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Assessing sustainable recyclability of battery systems: a tool to aid design for disassembly

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Abstract

This study, conducted with Northvolt, examines battery system recyclability and disassembly dynamics. It introduces indices for material and product recyclability, along with disassembly time assessment. The goal is to create a design tool to streamline the evaluation of battery disassembly, aiding in designing recyclable and serviceable components. These methodologies serve as a blueprint for enhancing battery systems' overall sustainability and circularity design, presenting a base for future product development in alignment with environmental and economic objectives.

Keywords: batteries, energy storage systems, design for x (DfX), circular economy, sustainability

1. Introduction and problem statement

Companies are gradually acknowledging the impact of resource scarcity in the production of goods and services, and a specific emphasis is required with regards to the battery industry. As the demand for electric vehicles (EV) and Energy Storage Systems (ESS) increases, the need for rare metals, such as nickel, becomes clear (Nordelöf et al., 2014), as they constitute a major part of battery cells. In the case of nickel, its mineral resource scarcity is projected to range from 43 % to 67 % of the total battery cell composition, with reserve estimates from 90 to 330 years (Le Varlet et al., 2020). The implication is apparent: if battery systems are not designed for recyclability, remanufacturing, reuse, or refurbishment, the risk of vital raw materials being disposed to landfills, leading to their depletion, is too high.

Since the battery industry is gaining global importance, sensibly managing waste and End-of-Life (EoL) products is crucial (Baars et al., 2020), as the sourcing of raw materials for battery production could become a challenge, enhanced by the geopolitical risks related to material locations, environmental and social concerns (Kelly et al., 2020; Nurdiawati and Agrawal, 2022; Rajaeifar et al., 2022). The need to design battery systems for ease of recycling is therefore high. Given the limited total lithium-ion battery recycling capacity in Europe in 2021, this is even emphasized (Baars et al., 2020).

While earlier studies have explored material recyclability and the impact of battery chemistries on emissions and material scarcity (Le Varlet et al., 2020; Nordelöf et al., 2014; Sakundarini et al., 2014; Villalba et al., 2002), the primary focus within the battery industry has been on the automotive sector (Alfaro-Algaba and Ramirez, 2020; Baars et al., 2020; Kelly et al., 2020; Lander et al., 2023; Rajaeifar et al., 2022). ESS intended for other applications have not been adequately evaluated, which shows the need for a comprehensive methodology to assess their recyclability and ease of disassembly.

To address these issues, this research is based on a collaborative project with Northvolt, a leading battery manufacturer, known for creating their own systems. The project aims to improve the quality of product design with a focus on dismantling and sorting procedures at facilities like Revolt, which disassemble battery products. The effect is to enable designers to improve battery systems through an optimized design and an evaluation of reusable and re-manufacturable materials. The project aims to quantitatively assess the recyclability of Northvolt's ESS and to develop a complete disassembly map. Consequently, a design tool for the evaluation of disassemblability in early design will also be proposed.

Currently, there is a multitude of methods for measuring and evaluating the recyclability of battery cells, particularly in EV applications. However, a significant gap still stands: previous studies (Li et al., 2018) have primarily analysed the recyclability of whole products, overlooking crucial considerations related to materials, as well as hazardous components inherent in batteries. The lack of practices that allow for a broad evaluation poses a challenge to the evolution of sustainable battery design.

The lack of a final solution for the issues at hand led to the formulation of two main research questions.

- RQ1: How can the recyclability of generic ESS be measured?
- RQ2: Is it possible to create an ESS disassembly evaluation tool for designers?

At the same time, the project aims to produce three key elements: (i) the development of an indicator for describing and measuring recyclability; (ii) the creation of a disassembly map for assessing the recyclability and ease of disassembly of products, accompanied by disassembly time calculations; (iii) the establishment of a methodology and a tool that can be implemented for Northvolt's products.

The recyclability calculations, disassembly map, and disassembly times will be applied to a product currently under development at Northvolt, testing their reliability and usability for future applications.

