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Assessment of disassembly difficulty level of lithium battery pack by integrating Ease of Disassembly Metric (eDiM) and difficulty rating approach

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ABSTRACT
The demand for batteries is expected to rise in line with the growing need for electric vehicles. As the number of electric vehicles increases, more battery waste will be generated, considering the average battery lifespan is only 10 to 15 years. If batteries are not recycled, this will lead to a significant accumulation of waste. Therefore, it is important to evaluate the ease of battery disassembly. This assessment can help manufacturers design batteries that are easier to disassemble. This study aims to determine the disassembly ease score and provide improvement recommendations using the Ease of Disassembly approach through eDiM and Difficulty Rating. The disassembly process is analyzed using the Ease of Disassembly Metric (eDiM) to evaluate difficulty levels based on standard disassembly operation time, and Difficulty Rating based on the indicators of Accessibility, Positioning, and Force. Based on the analysis results, the most difficult disassembly operations involve removing screws from the top cover, bottom cover, controller circuit, and BMS circuit, as well as detaching the nickel strip. The research findings indicate the presence of disassembly stages with low time values but high preference-based difficulty levels.

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1. INTRODUCTION

The growth of electric vehicles (EVs) in Indonesia has demonstrated a remarkable upward trend. In the first quarter of 2025 alone, EV sales surged by 43.4% compared to the same period the previous year, reaching 27,616 units. This growth was driven primarily by a 152.5% increase in Battery Electric Vehicle (BEV) sales and a 44.8% rise in Plug-in Hybrid Electric Vehicle (PHEV) sales [1]. The national EV market share expanded from 9% in 2023 to 15% in 2024 and is projected to reach 29% by 2030 [2]. Furthermore, the number of four-wheeled EVs is expected to grow to approximately 2.88 million units by 2034 [3]. While this rapid adoption supports Indonesia's transition toward sustainable mobility, it also raises new challenges—particularly the management of end-of-life EV batteries. At present, discussions regarding battery waste are relatively new, particularly in the context of electric motorcycles [4]. EV Battery was Given their limited lifespan, millions of used batteries will accumulate in the next 10–15 years, potentially leading to severe issues such as environmental contamination from heavy metals, fire hazards due to residual stored energy, and the need for extensive storage and waste-handling infrastructure [2].

One promising solution to these challenges is remanufacturing, a strategy that aligns with the principles of the circular economy. Through remanufacturing, used EV batteries can be systematically disassembled, repaired, and reassembled for reuse [5],[6]. This approach extends product lifecycles, reduces dependence on virgin raw materials, and mitigates negative environmental impacts. Beyond environmental benefits, remanufacturing also presents economic opportunities by enabling new business models in battery recovery, repurposing, and reuse [7]. However, implementing battery remanufacturing is far from straightforward. The complexity of battery design, material diversity, and safety risks often make the dismantling process particularly challenging, thereby reducing efficiency and profitability [8].

To perform remanufacturing process, especially for EV batteries, the dismantling process is the critical first step in battery remanufacturing, involving product design assessment, material identification, disassembly, and separation of components—whether by destructive or non-destructive methods [9].The efficiency of this stage is essential: inefficiencies not only increase operational costs but also undermine environmental and societal benefits. For this reason, systematic evaluation of the ease of disassembly has become a central focus in remanufacturing research [10].

To evaluate the disassembly process, two well-established methods are widely applied: the Difficulty Rating method and the Ease of Disassembly Metric (eDiM) method The Difficulty Rating Method relies on a structured but subjective scoring system. Components are evaluated based on preference based criteria such as accessibility, positioning of parts, tool requirements, force application, and potential risks during disassembly. The purpose of this method is to capture practical difficulties that operators face in real disassembly scenarios. Its strength lies in reflecting human-centric considerations, which are often overlooked in time-based assessments [11]. However, because it depends on expert judgment, it may introduce subjectivity and variability [12]. The Ease of Disassembly Metric (eDiM), in contrast, provides a more objective measurement of disassembly difficulty. This method evaluates components based on the actual time required for disassembly under defined conditions. The focus on processing time allows for quantitative comparison across different designs, making it particularly valuable for assessing efficiency [13]. eDiM helps identify which design aspects prolong the disassembly process and therefore contribute to higher costs and environmental impacts. Its limitation, however, is that it may not fully capture qualitative challenges such as ergonomics or operator fatigue [14].

