Battery pack remanufacturing decisions considering remanufacturing costs and risk priority number in determining repair or replacement

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ARTICLE INFO

Article history
Submission: 18 Sept. 2024
Revised: 5 February 2025
Accepted: 17 February 2025

Keywords
Battery Pack
Remanufacturing
Risk Priority Number
Remanufacturing Costs

https://doi.org/10.22219/oe.2025.v17.i1.128

ABSTRACT

Organizations The growth of electric vehicles is accompanied by an increase in the number of batteries and battery waste produced, which can ultimately have harmful effects on the environment. As a solution, battery pack remanufacturing has emerged as an effective alternative. However, challenges in the remanufacturing process include determining which battery pack components can be repaired and which require replacement with new components, ensuring that remanufacturing costs remain low while preventing potential future failures. This study aims to develop a remanufacturing decision model that integrates Failure Mode and Effect Analysis (FMEA) with a remanufacturing cost model. The study's results outline the relationship between failure modes and battery pack components, whereby each failure mode can be classified to determine appropriate repair or replacement actions. While specific actions have been formulated, remanufacturing costs remain the final determinant in the overall battery remanufacturing decision. Based on the analysis, repairs or replacement of new part on 13 components associated with failure modes still render the battery pack suitable for remanufacturing, with a potential cost saving of more than 40% compared to purchasing a new battery pack.

1. Introduction

In the remanufacturing process, component reuse must be carefully considered. For instance, the Battery Management System (BMS), which regulates power, is critical to ensuring the safety and reliability of battery packs (Rimon et al., 2019). Generally, the components within a battery pack are modular, with each component connected either in series or parallel (Kampker et al., 2021), thus allowing each component to support the functionality of others. Considerations such as severity levels, detectability, and the likelihood of future incidents are necessary to ensure that component reuse does not result in adverse effects.

Typically, remanufacturing costs are a determining factor in remanufacturing decisions. High remanufacturing costs for battery packs often lead users to dispose of battery packs instead of remanufacturing them, or discourage remanufacturers due to economic impracticality. An alternative is to extract valuable materials such as lithium, cobalt, and nickel within the batteries through recycling processes (Harper et al., 2019). Therefore, cost becomes an important consideration in remanufacturing decisions involving reuse, repair, and component replacement.

This study argues that battery pack remanufacturing decisions are crucial in reducing environmental impacts; therefore, remanufacturing decisions must be made with careful consideration to prevent potential adverse effects in the future. Additionally, economic factors should also be a criterion in remanufacturing decisions. Thus, this study aims to develop a remanufacturing decision

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model by considering the Risk Priority Number (RPN) in determining the reuse, repair, component replacement, and remanufacturing costs of battery packs.

Battery Pack Remanufacturing

The Battery pack is a combination of lithium battery cell which is connected in series and parallel for intended voltage and ampere. Currently, battery pack remanufacturing has become an area of interest for various industries. Several brands that produce electric and hybrid vehicles are now prepared to undertake battery remanufacturing. Tesla, as a company focused on electric vehicle manufacturing, has planned the remanufacturing of its battery packs along with the strategies to be implemented (Naor, 2023). Similarly, Nissan, which produces the electric vehicle Nissan Leaf, has begun investigating battery remanufacturing as a project to support the sustainability of the circular energy economy (Nissan News, 2024).

Battery pack remanufacturing has been widely discussed by researchers, including the potential of lithium battery remanufacturing in supporting the circular economy, where second-life battery reuse could be a solution for batteries that have weakened but are not yet fully damaged (Pagliaro & Meneguzzo, 2019). Key factors in building a battery remanufacturing ecosystem include the integration of circular economy principles, enhancement of technical expertise, and internal collaboration (Chigbu et al., 2024). To support the remanufacturing ecosystem and meet the need for second-life batteries, simple reconditioning development has been conducted by M. Rasheed et al. (2024) to optimize the performance of batteries reused for other purposes (Rasheed et al., 2024). The costs of battery remanufacturing have also been extensively studied, including cost savings for alternative uses through remanufacturing processes (Li, 2023), savings compared to new production (Xiong et al., 2020), and the cost-benefit of battery remanufacturing (Foster et al., 2014).

The potential to extend battery pack lifespan to nearly 100% health can be achieved by replacing its components with new units, allowing the battery to maintain the desired health condition (Mathew et al., 2017). This replacement decision in the remanufacturing process is made at the disassembly stage, which involves product quality inspection (Andrew-Munot & Ibrahim, 2013). To achieve the desired target, replacement following disassembly is not the only option. Reusing components can be another choice, as it has a lower environmental impact than replacement (Baxter et al., 2024), and offers cost savings of up to 40% (Smith & Keoleian, 2004).