2. Literature review on recyclability and disassemblability indices

More product variants enter the market every year, thus the need to manage material waste at their EoL. Circular economy addresses sustainable development by increasing resource circularity (Wang et al., 2022), through three main objectives (Ellen MacArthur Foundation, 2015): (i) maintain natural capital by balancing resource flows; (ii) optimize resource consumption by circulating products and materials; (iii) increase system efficiency by eliminating negative externalities. Companies are pushed to build circular systems that operates in a Resource Conservative Manufacturing framework (ResCoM) that includes four main areas: business model, product design, supply chain and ICT (Asif, 2017). In particular, circular product design emphasizes preserving a product's value and relying on remanufacturing (Den Hollander et al., 2017). A product is expected to have multiple usage phases to delay resource consumption. A designated performance period is established, and at the end of each lifecycle the product is reclaimed to restore its original characteristics (Rashid et al., 2013).

In order to design an easily recyclable and disassembable product, it is crucial to define how recyclability is measured. However, this should differentiate between two aspects.

2.1. Material recyclability

Material recyclability, dating back to waste management in the late 1960s, has seen evolving definitions. First, the ability of a material to regain the same original properties (Villalba et al., 2002). Indices like the Recyclability Index (R) focus on material price, while later approaches introduce a broader perspective. Other studies evaluate it with regards to EoL and environmental considerations (Vefago and Avellaneda, 2013). Those are purely qualitative analysis, in which four different EoL possibilities are defined: Reuse, Infrause, Recycle, and Infracycle, assessed against CO_2 emissions, waste reduction, performance in lifecycle and whether the material could be used as before. However, the analysis does not include a measure for the performance of materials, and neither a financial evaluation. To take into account the economic and environmental perspective (Equation 1), the Recyclability Potential Index (RPI) is introduced (Muthu et al., 2012).

$$RPI = EGI_1 + EGI_2, \tag{1}$$

where EGI_1 stands for Environmental Gain Index and EGI_2 is the Economic Gain Index.

2.2. Product recyclability

The other aspect is product recyclability, involving disassembly, disposal, and recycling costs. Profit to Loss Margin of Recycling ($PLM_{recycle}$) quantifies the viability of recycling but falls short in addressing environmental factors (Villalba et al., 2004). More recent approaches offer extended assessments, but hazardous materials and safety measures should be considered (De Aguiar et al., 2017; Li et al., 2018). To account for disassembly and recycling of whole products, Design for Disassembly (DfD) and Design for Recycling (DfR) are two approaches that help designers focus their efforts during the product development process (PDP). Factors include joint types, accessibility, and disassembly methods (Rosy Wei Chen et al., 1994). Such suggestions were reflected also in Fukushige et al. (2013), a case study to calculate the disassembly time (in seconds) and the recyclability rate (in percentage of mass). It only reported the mass of the material and its EoL, but not economic factors such as the cost of disassembly. DfD is particularly instrumental in designing sustainable products, including both recycling and disassembly considerations (Fukushige et al., 2013). The work by Feldmann et al. (2001), later adapted by Alfaro-Algaba and Ramirez (2020), showcases the optimal disassembly point as a trade-off between economic and environmental goals. The Disassembly Effort Index (DEI) (Das et al., 2000) considers the operational time, and the requirements on the physical tools, the fixtures, accessibility, instructions, hazards, and forces. Every factor has a score and a weight to calculate the cost of disassembly.

2.3. Disassembly time

For the evaluation of the disassembly time during product design, three are the main methodologies. The Maynard Operation Sequence Technique (MOST) uses standardised sequences to represent an average worker in average conditions (Zandin, 2002), based on the fact that objects usually follow patters such as move, grasp, position (Deshpande, 2007). This ensures a high accuracy (European Commission. Joint Research Centre., 2016), though it does not include any extra force required in specific steps, which may limit the analysis. The U-effort method is limited in considering only unfastening activities. It works well for screws- and nuts-based assembly (Das et al., 2000).