While each approach has its strengths, they also have limitations when used in isolation. The combination of these two methods creates a complementary evaluation framework. Difficulty Rating highlights preferences, human-centered challenges, while eDiM quantifies process efficiency. By integrating both perspectives, a more holistic understanding of product disassembly can be achieved [15].This dual-method approach allows researchers and designers to not only identify the most problematic components in terms of time but also to understand why those components are difficult to disassemble in practice. Consequently, product redesigns can be better targeted toward enhancing dismantling efficiency, safety, and sustainability.

Based on these considerations, this study aims to apply and compare the Difficulty Rating and eDiM methods in evaluating EV battery disassembly processes. The objective is to analyze the differences in results produced by these two approaches and to determine how their integration can provide a more comprehensive assessment framework. Ultimately, the findings are expected to support design improvements for EV batteries, making them easier to disassemble and more suitable for remanufacturing, thereby reinforcing the principles of circular economy in the EV industry.

2. RELATED WORK

2.1. Product Disassembly Capability

Product disassembly capability is defined as the ease with which a product can be disassembled, encompassing several key concepts such as disassembly without force, simple mechanisms, tool-less disassembly, and avoiding repeated use of the same or similar parts. Additionally, product disassembly capability involves ease of identifying disassembly points, a simple product structure design, and ensuring that no toxic materials are used in the product [16]. With the measurement of disassembly capability, it provides an understanding of whether a product can be recycled, as exemplified in steel–timber floor connections [17]. With this concept, manufacturers can more easily classify product components for repair, reuse, or recycling.

Remanufacturing is one of the primary reasons for product disassembly. As stated by Formentini et al. [18], End-of-Life (EOL) goals such as reuse, remanufacturing, and recycling, are among the main drivers for disassembling a product. The extent to which these EOL objectives can be achieved, however, is highly dependent on the product's disassembly capability. A high disassembly capability ensures that components can be separated efficiently as it simplifies the remanufacturing process, for example by reducing the number and complexity of connectors, thereby enhancing component accessibility [19]. Conversely, products with poor disassembly capability often limit recovery options to material-level recycling [20]. Therefore, disassembly capability serves as a critical factor in aligning product design with EOL strategies and in supporting sustainable manufacturing practices.

2.2 Ease of Disassembly Metric (eDiM)

The Ease of Disassembly Metric (eDiM) is an index used to evaluate the Product disassembly capability of a product. eDiM assigns reference values from a standardized table to each task involved in the disassembly process of a specific product. Based on the defined disassembly sequence, the overall eDiM score is calculated by summing all corresponding values. This index assesses the effort required to disassemble a product, either partially or completely. In addition, it estimates the time needed for disassembly, expressed in standard units of time, specifically in seconds. The following is an example of the use of an eDiM calculation sheet in the disassembly process of an LCD monitor as presented by Paul et al. [21].

The eDiM method was initially developed by Paul et al. [21] and was further refined in 2018 by Peeters et al. [22]. The latest development of the eDiM method not only assesses the ease of disassembly but also evaluates the ease of reassembly, i.e., the extent to which a product or component can be reassembled after disassembly. According to Vanegas et al. [13], the eDiM method is generally applied to determine the Product disassembly capability of products as well as to assess Design for Disassembly (DfD) strategies for repair, reuse, and recycling purposes. In the referenced study, the object of analysis was an LCD monitor.

