1 and option 2 facilitate battery collection and transportation but differ in cost and battery quality. Incentivized returns would incur higher costs due to customer rewards and complex logistics, but would likely yield higher-quality batteries with remaining usable life. In contrast, battery waste sorting is cheaper and simpler, however, would likely result in lower-quality batteries, as these are often used until failure before being discarded. This is reflected in the model, with a change in the number of "Best" and "Bad" cells in *Table 1*.

Battery Robotic Disassembly

The battery disassembly process would be outsourced to a partner organization such as Circuli-ion (Circu Li-ion, 2024) a company that specialises in battery disassembly. The proposed model would leverage purpose-built robotic systems specifically optimized for only gen 3 battery packs. Robotic disassembly allows for the efficient separation of components, including cells, plastic casings, BMS, nickel strips, and screws. This automated approach minimizes manual labour and is both cost-effective and scalable. The calculation of this cost includes fixed and operational costs to support the disassembly process. The number of operators is based on the quantity of batteries being processed, the shift duration is 8 hours, with a total working day in Belgium of 250 per year and a disassembly time of 1 minute, this is the maximum throughput of such a robotic disassembly process. If more throughput is required, then an additional robotic disassembly set-up would be required.

$$N_{bats/yr} = \frac{Time_{shift} * 60}{Time_{dissassemble}} * Working\ days$$

$$N_{bats/yr} = \frac{8 * 60}{1} * 250$$
$$= 120{,}000\ bats\ per\ year\ per\ operator$$

Each operator could manage approximately 120,000 battery packs annually. Operating two shifts per day allows the robotic disassembly station to process up to 240,000 packs per year, requiring two full-time operators. With an annual salary of €50,000 per operator, the total salary cost would be €100,000. The robotic equipment, with an initial investment estimated at €500,000, would depreciate over 10 years, resulting in an annual depreciation cost of €50,000. Consequently, the total maximum annual cost for the disassembly station would amount to €150,000.

$$C_{pack} = \frac{Annual\ cost}{Batteries} = €/bat$$

$$C_{per\ pack(min)} = \frac{150{,}000}{240{,}000} = €0{,}625/bat$$

$$C_{per\ pack(max)} = \frac{100{,}000}{120{,}000} = €0{,}833/bat$$

In the model, the disassembly time per battery is not 1 minute as in these simple calculations but rather modelled as a distribution ranging from (0,5 – 2) minutes. This range accounts for variations in battery condition and incorporates uncertainty in the disassembly process.

Cell Testing and Sorting

Each cell would undergo automated testing to measure its internal resistance and estimate its State of Health (SoH), a key metric that indicates the cell's remaining capacity and performance relative to its original specifications, with a SoH of 100% representing a new or like-new cell (Ufinebattery, 2024; Zatta et al., 2024). The cost of testing is assumed to be €0,1 per cell, based on a rapid electrical parameter testing technique. This assessment determines the value of each cell and enables sorting into three categories.

1. Recycling "bad cells": Cells with an SoH below 50% are designated for recycling.
2. Low-End Reuse "good cells": Cells with an SoH between 50% and 70% are suitable for low-demand applications.
3. High-End Reuse "best cells": Cells with an SoH above 70% qualify for high-demand applications, such as remanufactured Bosch gen 3 batteries, where they would be reassembled into packs sold at a reduced price.

Recycling

Cells with an SOH lower than 50% would be deemed "bad" and be binned for recycling. Due to their separation from the battery pack, these cells would yield a high CRM recovery rate as opposed to the current method of shredding battery packs as a complete unit and then separating the materials. All other components of the batteries such as the plastics, nickel strips etc are also recycled, due to their lower value and difficulty in reuse. The revenues generated from selling these components are listed in *Figure 3* and *Table 2.*

Low-end reuse

This study assumes cells with a SoH between 50% and 70% are classified as "good." While these cells retain sufficient serviceable life, their performance is inadequate for use in remanufactured Bosch gen 3 batteries, which are expected to exhibit a capacity and lifespan comparable to new batteries. Instead, these cells would be sold to companies producing low-end household energy storage systems, where energy density is less critical. Consequently, the resale value of these cells is lower than their potential value in remanufactured packs but higher than their recycling value. For this model, the estimated value of a "good" cell is €1, derived from a comparison of the recycling value (€0.47) and the price of a new cell (€2.10). This valuation reflects the intermediate market potential of these cells in secondary applications.