The European Commission. Joint Research Centre (2016) introduced the Ease of Disassembly Metric (eDiM), estimating assembly task time integrating DEI factors, excluding hazards. Six disassembly tasks: tool change, connectors, product manipulation, positioning, disconnection, and removal, are modelled using MOST methodology. This method offers a trade-off between accuracy and complexity, exemplified in a case study on an LCD screen within the electrical and electronic equipment field.

The introduction of a disassembly map stems from previous work on feature-based design for assembly (De Fazio et al., 1993), also used for advanced assembly planning (Khabbazi et al., 2017, 2018), and provides details to streamline disassembly. The map by De Fazio et al. (2021) delivers a full representation of a product architecture. With MOST methodology and eDiM, it joins disassembly time, target component identification, and disassembly penalties. The tool groups parts based on sequential dependency, sequential independency, or multiple dependency. Even reducing eDiM by 40 %, the complexity limits applicability in design drafting, with room for improvement in safety considerations.

While literature offers a comprehensive analysis of recyclability in general, a noticeable gap exists concerning the recyclability of complex ESS. This work aims to establish a clear definition of material and product recyclability for such systems, and the inclusion in the tailored disassembly map.

3. Methods

Based on the information retrieved from the literature, and with a LCA in accordance with the sustainability specialists within the company, two different formulas for material and product recyclability were created, to fulfil Northvolt's requirements. The approach aimed to ensure coverage of recyclability factors, with focus on feasibility of calculations and usability. Economic and environmental considerations were combined in line with Muthu et al. (2012). For the price of materials, Costdata (https://www.costdata.de/en/) was used with values from London Metal Exchange (The London Metal Exchange, 2023). The environmental data were obtained from literature mentioning materials used for similar purpose. The other values in the equation came from existing data from LCA. As most of the parameters do not have the same units, they are normalized to a scale ranging from 1 to 5, in accordance with Muthu et al. (2012). For the economic gain index, the waste price is divided by the raw material price: the closer to 1, the more the material is recyclable. When it is lower than 1, it means that the material would be reused, used for energy recovery, or landfilled. Environmental gain index scales values to the same range and adds them together to see the percentage of energy and resource consumption the materials require. Then, the RPI is averaged between the two gain indexes.

Product recyclability, given the complexity of batteries, rather than being calculated with many factors, required focusing on a key metric: the mass-based profit-to-loss margin for recycling. This approach encompasses most of the considerations found in the literature. The product recyclability index ($PLM_{recyclability}$) is shown in Equation 2, and the terms are explained in Villalba et al. (2004):

$$PLM_{recyclability} = \Sigma_{(i=1 \ldots n)} M_i(V_i + C_l - C_r) - M_{total}C_d, \qquad (2)$$

The costs of recycling and disposal are simplified in this work. The disassembly cost (C_d) is derived from a more reliable approach, as the primary focus of this research is the development of a disassembly tool. C_d, is defined within another study, and in Equation 3 (Lander et al., 2023).

$$C_d = \text{Labour costs} * t_{disassembly}/m_{component}. \qquad (3)$$

The mass (m) and material are given by the company, together with the disassembly time, that is measured on the company's site. The scrap material price that is not know from previous calculations is obtained from material databases or suppliers. The disposal costs are calculated by multiplying the industrial electricity price (European Commission. Directorate General for Energy. et al., 2020) by the landfill use of each material. The recycling costs come from previous studies. The disassembly cost is divided by the weight in order to obtain the cost per kilogram of component.

3.1. Disassembly map

Initially, a draft of the disassembly map was outlined based on the CAD model and the type of connections between parts. A visit to Northvolt's recycling facility in Vasterås, Sweden, further enriched the data by providing insights from the local experts into target components, recycling methods, and safety considerations. Subsequently, a second draft of the disassembly map was created and evaluated through a simulated assembly line, accounting for recyclability and repairability of components. Feedback from the manufacturing and aftermarket teams guided the finalization of the disassembly map, with any suggested changes or improvements. For disassembly time, the MOST methodology is employed, aligning with European standards and Northvolt's preference for a reliable and recognized method. Once the disassembly sequence is established, times are calculated for different product variants and with manual screwdrivers and power tools. To validate the accuracy of the calculated values, comparisons are made with real, measured data obtained by the manufacturing team in a real industrial setting. This comparative analysis aims to ascertain the reliability of the calculated times.