2.3 Difficulty Rating

The Difficulty Evaluation Score was introduced by McGlothlin [12] to assess the level of disassembly difficulty efficiently using a preference based evaluation approach. In its application, the evaluation involves expert judgment. This method is particularly suitable for assessing aspects that are less appropriate to be measured based on time, such as accessibility, positioning. Accessibility refers to the ability of a component or joint to be reached during the disassembly process [23]. In practice, a component may be located behind other components, requiring additional effort to access it. However, this effort is not appropriately assessed solely based on time. Moreover, it is also unsuitable to establish standardization that relies entirely on the duration of the disassembly activity for the component concerned.

3. RESEARCH METHODS

The research procedure in this study begins with defining the objectives and scope of the research. Following this, First, a thorough literature review is conducted to gain an understanding of the relevant concepts, methodologies, and previous studies associated with the research topic. Second, the criteria for the Ease of Disassembly Metric (eDiM) and Difficulty Rating are determined to establish suitable assessment parameters that affect the ease of product disassembly. Nine criteria have been established based on the eDiM criteria introduced by Paul et al. [21], excluding the identifiability and positioning criteria. Then, the eDiM criteria are presented in Table 1.

Three difficulty rating criteria are introduced: accessibility, positioning, and force [12]. The positioning criterion, previously defined as part of the eDiM framework, is subsequently incorporated into the difficulty rating criteria. Likewise, identifiability is redefined as accessibility, as both criteria are more suitably assessed through preference-based evaluation, as shown in Table 2.

Table 1. eDiM criteria

No.	Criteria	Definition
1	Disassembly sequence of components	The names of the components are listed in sequence
2	Disassembly sequence of connectors of components	The sequence of steps to disconnect the connector in a battery product
3	Number of connectors	The number of connectors of the same type
4	Number of product Manipulations	The number of products or components that must be held, rotated, flipped, or moved during the disassembly process
5	Tool Type	The type of tools used to disassemble the product
6	Tool Change (s)	The time required for tool replacement
7	Manipulation (s)	The time required to perform manipulation
8	Disconnection (s)	The time required to disconnect the connector, for example, to unscrew a screw
9	Removing (s)	The time required to lift the separated component and place it into the container

Table 2. Difficulty rating criteria

No.	Criteria	Definition
1	Accessibility	The measure of ease of access to a component. This primarily indicates how easily the component can be reached or operated during disassembly. It is scored on a scale from 1 to 4
2	Positioning	The measure of how accurately a tool or hand must be positioned and directed to perform a task. For example, higher accuracy is required when placing a screwdriver blade on a screw head compared to a simple grasp and removal task. It is scored on a scale from 1 to 4
3	Force	The measure of the amount of force or effort required to disassemble a product or part. For example, more effort is needed to remove components fastened tightly than to remove loosely fitted components. Greater force is also required to separate bonded components or break parts. It is scored on a scale from 1 to 4

For the integration of these two approaches, this study proposes the following methodology:

1. The identification of all components and connectors
2. Data Collection, data input for the Ease of Disassembly Metric (eDiM) was performed according to eDiM criteria as shown in Table 1. Once the data was gathered, it underwent rigorous testing to ensure its quality.
3. Data sufficiency and uniform testing was employed to verify whether the amount of collected data was adequate, with the understanding that an increased number of observed cycles would yield data and timing closer to the true values, data uniformity testing was conducted to assess whether the measurement data was consistent and derived from a single system, involving the calculation of the Upper Control Limit (UCL) and Lower Control Limit (LCL).
4. The calculation of the eDiM score was then based on the standard time, which was computed using the Stopwatch Time Study technique.