High-End Reuse: Remanufacturing Battery Packs

Cells deemed "best" (SoH > 70%) undergo further processing to ensure compatibility and longevity. They are balanced to the same float voltage and grouped by SoH. They are then sent to the battery manufacturing plant together with the BMS' in the next process.

Logistics to Remanufacturing plant

The "best" cells, along with all extracted BMS units, would be transported to the battery assembly plant for further processing. This transportation would follow a point-to-point logistics model, similar to the logistics from the battery sorter to the robotic disassembly facility. Accordingly, the same cost uncertainty values are applied, reflecting the variability in transportation expenses.

Test BMS

At the battery production facility, the BMS units would undergo testing using a custom-designed test jig. This process, likely manual, would involve a worker inserting the PCBs into a test jig where basic functionality checks are performed and subsequent reconfiguration of "good" BMS units for use in remanufactured battery packs. The cost of testing each BMS is estimated at €0,5 based on high-volume standardised PCB testing (PCB online Team, 2021).

Remanufactured battery reassembly

The "best" cells and "good" BMS units would then be reassembled into remanufactured battery packs using new plastic housings, nickel strips, and screws at Bosch's automated manufacturing plant. These remanufactured gen 3 batteries would be sold at 70% of the price of a new battery, representing the primary source of revenue and a key innovation of this model.

Monte Carlo simulation

To identify the optimal battery collection option and simulate the overall cost, revenue, and profit of the model, while accounting for uncertainties in variables such as logistics and testing, a Monte Carlo simulation was developed. This model was implemented in Excel using the ModelRisk Monte Carlo software add-in (Vose software, n.d.). The input variables for the model, detailed in *Table 1*, are characterized by minimum, mode, and maximum values, assuming a normal distribution as previously discussed in the paper.

Table 1: Model inputs

Variable name (per pack)	Min	Mode	Max
Option 1: Incentivised return			
Reverse logistics	€0,5	€1	€2
Deposit refund cost	€2	€3	€4
Best cells %	20%	30%	40%
Option 2: Battery waste sorting			
Sorting		€1	
Reverse logistics	€0,3	€0,5	€0,8
Best cells %	10%	20%	30%
Applies to option 1 and option 2			

Robotic disassembly time	0,5min	1min	2min
Testing cells (per cell)		€0,1	
Logistics to Bosch	€0,3	€0,5	€0,8
Test BMS		€0,5	

The Monte Carlo model runs two simulations (Option 1 and Option 2), each with 5000 samples, and a manual seed of 1 (for reproducibility of results). The results of this model will be discussed below.

To simulate a realistic business model, a quantity of batteries is needed. This quantity would represent the number of batteries that could be processed in one year. This number is an uncertainty and therefore a distribution, with a range from (120 000 – 240 000). These come from the minimum and maximum number of batteries that can be processed by 1 or 2 operators and one robotic disassembly line, as discussed previously.

Results

Recycling values

The first step involves calculating the value of the recycled component materials extracted from the battery. A key advantage of this proposed process is that the separation of individual components significantly increases their recycling value compared to shredding, where materials are mixed, reducing their purity and therefore value. Additionally, the extraction efficiency of CRMs is higher in this method, as material loss during processing is minimized due to precise separation. The disassembled gen 2 battery is provided below in *Figure 3* to show its components. The gen 2 battery was easily accessible at the time of this study, hence the use of the gen 2 bill of materials (BOM). The weights and components (with identification numbers matching *Figure 3*) in *Table 2* have been adjusted for gen 3 specifications. For instance, cell weights reflect the use of Type 21700 lithium cells in gen 3, replacing Type 18650 cells in gen 2.