The main contribution of this thesis to the design tool focuses on determining the penalties derived from the disassembly map and existing procedures measured by the MOST and eDiM methodologies.

The integration of disassembly time calculations and the disassembly map involves careful comparison of sustainability calculations. Through an iterative process and collaboration with engineering team, essential data is identified for a more quantitative evaluation of disassembly. Penalties are assigned values in seconds, and distinctions are made between various types of connectors within the same part to reflect real-world scenarios accurately. The tool underwent testing and refinement through collaboration with design and mechanical engineers, ensuring valuable feedback was incorporated.

Table 1. Factors considered for material recyclability, split in economic and environmental

Economic factors	Raw material price		P_{raw}
	Scrap material price		P_{scrap}
Environmental factors	Production phase (P)	Cumulative Energy Demand (CED) Global Warming Potential (GWP)	CED GWP
	Landfilling phase (L), Recycling phase (R)	CO_2 emmissions Toxicity Radiation Land Use Resource Use Water Use	CO_2 T R L_U R_U W_U

4. Results of the material recyclability index and evaluation

In this Section, we present the results of our study, with a detailed analysis of the material recyclability and disassembly aspects of battery systems, using the methods and equations presented before.
The material RPI was calculated using Equations 4, 5, 6.

$$RPI = (EGI_1 + EGI_2) / 2; \tag{4}$$

$$EGI_1 = EF_P + EF_L + EF_R =$$

$$(CED + GWP)_P + (CO_2 + T + R + L_U + R_U + W_U)_L + (CO_2 + T + R + L_U + R_U + W_U)_R; \tag{5}$$

$$EGI_2 = P_{scrap}/P_{raw}, \tag{6}$$

where the terms are defined in Table 1. Table 2 shows the coefficients affecting material recyclability for aluminium and steel, and the resulting RPI. The coefficients are normalized on a scale of 1 to 5. The recyclability index resulted in a value of 0.75 for aluminium and 0.59 for steel. These values indicate that both materials are suitable for recycling, with aluminium showing higher recyclability than steel.

Table 2. Indices for the different factors affecting material recyclability, EGI1, EGI2, and RPI

		Material			
		Aluminium		Steel	
Price	Price raw (USD/ton)	2364.000		728.960	
	Price waste (USD/ton)	2091.000		383.000	
Production	CED (MJ per kg)	157.590	4	24.410	1
	GWP (100a) in kg CO2 eq	16.760	5	2.440	2
Landfilling	IPCC total (kgCO2 eq)	0.027	1	0.027	1
	Toxicity (CTUe)	0.005	1	0.005	1
	Radiation (kBq U235 eq)	0.000	1	0.000	1
	Land Use (mPt)	130.000	5	130.000	5
	Resource use (MJ)	0.358	1	0.358	1
	Water use (m^3 eq)	0.002	1	0.002	1
Recycling	IPCC total (kgCO2 eq)	0.548	1	0.366	1
	Toxicity (CTUe)	0.019	2	0.047	3
	Radiation (kBq U235 eq)	0.006	1	0.095	2
	Land Use (Pt)	0.572	1	2.230	1
	Resource use (MJ)	7.900	2	5.860	2
	Water use (m^3 eq)	0.005	1	0.720	2
Environmental Gain Index	EGI1	0.61		0.66	
Economic Gain Index	EGI2	0.885		0.525	
Recyclability Potential Index	RPI	0.75		0.59	

The disassembly map underwent multiple development stages, with inputs from project stakeholders. The initial stage was based on the bill of materials, then adding alternatives in the disassembly process, detailed warnings, penalties, except those concerning electric hazards. The recycling team gave ideas to restructure the map, reorganizing the disassembly steps and introducing new procedures for system discharge and coolant removal. Also, penalties referenced in the literature were integrated into this stage. The final stage of the disassembly map included inputs from the production and aftermarket teams. Factors of serviceability, target components, and penalties for unconsidered parts were included. Symbol usage in the map was re-elaborated to enhance clarity. Notably, the crushing step was excluded from the map as it fell beyond the project's scope, focused solely on evaluating the disassembly process.