Risk Periority Number

Remanufactured products must meet quality standards or target specifications and functions equivalent to the original product. Likewise, battery packs carry risks such as overheating, short circuits, and local heat accumulation, which may lead to fires, explosions, or smoke emissions (Chen et al., 2021). Chen et al. (2021) (Chen et al., 2021) also noted in their study that poor control systems are one of the potential causes of these risks. This implies that battery packs must have a reliable control system, and their components should be in good condition. Therefore, during the disassembly process, remanufacturers need to consider decisions related to reuse, repair, and the replacement of new components.

The Failure Mode and Effect Analysis (FMEA) approach is commonly used by previous researchers to determine the Risk Priority Number, which includes Severity, Occurrence, and Detectability. In the context of battery packs, FMEA has been utilized by several researchers, including (Singh & Pahuja, 2018), who assessed the RPN of EV inverters and conducted a qualitative risk analysis of failure modes at various levels (cell, module, and battery pack), while setting design guidelines by considering failures at the cell and module levels. Another study, (Bubbico et al., 2018), focused on identifying hazards associated with the use of used lithium batteries, providing a comprehensive overview of failure types for each battery component down to the cell level, along with the specific failures of each component. Furthermore, (Nourbakhsh Borujerd et al., 2023) conducted a risk assessment on immersion-cooled battery packs (ICBP) in electric vehicles, focusing on identifying critical failure modes and suggesting actions to reduce or prevent failures. Lastly, (Kirana et al., 2023), aimed to improve electric vehicle safety systems by identifying potential failure modes, evaluating risks, and outlining the implementation of a safety shutdown system. However, all of these studies focus on new battery products and have not specifically addressed used batteries intended for remanufacture as second-life batteries.

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Battery pack component assessment using FMEA can objectively inform decision-making following inspection at the disassembly stage. The level of hazard posed by component damage will be a key consideration, with the goal of enhancing battery safety, especially in second-life applications. Therefore, this consideration is a focal point of the present study.

Remanufacturing Cost

Remanufacturing costs are expenses incurred from the activity of rebuilding a product to meet specified quality targets. These costs are directly related to the ease of remanufacturing used components (Zhang et al., 2019). In other words, the easier a used component is to repair and restore to usable condition, the lower its remanufacturing cost, and vice versa. This cost serves as a reference for remanufacturers when deciding whether to continue with the remanufacturing process. This is because if the number of components needing repair or replacement increases, remanufacturing costs may rise to a level comparable to the cost of a new product.

Remanufacturing cost models have been developed previously. For example, Pin-Pin et al. (2015) (Pin-pin et al., 2015) developed a predictive remanufacturing cost model by considering the relationship between features and cost effects. Zhang et al. (2019) [26] took failure types into account when estimating remanufacturing costs for used products. Reddy Abbu et al. (2022) (Reddy Abbu et al., 2022) proposed a remanufacturing cost model divided into three stages: disassembly, fabrication, and assembly. Existing cost models can generally be applied to battery pack remanufacturing; however, adjustments to the cost components considered are necessary.

2. Methods

In response to the issues described above, the decision model for battery pack remanufacturing needs to incorporate cost considerations arising from the remanufacturing process. In this model, the decision to repair or replace components with new component must take into account risk factors, the frequency of potential occurrences, and detectability, both through control systems and human observation. Accordingly, the decision-making concept in this study can be presented as in Fig. 1.

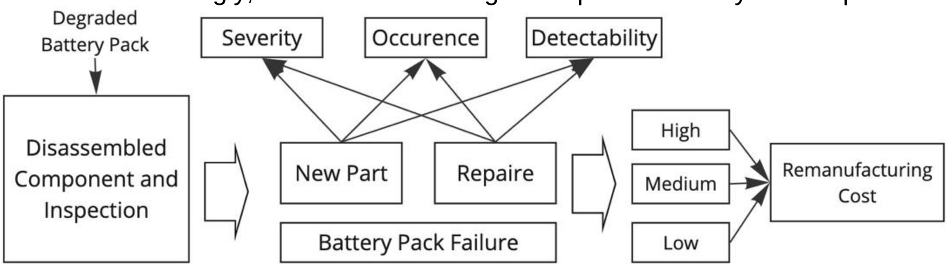

Fig. 1 Decision concepts.