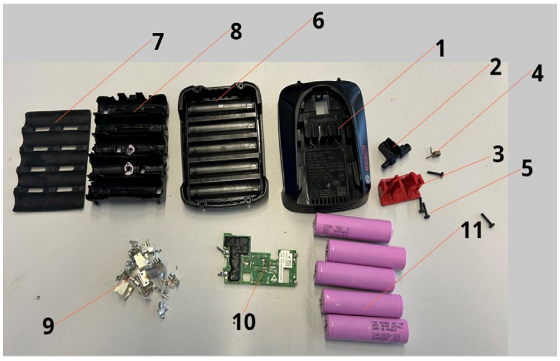

Figure 4: Bosch power for all (PFA) gen 2 battery disassembled (labels in Table 2)

Recycling values are sourced as indicated, except for the housing, made of PC/ABS FR40, where the general plastic waste value of €454/ton (Eurostat, 2024) was used due to a lack of specific pricing for plastic with FR40. The flame-retardant additive complicates recycling, reducing demand or increasing costs; thus, the analysis applies a 50% reduction in its value. As with the previously mentioned Fuji Film example, it is possible that these plastics could be repurposed to manufacture new housings. However, the viability of this option remains uncertain due to the unknown condition of the housing. Additionally, since the value of these housings is significantly lower than the cells, this possibility was excluded from this study.

Table 2: Recycling value of Gen 2 battery

Part (*Figure* 3 number)	Material	N	Weight	Value (€/ton)	Source	Value (€)
Housing (1,6)	PCABS FR40	2	91,2	€227*	(Eurostat, 2024)	€0,02
Housing (cells) (8)	PCABS FR40	1	24,6	€227*	(Eurostat, 2024)	€0,006
Push button (3)	ABS	1	4,6	€454	(Eurostat, 2024)	€0,002
Rubber plate (7)	Elastomer	1	4,9	€454	(Eurostat, 2024)	€0,002
Nickel (9)	Nickle		10,3	€8510	(Rockawayrecycling, 2024)	€0,087
Screws (5)	Steel	4	1,8	€220	(Metaloop, 2024)	€0,004
Spring (4)	Steel	1	0,4	€220	(Metaloop, 2024)	€0,001
Cells (Bad) (11)	21700 LiPo	X	360	€1381	(Scrapmonster, 2024)	Variable

BMS (Bad) (10)	PCB Grade 1	0,5	7,9	€4500	(Repairprice.co.uk, 2024)	€0,04
Total recycling value (excl cells)					€ 0,154	

The recycling value per pack is €0.154, a low figure due to unknown material compositions, such as screw steel grades or elastomer types, leading to conservative estimates. A detailed analysis of gen 3's BOM and material composition analysis would be necessary for more accurate pricing, which wasn't possible for this study. This would likely increase the estimated recycling value.

Monte Carlo simulation

The first outcome of the Monte Carlo simulation is the total profit, illustrated in *Figure 4*. This profit is calculated by multiplying the annual number of battery packs processed by the total revenue (from best and good cells, functional BMS units, and recycling value), minus all associated costs (including logistics, robotic disassembly, deposit refunds for Option 1, and sorting fees for Option 2). The simulation is repeated 5,000 times, with each iteration sampling different values from the distributions of the variables, resulting in a distribution of potential profit outcomes for both options.
The resulting distributions represent the best, worst, and most likely scenarios for each option. The analysis reveals that Option 2 is more likely to be profitable, with a mean profit of €278,192, compared to Option 1, which shows a mean loss of €175,814. However, it is noteworthy that Option 1 can still achieve profitability in some scenarios, as indicated by instances with positive profit, while Option 2 may occasionally result in a net loss, as shown by some instances with negative profit. These variations arise from the high degree of uncertainty in the input variables. Further research and data collection could reduce this uncertainty and narrow the distributions, though the general conclusion of the study is unlikely to change unless the variables are significantly shifted.