The ultimate version of the disassembly map captures the structural breakdown of Product X, exhibiting target components and initial considerations. Serving as a benchmark for future revisions, it provides an overview and immediate identification of areas for improvement. Space limits do not allow to showcase the map here, but a visual example representation is available upon request.

Table 3 shows the calculations of part and product cost for various components of Product X, although certain materials and component names have been omitted for confidentiality reasons. Utilizing Equation 2, the PLM for recycling is computed for both the entire product and individual components. The analysis shows that while the overall Product X is profitable for recycling, a closer examination of the individual components indicates that nearly 50 % of them carry a negative value. This suggests that recycling these specific components might not be economically feasible.

Table 3. Product recyclability evaluation

Part	Mass (kg)	Mat.	Scrap material price (USD/ton)	Saving on disposal costs (USD/ton)	Disassembly time (s)	Recycling costs (USD/ton)	Disassembly cost (USD/kg)	Mi(Vi+Cl-Cr)	PLM
A	2.11	Al	2091	12.69	44.6	200	0.29	4.02	3.40
B	2.11	Al	2091	12.69	4	200	0.03	4.02	3.96
C	0.198	X	2204.63	15.74	15.6	770	1.08	0.29	0.07
D	11	Al	2091	12.69	35.6	200	0.04	20.94	20.45
E	2.02	Al	2091	12.69	44.8	200	0.31	3.85	3.23
F	7.51	Al	2091	12.69	341.6	200	0.63	14.30	9.60
G	0.067	Al	2091	12.69	15.5	200	3.18	0.13	-0.09
H	0.48	X	2204.63	15.74	95.9	770	2.75	0.70	-0.62
I	0.078	Pl.	3709	15.74	78.5	780	13.85	0.23	-0.85
J	0.05	El.	2770	0	109.3	1100	30.08	0.08	-1.42
K	119.68	Y	3362.99	2049.47	197.3	3000	0.02	288.72	286.01
Product	145.30				982.7		0.09	337.26	323.74
							Mtotal*Cd	13.52	

The time calculations were conducted in the disassembly map using MOST, focusing on the disassembly sequence from the initial draft. The time results for product variant 1, are detailed in a separate file that can be consulted upon request. The results of the comparison with the estimated disassembly time from the manufacturing team are in Table 4. They show differences when both options were measured using manual tools. However, when assessing the tasks individually, the differences were notably reduced.

These calculated times and references for specific disassembly tasks were integrated into a tool developed in collaboration with the sustainability team, intended for use during the PDP, offering a robust framework supported by precise task timings for enhanced disassembly planning.

Table 4. Comparison between actual disassembly time and the assembly time estimations from the manufacturing team