The steps to achieve the research objectives are based on the following methodology:

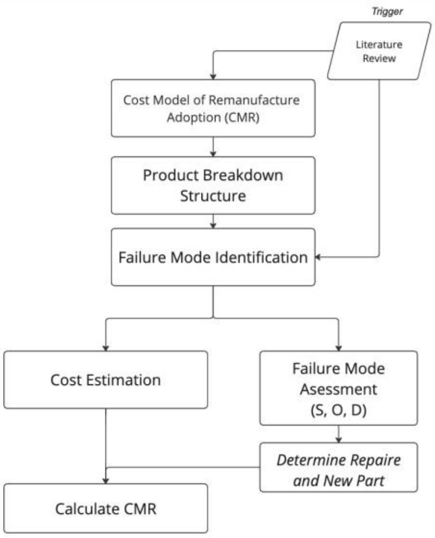

Fig. 2 Research methodology.

Based on Fig. 2, this research begins with a literature review on failure assessment models for lithium batteries and their general components. The use of FMEA as an analysis method also serves as a trigger for developing this decision model. The remanufacturing cost model for lithium battery components, as a consideration in decisions regarding repair, and new component replacement, will refer to the model proposed by (Abbu et al., 2022), with adjustments to cost components to align with the characteristics of lithium battery products.

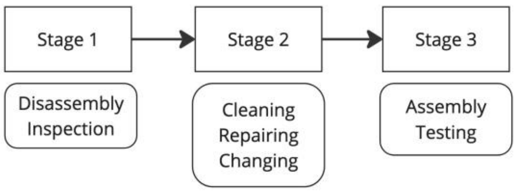

Fig. 3 Remanufacturing stage, Adopted from Abbu et al. (2022).

As shown in Fig. 3, the remanufacturing process consists of three stages. The first stage is the disassembly and inspection of the battery pack components. The second stage involves cleaning the components, followed by the repair or replacement of components. The third stage is the reassembly of components and performance testing of the product. Based on these three stages, the CMR model is formulated as follows (Abbu et al., 2022):

$$CRM_{BP} = K_1 + \sum_i^z Qi\, K_2 + K_3 + K_{MH} + K_S + K_A \qquad (1)$$

The total costs associated with each stage of the process are represented as follows: K1 denotes the total cost at Stage 1 per unit, K2 represents the total cost at Stage 2 per unit, and K3 refers to the total cost at Stage 3 per unit. Additionally, Qij indicates the quantity of components i for failure mode j, while KMH stands for the total material handling cost per unit. Ks represents the total storage cost per unit, and Ka signifies the total additional cost per unit.

As an initial step, the lithium battery pack will be broken down into a Product Breakdown Structure (PBS). The structure divides the battery pack into its main components and subcomponents that make up the entire product. A battery pack with lithium-ion 72 Volt/20 Ah, by 80 cells composition in serial and parallel, was used in this research. The battery pack will disassembly to identify type and number of components inside. This process involves identifying and grouping each component of the battery pack, from the battery cells to the battery management system, into a structured hierarchy.

Risk analysis based on failure modes in the battery pack is then conducted by identifying failure modes and their relationships with battery components. The potential root causes and effects of failure on battery performance are then identified through intensive discussions with battery pack assemblers. This process is accompanied by an RPN assessment on a scale of 1 to 5, where a higher score indicates that a failure mode has a severe effect, a high likelihood of future occurrence, and is difficult to detect (see Apendix A – C) (Hosianna et al. 2021). The resulting RPN is categorized into three groups based on three RPN value intervals: low, medium, and high. An RPN value of less than or equal to 25 is categorized as low. This category assumes that the related components do not require replacement or that repair alone is prioritized. The second category is medium, if the RPN value is greater than 25 and less than or equal to 50. Meanwhile, the high category includes RPN values greater than 50. Components in the medium and high categories are prioritized for replacement. This is done considering that the battery poses a potential hazard risk to users.

The identification and estimation of all costs associated with remanufacturing components are carried out by referencing the costs at each stage of remanufacturing (Fig. 3). The identified costs include estimates for reuse, inspection, labor, material handling, storage, and others. Additionally, estimates for new components and repair costs for battery pack assemblers are also considered.

The remanufacturing cost calculation is performed as a combination of all possible actions taken due to a specific type of failure. Among the three RPN categories (low, medium, high) for each failure type, only the high category is assigned a decision for new component replacement. Meanwhile, the other categories are given a repair decision for components that can potentially be fixed, and reuse for components that are not relevant to the type of failure. The calculated costs are then compared with the cost of a new battery pack. The remanufacturing feasibility categories are divided into three: Very

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Feasible (CMR < 40% of the New Price), Feasible (40% < CMR < 70% of the New Price), and Less Feasible (CMR > 70% of the New Price).