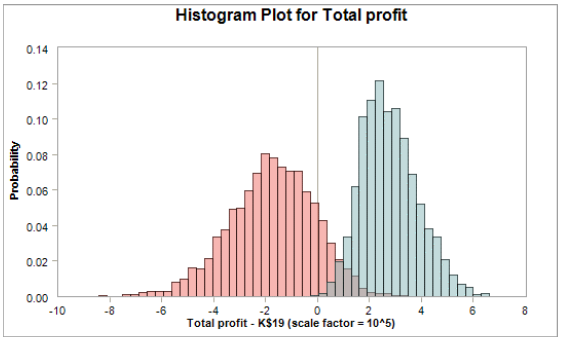

Figure 5: Histogram plot for total profit of Option 1(red) and Option 2(blue)

The tornado plot presented in *Figure 5* illustrates the sensitivity of total profit to the uncertainty of the input variables for Option 1. The most significant source of uncertainty is the deposit refund, which ranges between €2 and €4, as detailed in *Table 1*. This variability substantially impacts expenses, as the refund is applied to every battery pack returned. Reserve logistics follows closely as another major source of uncertainty, given its similar impact on costs. Reducing the uncertainty of these inputs could significantly enhance the reliability of the model's predictions. A pilot study could be conducted to establish a narrower distribution for the deposit refund, while an analysis of logistics routes could provide more accurate estimates of transportation costs between the retailers and the disassembly plant. Such refinements would help minimise uncertainty and improve the robustness of Option 1's financial projections.

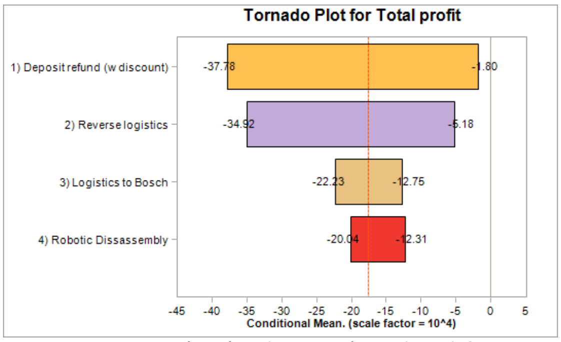

Figure 6: Tornado plot for total profit of Option 1

The tornado plot for Option 2, shown in *Figure 6,* highlights reverse logistics as the largest contributor to variability, similar to Option 1. Other expenses, such as robotic disassembly and logistics to Bosch, also exhibit the same uncertainties as those identified in Option 1.

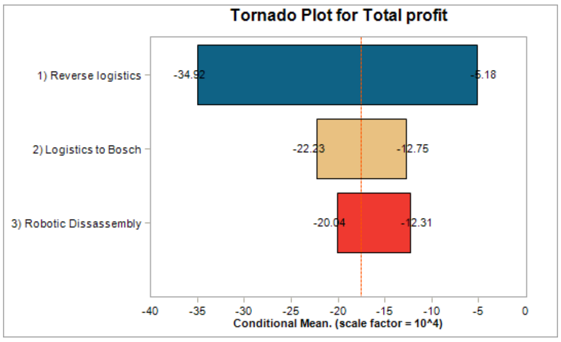

Figure 7: Tornado plot for total profit of Option 2

Figures 7 and *8* present the box plots of all revenues and expenses contributing to the profit calculation, expressed on a per-battery basis. A key difference between Option 1 and Option 2 is the revenue generated. As discussed, Option 1 is expected to yield a higher percentage of "best" cells, as the financial incentive encourages customers to return battery packs before they are fully depleted. However, this benefit comes at a significant cost due to the deposit refund. The simulation aimed to determine whether the improved cell quality in Option 1 would offset this additional expense. As shown in *Figure 4*, the results indicate that it does not, making Option 2 the more cost-effective choice.