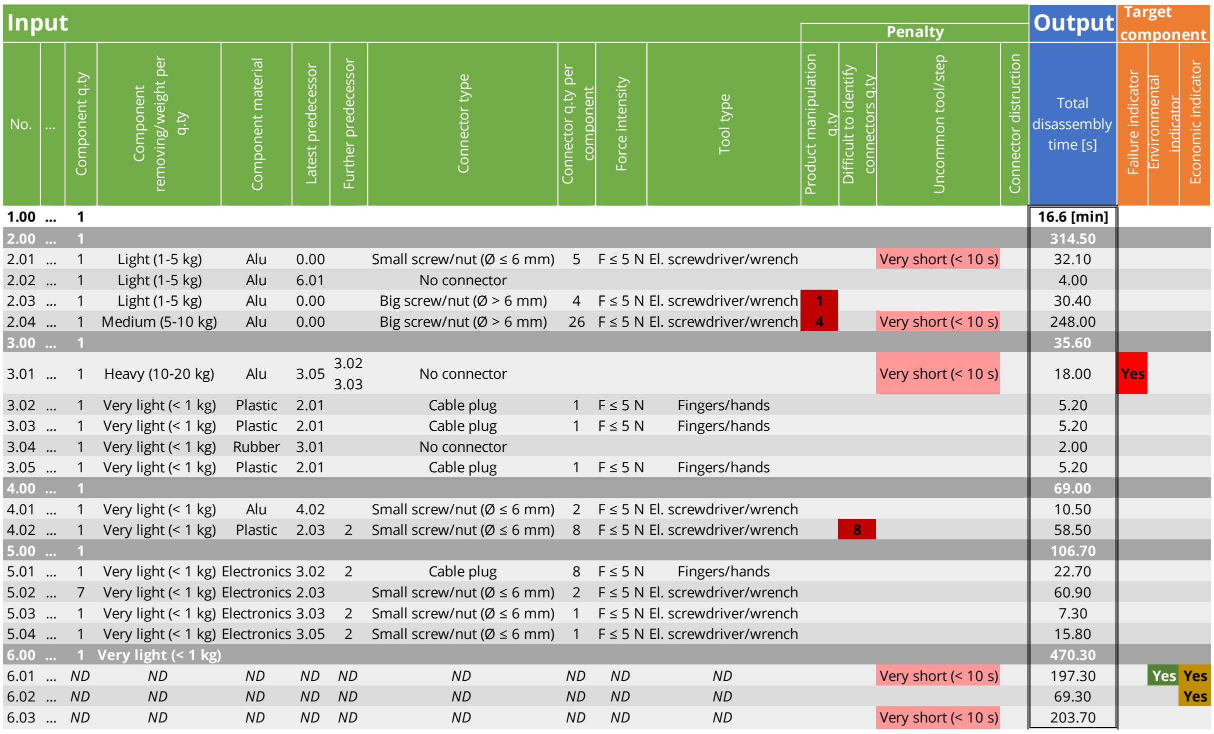
	Task X	Task Y	Task Z	Variant 1	Variant 2
Disassembly time (min)	1.97	3.94	11.79	18.36	31.50
Disssembly time (Manufacturing) (min)	2.10	3.90	13.30	22.80	39.00
Variation (%)	+6.59	-1.02	+12.81	+24.18	+23.81

4.1. Disassembly design tool

The tool, initially developed by the sustainability team and refined in this work, is currently an Excel sheet that helps structuring the input from the engineering team. It includes a list of components from the initial BOM, with details such as weight, material, antecedent component in the disassembly, connectors, and an automatically generated sequential disassembly time calculation. Improvements were then incorporated into the tool, which can be visualised in Figure 1.

1. The tool accommodates up to three different connector types for a single component, offering increased flexibility and specificity in the disassembly process.
2. To streamline the process, the tool autonomously selects the appropriate physical tool based on the component's weight and connector type. However, the responsible engineer retains the option to override this selection if required.
3. Several penalties, such as product manipulation, low identifiability of connectors, uncommon process, and connector destruction, were introduced. These penalties account for challenges such as the moves to remove a component, difficulties in component identification, additional time for non-standard processes, and the complexities associated with permanent joints.
4. The tool incorporates failure, environmental, and economic indicators to identify target components, to assess the EoL concerns based on the focus on recyclability or repairability.
5. Utilizing the previous number filled in at the onset, the tool generates a Gantt chart showcasing the total disassembly time and the sequential order of operations.

As a final output, it provides two distinct values for disassembly time, representing the best- and worst-case scenarios. The initial calculation captures the worst-case scenario, assuming a 100 % sequential disassembly process. Additionally, the Gantt chart displays the time required if resources were unlimited, allowing for parallel task completion wherever feasible.