3. Results and Discussion

Failure Mode Identification and Assessment

There are 14 types of failures identified in the battery pack with 13 Component from 33 Battery Pack Component. As shown in Table 1, the BMS component is associated with four types of failures: FM1, FM3, FM4, and FM7. Similarly, the Circuit Controller is linked to four types of failures, namely FM3, FM4, FM12, and FM14. These two components have the most connections to failure types, compared to other components that are only linked to one or two failure types. When considering the number of components affected, the failure mode related to the burned and non-functional wiring circuit in the module (FM8) is associated with four components, the highest number among all failure types, although its RPN value is not higher than the others.

The BMS burning (FM3) and overall low power output (FM13) have the highest RPN among other failures, making them the top priority and categorized as high risk. Therefore, the components associated with these failure modes are prioritized for replacement with new components.

Remanufacturing Cost Analysis

In stage 2, the components that are disassembled will be repaired or replaced according to the RPN levels determined earlier. However, not all components with low RPN values will be repaired. This considers the complexity or impossibility of repairing the component, such as components that are likely to be damaged during disassembly or components that are very small in size. The subsequent cost calculations using a Python program. As shown in Table 2, 209 remanufacturing costs are generated based on combinations of repair and new components. The conditions that lead to the highest costs from these combinations are when all cells are replaced, related to the failure modes of the outer cell layer burning (FM6) and overall low power output (FM13). It is undeniable that cells are the most expensive components compared to the others.

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Table 1 Failure Mode and Effect Assessment (FMEA)

No	Code	Failure mode	O	Potential Effects	S	Potential Causes	D	Related Component	Component Code	RPN	Category
1	FM1	BMS circuit broken	1	Cannot manage battery power	4	Mechanical impact	3	BMS Circuit	BMS5	12	Low
2	FM2	Main body dented	1	Other connected components cannot be installed	3	Mechanical impact	2	Body Case	CE6	6	Low
3	FM3	BMS burned	2	Cannot manage battery power	4	Exposed to surrounding heat due to overheating	5	BMS Circuit Controller Circuit	BMS5, BMS6	40	Medium
4	FM4	Control circuit burned	2	Cannot process information from sensors	3	Prolonged operation causing overheating	4	BMS Circuit Controller Circuit	BMS5, BMS6	24	Low
5	FM5	Module experiences swelling	2	Cell not securely installed	3	Exposed to surrounding heat due to overheating	5	Modul	CE2	30	Medium
6	FM6	Outer layer of the cell burned	2	Cell substance prone to detachment	3	Exposed to surrounding heat due to overheating	5	Cell	CE1	30	Medium
7	FM7	BMS not functioning	2	Cannot monitor remaining power	2	Electrical component disconnected	3	BMS Circuit	BMS5	12	Low
8	FM8	Wiring circuit in the module burned and not functioning	1	Charging and power discharge not functioning	4	Short circuit caused by water exposure or a short circuit	3	Nickle Strip Kabel Positif Kabel Negatif Kabel Sensor	CE5, BMS7, BMS8, BMS12	12	Low
9	FM9	Power not flowing to the cell	1	Battery power depleted	3	In/Out charging cable not properly connected	1	Kabel in/out charging	BMS10	3	Low
10	FM10	Charging port damaged	2	Battery power depleted	3	Charging port is worn out	3	Port Charging	BA7	18	Low
11	FM11	Check button not functioning	2	Battery condition cannot be determined	2	Check button damaged	2	Check Button	BA5	8	Low
12	FM12	Battery temperature information not detected	2	Prone to overheating	3	Sensor damaged	2	Controller Circuit Sensor Cable	BMS6, BMS12	12	Low
13	FM13	Overall electrical power output is low	4	Battery usage time reduced	2	Some cells not functioning	5	Cell	CE1	40	Medium
14	FM14	Stored power in each cell is not maximized	3	Battery usage time reduced	3	Poor charging management	5	BMS Circuit Controller Circuit	BMS5, BMS6	45	Medium

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Table 2 Cost calculation results

index	code	mode	cs1	cc(ij)	q(i)	cr(ij)	cs3	kmh	ka	ks	CRM
0	BMS5	FM1	175000	NaN	NaN	110000	175000	72488	24163	96650	653301
1	CE6	FM2	175000	30000	1	NaN	175000	72488	24163	96650	573301
2	BMS5	FM3	175000	550000	1	NaN	175000	72488	24163	96650	1093301
3	BMS6	FM3	175000	500000	1	NaN	175000	72488	24163	96650	1043301
4	BMS5	FM4	175000	NaN	NaN	110000	175000	72488	24163	96650	653301
..	..	..	..	..	..	..	..	..	..	..	..
208	BMS5	FM14	175000	550000	1	NaN	175000	72488	24163	96650	1093301
209	BMS6	FM14	175000	500000	1	NaN	175000	72488	24163	96650	1043301