5. Determining the Performance Rating (PR) and Allowance. The standard time was calculated by referring to both the time required by a normal worker to reasonably complete the task under optimal working conditions and the formula provided by Barnes [24].
6. Assesing Difficulty Rating assessments were conducted by expert assessment. Scores were recorded on a Difficulty Rating form using a scale from 1 to 4 for criteria as shown in Table 2, based on the classification [12], where 1 indicated no difficulty and 4 indicated significant difficulty in performing the disassembly task. The assessment criteria focused on accessibility, positioning, and force. Then, scores from respondents were averaged and summed across the three Difficulty Rating criteria to obtain the final Difficulty Rating score.
7. The eDiM score (standard time) and the Difficulty Rating score use different units, an integration of these scores was necessary. This integration was performed through log Min-Max normalization, which the method effectively reduces data variability and results in a normal data distribution [25], particularly for the eDiM data. This method that first applies a logarithmic transformation and then proceeds with Min-Max normalization. The formula is expressed as follows:

$$Y_{ij} = \frac{\log X_{ij}}{log[max\{X_{ij}\}]} \quad (1)$$

where Y_{ij} represents the normalized scores of eDiM and Difficulty Rating. X_{ij} represents the integrated assessment score of the respondents for operation i with respect to criterion j. The integrated score was calculated by multiplying the two individual scores to obtain the final score for both approaches. A higher final score indicates that the operation is more difficult and therefore, considered a higher priority

4. CASE STUDY AND DISCUSSION

4.1. Object Descriptions

In this study, a lithium-ion battery with a capacity of 72V 20Ah was chosen as the research object and dismantled to examine its components and functions. After dismantling, found 25 operations as shown in Table 3. Additionally, two experts were involved to evaluate the difficulty rating indicator.

Table 3. Object components

Disassembly Sequences of Component	Disassembly Sequences of Connector of Component	Number of Connectors	Number of Product Manipulation	Tool Type	Operation number
Top Cover	Top Cover Screw	12	1	Philip Screwdriver	1
Bottom Cover	Bottom Cover Screw	12	1	Philip Screwdriver	2
Rubber Seal Top Cover		1			3
Rubber Seal Bottom Cover		1			4
Body Case					5
Input Charger Cover	Charger Input Screw	3	1	Philip Screwdriver	6
Input Charger	Charger Input Screw	1		Philip Screwdriver	7
Check Button	Controller Cable In/Out Check Button	1			8
Check Button	Check Button Screw	5		Philip Screwdriver	9

Disassembly Sequences of Component	Disassembly Sequences of Connector of Component	Number of Connectors	Number of Product Manipulation	Tool Type	Operation number
Double Tape Pelindung					10
Controller Circuit	Negative Fiber Cable	1		Long Nose Pliers	11
Controller Circuit	Positive Fiber Cable	1		Long Nose Pliers	12
Controller Circuit	Sensor Cable	1			13
Controller Circuit	Controller Circuit Screw	4		Philip Screwdriver	14
BMS Circuit	Bms Cable In/Out Check Button	1		Long Nose Pliers	15
BMS Circuit	Communication Cable	1			16
BMS Circuit	Negative Cable In/Out Cell	2		Long Nose Pliers	17
BMS Circuit	Positive Cable In/Out Cell	2		Long Nose Pliers	18
BMS Circuit	BMS Circuit Screw	4		Philip Screwdriver	19
BMS Base	Long Bolt	4		Screwdriver	20
Module Separator		1		Flat-Head Screwdrive	21
Nickel Strip				Long Nose Pliers	22
Top Base Module		1			23
Bottom Base Module		1			24
Cell					25

4.2. Performance Rating and Allowance

The direct time measurement was used as the input for eDiM. The normal time required by the eDiM criteria must be obtained by considering both the performance rating and the allowance. Based on observations, the operator's "skill" factor was assigned a value of –0.05, as the operator understood the general working procedure but lacked technical proficiency. The "effort" factor was rated 0 because the physical exertion and energy used by the operator were average or within standard expectations. The operator did not demonstrate excessive or insufficient effort, and the working pace remained within normal limits. There were no indications of working too fast or too slowly; therefore, no additional adjustments were required. The "condition" factor received a value of 0.02 due to adequate workspace and accessible tools; however, the operator worked in a standing position with a table height that was not ergonomically aligned with their stature, preventing the achievement of an excellent or ideal rating. The "consistency" factor was rated 0.03 because the operator demonstrated a relatively high level of consistency with minimal variation between cycle times. The total performance rating was 0. obtained from the sum of the four factors (–0.05 + 0 + 0.02 + 0.03 = 0). Based on this rating, an adjustment factor of 1 was determined. This value, increased by 1, was used as a multiplier for the observed time to obtain the normal time.