Input											Penalty				Output	Target component		
No.	...	Component q.ty	Component removing/weight per q.ty	Component material	Latest predecessor	Further predecessor	Connector type	Connector q.ty per component	Force intensity	Tool type	Product manipulation q.ty	Difficult to identify connectors q.ty	Uncommon tool/step	Connector distruction	Total disassembly time [s]	Failure indicator	Environmental indicator	Economic indicator
1.00	**...**	**1**													**16.6 [min]**			
2.00	**...**	**1**													**314.50**			
2.01	...	1	Light (1-5 kg)	Alu	0.00		Small screw/nut (Ø ≤ 6 mm)	5	F ≤ 5 N	El. screwdriver/wrench			Very short (< 10 s)		32.10			
2.02	...	1	Light (1-5 kg)	Alu	6.01		No connector								4.00			
2.03	...	1	Light (1-5 kg)	Alu	0.00		Big screw/nut (Ø > 6 mm)	4	F ≤ 5 N	El. screwdriver/wrench	**1**				30.40			
2.04	...	1	Medium (5-10 kg)	Alu	0.00		Big screw/nut (Ø > 6 mm)	26	F ≤ 5 N	El. screwdriver/wrench	**4**		Very short (< 10 s)		248.00			
3.00	**...**	**1**													**35.60**			
3.01	...	1	Heavy (10-20 kg)	Alu	3.05	3.02 3.03	No connector						Very short (< 10 s)		18.00	**Yes**		
3.02	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
3.03	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
3.04	...	1	Very light (< 1 kg)	Rubber	3.01		No connector								2.00			
3.05	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
4.00	**...**	**1**													**69.00**			
4.01	...	1	Very light (< 1 kg)	Alu	4.02		Small screw/nut (Ø ≤ 6 mm)	2	F ≤ 5 N	El. screwdriver/wrench					10.50			
4.02	...	1	Very light (< 1 kg)	Plastic	2.03	2	Small screw/nut (Ø ≤ 6 mm)	8	F ≤ 5 N	El. screwdriver/wrench		**8**			58.50			
5.00	**...**	**1**													**106.70**			
5.01	...	1	Very light (< 1 kg)	Electronics	3.02	2	Cable plug	8	F ≤ 5 N	Fingers/hands					22.70			
5.02	...	7	Very light (< 1 kg)	Electronics	2.03		Small screw/nut (Ø ≤ 6 mm)	2	F ≤ 5 N	El. screwdriver/wrench					60.90			
5.03	...	1	Very light (< 1 kg)	Electronics	3.03	2	Small screw/nut (Ø ≤ 6 mm)	1	F ≤ 5 N	El. screwdriver/wrench					7.30			
5.04	...	1	Very light (< 1 kg)	Electronics	3.05	2	Small screw/nut (Ø ≤ 6 mm)	1	F ≤ 5 N	El. screwdriver/wrench					15.80			
6.00	**...**	**1**	**Very light (< 1 kg)**												**470.30**			
6.01	...	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*			Very short (< 10 s)		197.30		**Yes**	**Yes**
6.02	...	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*					69.30			**Yes**
6.03	...	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*			Very short (< 10 s)		203.70			

Figure 1. Visualization of the disassembly design tool with its main components; columns marked with "..." are removed for confidentiality reasons and to save space; rows marked with "ND" cannot be displayed for confidentiality reasons

5. Discussion over the potential of the design tool

The assessment of a battery system's recyclability involves two key parameters. The material recyclability potential index offers insight into the recyclability of the product's materials, laying a full picture of its environmental and economic impacts during production, landfill, and recycling phases. It accounts for environmental factors like toxicity, radiation, and water usage, relevant to the specific product. Where material information was readily available, the calculations were performed. For innovative or recent materials where scrap material prices or specific environmental factors were unavailable, these calculations were more challenging. The results for such materials should be further evaluated, and future analyses will encompass additional materials whenever needed. In analysing the product's overall recyclability, the PLM for recycling was calculated with modifications in the disassembly cost assessment. The results varied whether the entire product or individual components were assessed. Some components were deemed economically unfeasible to recycle. These elements showed common attributes: being lightweight and pricey, incurring considerably higher disassembly costs, making it impractical. Retaining them within the overall product might not be optimal. There is need for further analysis to determine the optimal disassembly points for each of them.