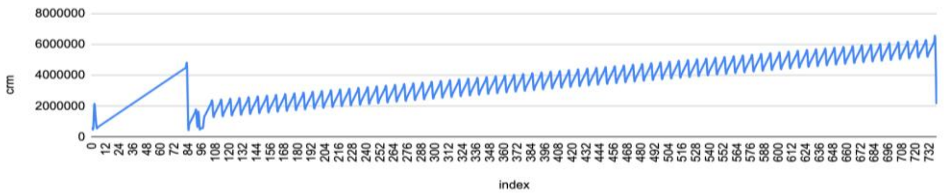

Fig. 4 Remanufacturing cost based on quantity combination.

If the number of components is included in the remanufacturing cost calculation, a total of 732 cost combinations are obtained. As shown in Figure 4, the remanufacturing cost can reach IDR 6,286,602, or 54.48% of the new price. This cost arises when remanufacturing involves replacing 80 cells while reusing other components. If there is a 40% reduction from the new price, replacing all the cells can still be considered a viable decision for remanufacturing the battery pack, even with all the existing damage conditions. However, in this case, only one type of damage occurs in the battery pack.

4. Conclusion

Failures in battery pack components are closely related to the decisions made during the remanufacturing process. Decisions made during the disassembly stage, such as reuse or replacement with new components, need to be carefully and accurately carried out. Damage to specific components needs to be thoroughly considered. In this study, each of the 14 identified failure modes is associated with one or more related components. Since each failure mode falls into a different category, the same component may require different actions depending on the type of failure. To achieve efficiency, these decisions need to be made thoughtfully after the inspection process. Additionally, these decisions should be made objectively by considering the potential hazard level, likelihood of occurrence, and detectability. In this way, the safety and performance of the remanufactured battery pack can be assured.On the other hand, by taking remanufacturing costs into account, the feasibility of remanufacturing actions for battery packs becomes more comprehensive for the remanufacturer, making the economic value of the remanufactured battery pack more competitive compared to a new battery pack.

The integration of FMEA and remanufacturing costs as a decision model in this study demonstrates how remanufacturing actions can be determined. The categorization of failure levels related to other components is a key concern. Efforts to maximize the reuse of components in battery packs are expected to be realized. Additionally, severity potential, occurance level, and detectability have been considered. Given the need to ensure user safety for second-life battery packs, their quality should meet the original standards. Likewise, remanufacturers expect guarantees in the form of economic benefits from battery pack remanufacturing. By incorporating remanufacturing costs as a consideration, greater certainty can be provided for remanufacturers. Therefore, this decision model can be used by remanufacturers to make informed decisions regarding battery pack remanufacturing.

Although there are still limitations in this study, such as not delving deeply into multi-failure scenarios within a single battery pack component, this decision model is generally expected to

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encourage further research into remanufacturing decisions for battery packs. The potential cost of remanufacturing a battery pack with multiple failures may increase and exceed 70% of the new price. Therefore, this limitation becomes an interesting focus for future studies.

Acknowledgments

Muqimuddin conducted the initial study, designed the research concept, and analyzed and interpreted the research results. F.A. Pratikno developed the FMEA (Failure Modes and Effects Analysis) instrument and performed its evaluation, while C.D.P. Hertadi was responsible for developing the remanufacturing cost calculation model.

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Appendix A. Likelihood Severity

Description	Category	Score
The severity of component damage significantly affects the occurrence of effects; therefore, replacement is highly necessary.	Extremely Severe	5
	High	4
The severity of component damage has a minimal impact on the occurrence of effects; therefore, replacement is less necessary.	Moderate	3
	Low	2
The severity of component damage does not affect the occurrence of effects.	Not Severe	1

Appendix B. Likelihood Occurance

Description	Category	Score
A Failure Mode with a high likelihood of recurring in the future requires immediate replacement.	Very Likely	5
	High	4
A Failure Mode with no likelihood of recurring in the future does not require replacement.	Moderate	3
	Low	2
A Failure Mode with a moderate likelihood of recurring in the future requires less urgent replacement.	Impossible	1

Appendix C. Likelihood Detectability

Description	Category	Score
A Failure Mode that is very difficult to detect requires immediate replacement.	Very Difficult	5
	Less Easy	4
A Failure Mode that is easy to detect requires less urgent replacement.	Moderate	3
	Easy	2
A Failure Mode where damage is very easy to detect does not require replacement.	Very Easy	1