Allowance is also required in determining the standard time as a tolerance for the operator. The allowance accounts for seven factors, including: physical exertion was very light (7%) due to the activity being conducted on a workbench; a standing working posture (1.5%) which may contribute to fatigue; normal work motions (0%); and high accuracy requirements (7%) as many small components must be disassembled carefully. These are further influenced by moderate temperature conditions (3%), favorable atmospheric conditions, and a good working environment (0%). Therefore, the total allowance value obtained from the sum of all factors was 18%.

4.3. eDiM and Difficulty Rating Score

Table 4 presents a comparison between the eDiM ranking and the Difficulty Rating ranking for each disassembly operation. The eDiM ranking reflects the order of operations based on disassembly time, where rank 1 indicates the longest disassembly time and rank 25 the shortest. Meanwhile, the Difficulty Rating ranking is calculated based on the total scores from three aspects: Accessibility, Positioning, and Force, which are then ranked accordingly. However, since some operations share the same Difficulty Rating score, the rankings are repeated, resulting in only six ranks instead of 25. In this ranking system, rank 1 denotes the operation with the highest difficulty, and rank 6 the easiest.

Table 4. Disassembly difficulty ranking

Operation number-	eDiM Score	eDiM Rank	Difficulty Score	Difficulty Rating Rank
1	299.38	3	3.00	6
2	385.16	2	4.00	4
3	33.93	15	3.00	6
4	24.87	16	3.00	6
5	228.53	4	3.00	6
6	81.74	9	3.00	6
7	6.50	25	3.50	5
8	9.01	24	3.00	6
9	96.40	8	3.00	6
10	180.15	6	3.00	6
11	59.17	12	3.50	5
12	69.13	10	3.50	5
13	50.62	14	3.00	6
14	55.05	13	5.00	2
15	10.34	20	3.00	6
16	9.11	23	3.00	6
17	10.13	21	3.00	6
18	12.46	19	3.00	6
19	62.56	11	4.50	3
20	99.16	7	3.50	5
21	9.63	22	3.00	6
22	1243.87	1	6.00	1
23	15.50	17	3.00	6
24	12.54	18	3.00	6
25	185.84	5	3.00	6

Based on the results presented in Table 4, it can be identified that the operation with the longest standard time is Operation 22 (Nickel Strip removal) with a time of 1243.87 seconds, followed by Operation 2 (Bottom Cover Screw removal from the Bottom Cover) with a time of 385.16 seconds, Operation 1 (Top Cover Screw removal from the Top Cover) with a time of 299.38 seconds, and Operation 5 (Body Case removal) with a time of 228.53 seconds, and so forth. Subsequently, the Difficulty Rating is ranked based on the total score obtained previously. The operations are sorted in descending order according to their total Difficulty Rating scores, revealing that the highest Difficulty Rating is found in Operation 22 (Nickel Strip removal) with a score of 6, followed by Operation 14 (Controller Circuit Screw removal from the Controller Circuit) with a score of 5, Operation 19 (BMS Circuit Screw removal from the BMS Circuit) with a score of 4.5, and Operation 2 (Bottom Cover Screw removal from the Bottom Cover) with a score of 4, and so on.