This information was utilized to formulate a user-friendly design tool that includes disassembly considerations. For it to be as efficient as possible, it should ask for a balanced amount of information. Its objective is to assist engineers to design a product that is easy to disassemble, whilst not complicating the PDP. For that reason, the drafts for the disassembly map were created based on the literature. These maps constituted the starting point to evaluate the disassemblability of the product, and then they were shown to the different stakeholders in the process to see if some improvements could be included.

Some limitations emerged when analysing the disassembly sequence with only the disassembly map. This map does not measure the disassembly time, only gives sequence order, target components, and penalties. Therefore, measuring the time for each step and the whole product is needed, as these values are also used in the recyclability calculations. Such reasons suggest using the MOST methodology to measure the disassembly time. An early analysis of the product can be done by finding the bottlenecks in the disassembly sequence. This methodology is also compliant with the European standards.

Moreover, the disassembly map showed to be efficient for one use, but not to be implemented for every product at Northvolt. A personalized map for every product is time-consuming, which is not the tool's intended purpose. That is why in the disassembly tool, the goal is to automatically create a representation of the disassembly sequence, showing as well how much time every task takes to complete.

The MOST methodology proved to be reliable to calculate disassembly time, despite being developed over 20 years ago. After comparing the times calculated with the disassembly tool and the data obtained from manufacturing, it could be seen that the deviations in time are limited, thus allowing for comparison between the calculated and the actual times. The biggest difference in tasks corresponds to Z, which mainly consists of unscrewing several connectors. The difference in fractions of seconds for every screw connection might accumulate and become more significant the more screws have to be removed. Another factor contributing to this difference might be that both cases compared manual disassembly. Although both are performed manually, the MOST methodology calculates manual screw removal based on the number of turns required to remove the screw, which might not be the most precise way to calculate disassembly time. In the future, a more appropriate methodology for the calculation of disassembly time might be established. However, in order for the tool times to be acceptable and replicable through the company's portfolio, or even for other companies, such methodology should be as generic as possible, available to the public, and considering as many procedures as possible.

The results don't include all the parameters needed for a disassembly tool. The one Northvolt aims to develop in the long run must measure disassembly time and, simultaneously, reveal the product's weaknesses in terms of disassemblability. This is why the outputs of the disassembly map and time calculations are implemented in the tool. The identification of target components, together with the disassembly penalties, are essential components from the disassembly map that have also been included. Furthermore, the representation of the disassembly sequence is an outcome similar to the disassembly map from the literature but will also include the time required for every task.

6. Conclusion and future works

This project explores the approaches to evaluate recyclability and disassembly within battery systems. It gathers information from the literature and formulates an assessment for Northvolt’s products. The approach uses material recyclability, incorporating both economic and environmental considerations, as well as evaluating the recyclability profitability and disassembly time.

The outcomes from this project are included into an evolving tool, planned for implementation within the company. This tool aims to streamline the assessment of product disassembly by computing disassembly times and inspecting component connections. The tool not only helps in identifying the crucial components in terms of recyclability and reusability, but also contributes to enhancing the overall design for easier disassembly. The current version allows to evaluate design improvements, especially in terms of speed of disassembly and hazard considerations, meeting most recycling objectives.

This study has some limitations. With more disassembly data and a bigger product portfolio, it would be possible to perfect the material recyclability index and the overall product recyclability index. Future research should also focus on the environmental impact analysis, predict material prices more accurately, and expand on the tools for disassembly, thus refining the reliability of the calculation. Further works will also involve the refinement and expansion of the proposed tool, methodology, and findings to cater to a broader industrial context. Explicit guidance on adapting and applying the tool across different industrial practices should be included, thus ensuring the contributions of this work extend beyond the specific case study with Northvolt. The goal is to offer insights to a broader range of practitioners, contributing to sustainable practices in engineering design on a wider scale.

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