To mitigate these costs, market research could be conducted to identify the optimal battery return voucher value. While this study used a €10 voucher, discounted to (€2 – €4), a lower nominal voucher value might achieve similar battery return rates, significantly reducing costs while maintaining benefits. Additionally, profitability could be improved by enhancing the recycling value of components not reused. Given that these parts are sorted and separated without impurities, negotiating higher prices based on their purity could represent another pathway to improve revenue.

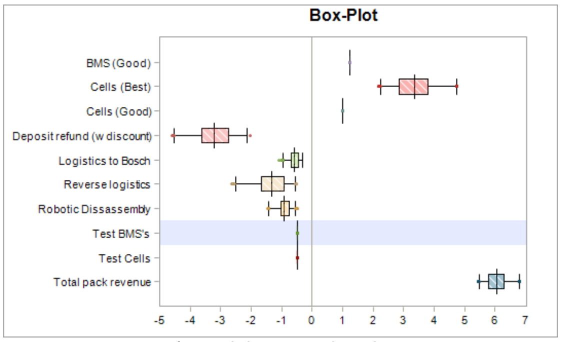

Figure 8: Box plot of factors for Option 1

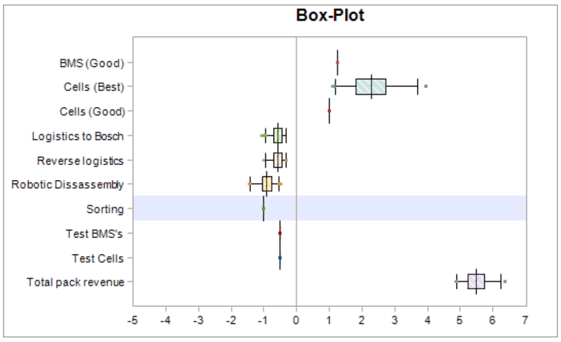

Figure 9: Box plot of factors for Option 2

Conclusions

This study presents an innovative circular economy model for Bosch gen 3 batteries, integrating reverse logistics, robotic disassembly, SoH-based categorization, and incentivized returns. The model demonstrates how combining these elements can potentially maximize the reuse of CRMs, reduce electronic waste, and provide a scalable approach to battery remanufacturing and recycling.

The Monte Carlo simulation revealed key insights into the viability of two collection options. Option 1, which involves incentivized customer returns, is assumed to yield higher-quality "best" cells; however, this benefit comes with significant costs, making it less likely to be profitable under current assumptions. Conversely, Option 2, based on battery waste sorting at recycling facilities, is more cost-effective and more likely to yield a positive profit, albeit with likely lower-quality cells.

The Monte Carlo method effectively simulates uncertainties but has limitations. Its accuracy depends on input distributions, which may not fully reflect real-world variability. The model assumes independence between variables like logistics costs and battery return rates, oversimplifying potential correlations. It also provides a static analysis, excluding long-term market shifts and regulatory changes. Additionally, reliance on estimated data for key variables introduces potential inaccuracies. Recognising these limitations highlights the need for empirical validation, pilot studies, and real-world data to improve model accuracy.

To improve the profitability and scalability of both collection models, further research is needed to refine key uncertainties, such as deposit refund values and logistics costs. Enhancing the recycling value of non-reusable components (such as the FR40 plastic casings) through better pricing strategies and exploring automated cell identification at recycling centres could further optimise efficiency. A key sustainability trade-off lies between remanufacturing and direct recycling. While remanufacturing retains embedded energy and reduces reliance on mined materials, prolonged cell use may lower recoverable material value and increase waste from failures. Future research should assess whether extending battery life or prioritising early remanufacturing offers greater economic and environmental benefits. Integrating life cycle assessments (LCAs) into profitability models would provide a more comprehensive view, guiding policy and industry adoption.

Overall, the model underscores the potential of circular business practices to address global resource challenges and sets a benchmark for improving end-of-life battery management.

Acknowledgements

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