4.4. Integration of eDiM and Difficulty Rating

From the displayed rankings, it can be observed that several operations show consistency between disassembly time and difficulty level. For instance, operation 22 (disassembly of the nickel strip using Long Nose Pliers) holds an eDiM rank of 1 (longest time) and a Difficulty Rating rank of 1 (most difficult), indicating that the more difficult an operation is, the longer the time required. However, some operations show discrepancies between disassembly time and difficulty level. For example, operation 1 (disassembly of the Top Cover Screw from the Top Cover) has an eDiM rank of 3 (relatively long time) but a Difficulty Rating rank of 6 (considered easiest). The prolonged time is attributed to the high number of connectors (screws), totaling 12, which increases disassembly time, although removing the screws is relatively easy. Another example is operation 25 (disassembly of lithium cells), which has an eDiM rank of 5 (long time) but a Difficulty Rating rank of 6 (relatively easy), indicating the operation is easy despite the lengthy disassembly time. This is also caused by the large number of lithium cells, totaling 80. although the disassembly process itself is very simple. Conversely, operation 14 (disassembly of the Controller Circuit Screw from the Controller Circuit using a Phillips Screwdriver) has an eDiM rank of 13 (relatively fast) but a Difficulty Rating rank of 2, implying that although the disassembly time is not long, the difficulty level is relatively high. This is due to the high difficulty in Accessibility and Positioning of the Controller Circuit Screw, as its location is difficult to reach with a Phillips Screwdriver.

These results demonstrate that although some rankings align, there are discrepancies that require further analysis. Therefore, integrating both approaches is crucial to produce more robust outcomes by weighting objective and subjective assessments equally. The integration results are presented in Table 5.

Table 5. Integration results and rankings

Operation number-	Normalized eDiM Score	Normalized Difficulty Score	Integrated Score	Rank
1	0.80	0.50	0.40	5
2	0.84	0.67	0.56	2
3	0.49	0.50	0.25	15
4	0.45	0.50	0.23	16
5	0.76	0.50	0.38	6
6	0.62	0.50	0.31	13
7	0.26	0.58	0.15	25
8	0.31	0.50	0.15	24
9	0.64	0.50	0.32	12
10	0.73	0.50	0.36	9
11	0.57	0.58	0.33	11
12	0.59	0.58	0.35	10
13	0.55	0.50	0.28	14
14	0.56	0.83	0.47	3
15	0.33	0.50	0.16	20
16	0.31	0.50	0.16	23
17	0.33	0.50	0.16	21
18	0.35	0.50	0.18	19
19	0.58	0.75	0.44	4
20	0.65	0.58	0.38	7
21	0.32	0.50	0.16	22
22	1.00	1.00	1.00	1
23	0.39	0.50	0.19	17
24	0.36	0.50	0.18	18
25	0.73	0.50	0.38	8

4.5. Discussion

Based on the integrated ranking results presented in Table 5, it is evident that the most challenging operation overall is Operation 22 (disassembly of the Nickel Strip using Long Nose Pliers). This design is commonly used in battery pack assembly due to its cost-effectiveness and ease of manufacturing. However, during the disassembly process, this design exhibits a significant drawback: the nickel strip is prone to tearing or damage. This issue arises from the material's insufficient thickness. The thinness of the nickel strip makes the component difficult to disassemble, as the strip connected to the battery tends to tear when pulled using Long Nose Pliers, which is an undesired failure. Consequently, the removal process requires greater effort and repeated pulling, resulting in longer disassembly times as indicated by the eDiM metric, as well as higher force exertion as reflected in the Force indicator of the Difficulty Rating.

Regarding the Bottom Cover Screw, which ranks second in difficulty as operation 2 (disassembly of the Bottom Cover Screw from the Bottom Cover using a Phillips Screwdriver), Design of the buttom cover, which uses 12 screws evenly distributed around the perimeter to secure the bottom cover to the battery pack body case. This fastening system provides good strength and stability. However, in terms of ease of disassembly, the use of these screws results in a relatively long disassembly time as indicated by the eDiM metric. This approach is inefficient regarding time, and the removal process requires an additional tool a Phillips screwdriver which further prolongs the disassembly time.

Regarding the Controller Circuit Screw and BMS Circuit Screw, which rank third and fourth in overall difficulty specifically, operation 14 (disassembly of the Controller Circuit Screw from the Controller Circuit using a Phillips Screwdriver) and operation 19 (disassembly of the BMS Circuit Screw from the BMS Circuit using a Phillips Screwdriver). Design of the BMS circuit and controller circuit, both of which utilize screws for mounting. This method requires the use of tools such as a Phillips screwdriver during the disassembly process and presents challenges due to the limited accessibility of the screw positions. The screws are located in confined areas, making them difficult to reach. This design limitation is reflected in the high Difficulty Rating scores, particularly in the indicators of Accessibility and Positioning for these components.

Regarding the Top Cover Screw, which ranks fifth in overall difficulty specifically operation 1 (disassembly of the Top Cover Screw from the Top Cover using a Phillips Screwdriver). Design of the Top Cover, which still employs screws along all sides as fastening elements. The use of screws requires additional tools such as a Phillips screwdriver and results in a relatively long disassembly time. This inefficiency is reflected in the eDiM indicator, which shows a high value for this operation.

5. CONCLUSION

This study reveals that while time-based criteria for assessing ease of disassembly can establish prioritization, they do not adequately reflect the true level of difficulty. In this regard, the inclusion of force, accessibility, and positioning as qualitative indicators of difficulty rating is essential, since they capture practitioner perspectives that may diverge significantly from the eDiM criteria (Tool Change, Manipulation, Disconnection, and Removing). This divergence highlights a potential gap in current assessment frameworks, where operational complexity is not fully represented by time-based measures alone. Through this integration, it can serve as a reference for improving sustainable product design, and it also has implications for future research on Robot based disassembly or AI-based evaluations.

Nevertheless, the study is subject to limitations, particularly concerning the weighting of aggregated scores between the two approaches. Without an appropriate weighting mechanism, there is a risk of bias toward either eDiM or Difficulty Rating, which may affect the validity of the prioritization outcome. Future research should therefore focus on developing a more robust integration framework that accounts for the relative importance of each criterion and explores how subjective practitioner perspectives can be systematically incorporated into quantitative disassembly assessments.

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REFERENCES

[1] GAIKINDO, "Indonesia Automotive Industry Data 2025 Q1 EV Market Report," 2025.

[2] Ministry of Industry of the Republic of Indonesia, *Indonesia Electric Vehicle Roadmap 2030*. 2024.

[3] IEA, "Global EV Outlook 2024," 2024.

[4] A. Purwani, S. M. Budijati, and H. M. Asih, "Management of battery waste recycling by electric motorbike workshops: A literature review," *OPSI*, vol. 17, no. 1, p. 216, Jun. 2024, doi: 10.31315/opsi.v17i1.12173.

[5] A. Neri, M. A. Butturi, and R. Gamberini, "Sustainable management of electric vehicle battery remanufacturing: A systematic literature review and future directions," *J Manuf Syst*, vol. 77, pp. 859–874, Dec. 2024, doi: 10.1016/j.jmsy.2024.10.006.

[6] A. Pandey, S. Patnaik, and S. Pati, "Available technologies for remanufacturing, repurposing, and recycling lithium-ion batteries: an introduction," in *Nano Technology for Battery Recycling, Remanufacturing, and Reusing*, Elsevier, 2022, pp. 33–51. doi: 10.1016/B978-0-323-91134-4.00020-0.

[7] M. Foster, P. Isely, C. R. Standridge, and M. M. Hasan, "Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries," *Journal of Industrial Engineering and Management*, vol. 7, no. 3, Jun. 2014, doi: 10.3926/jiem.939.

[8] D. Salmon, C. W. Babbitt, G. A. Babbitt, and C. E. Wilmer, "A framework for modeling fraud in E-waste management," *Resour Conserv Recycl*, vol. 171, p. 105613, Aug. 2021, doi: 10.1016/j.resconrec.2021.105613.

[9] J. Hathaway, C. A. Contreras, R. Stolkin, M. E. Asif, and A. Rastegarpanah, "Technoeconomic Assessment of Electric Vehicle Battery Disassembly -- Challenges and Opportunities from a Robotics Perspective," 2024. doi: 10.2139/ssrn.4803459.

[10] VDI 2243, "Recycling-Oriented Product Development," 2002.

[11] J. Huang, C. Cui, W. Jiang, and L. Zhu, "Peony diagram modeling for improving the easy disassembly design of mobile electronic products," *Sci Rep*, vol. 15, no. 1, p. 1266, Jan. 2025, doi: 10.1038/s41598-025-85402-7.

[12] S. McGlothlin and E. Kroll, "Systematic estimation of disassembly difficulties: application to computer monitors," in *Proceedings of the 1995 IEEE International Symposium on Electronics and the Environment ISEE (Cat. No.95CH35718)*, IEEE, 1995, pp. 83–88. doi: 10.1109/ISEE.1995.514955.

[13] P. Vanegas *et al.*, "Ease of disassembly of products to support circular economy strategies," *Resour Conserv Recycl*, vol. 135, pp. 323–334, Aug. 2018, doi: 10.1016/j.resconrec.2017.06.022.

[14] J. G. Erdmann, J. Koller, J. Brimaire, and F. Döpper, "Assessment of the disassemblability of electric bicycle motors for remanufacturing," *Journal of Remanufacturing*, vol. 13, pp. 137–159, 2023, doi: 10.1007/s13243-023-00124-1.

[15] L. Frizziero, G. Donnici, and M. Freddi, "Design for Disassembly combined with augmented reality for optimization of maintenance processes," *Frontiers in Sustainability*, vol. 3, Dec. 2022, doi: 10.3389/frsus.2022.1066448.

[16] H. S. Mok, H. J. Kim, and K. S. Moon, "Disassemblability of Mechanical Parts in Automobile for Recycling," *Computers ind. Engng*, vol. 33, pp. 621–624, 1997.

[17] D. V. Bompa, M. Kariuki, V. Ungureanu, and A. Y. Elghazouli, "Disassembly capability and circularity potential of steel-timber floor connections," *J Constr Steel Res*, vol. 235, p. 109806, Dec. 2025, doi: 10.1016/j.jcsr.2025.109806.

[18] G. Formentini *et al.*, "A review of disassembly systems for circular product design," *J Clean Prod*, vol. 506, p. 145459, May 2025, doi: 10.1016/j.jclepro.2025.145459.

[19] T. Pulikottil, N. Boix Rodríguez, W. Sterkens, and J. R. Peeters, "Ease of robotic disassembly metric and information for digital product passports in flexible remanufacturing systems," *Sustain Prod Consum*, vol. 58, pp. 123–139, Sep. 2025, doi: 10.1016/j.spc.2025.06.008.

[20] X. Lai, N. Wang, B. Jiang, and T. Jia, "Choosing Recovery Strategies for Waste Electronics: How Product Modularity Influences Cooperation and Competition," *Sustainability*, vol. 16, no. 20, p. 9035, Oct. 2024, doi: 10.3390/su16209035.

[21] Paul. Vanegas *et al.*, "Study for a method to assess the ease of disassembly of electrical and electronic equipment : method development and application to a flat panel display case study," Publications Office, 2016. doi: 10.2788/130925.

[22] Peeters J. R., Tecchio P., Ardente F., Vanegas P., Coughlan D., and Duflou J.R., “eDIM: further development of the method to assess the ease of disassembly and reassembly of products Application to notebook computers,” 2018. doi: 10.2760/864982.

[23] F. De Fazio, C. Bakker, B. Flipsen, and R. Balkenende, “The Disassembly Map: A new method to enhance design for product repairability,” *J Clean Prod*, vol. 320, p. 128552, Oct. 2021, doi: 10.1016/j.jclepro.2021.128552.

[24] R. M. . Barnes, *Motion and time study : design and measurement of work*. Wiley, 1980.

[25] D. Curran-Everett, “Explorations in statistics: the log transformation,” *Adv Physiol Educ*, vol. 42, no. 2, pp. 343–347, Jun. 2018, doi: 10.1152/advan.00018.2018.