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Assessment of the Automation Potential of Electric Vehicle Battery Disassembly

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Abstract

Electric vehicles (EV) offer an environment friendly solution to transportation and there are predictions for high sales of EVs in future. The most expensive parts of those vehicles are their batteries which need to be recycled after use. Currently, there are major challenges in disassembling and recycling EV batteries due to the large variety of types, sizes and design complexity. This paper provides a brief summary on current studies for the disassembly of EV batteries as well as the assessment of automation potential for EV battery disassembly steps. A *2017 Chevrolet Bolt* battery was used to generate a disassembly graph, which shows connections and constraints of all parts and fasteners, and a 46-step disassembly sequence. An automation assessment of the *2017 Chevrolet Bolt* battery and *Audi Q5* battery was conducted on all the steps to determine, based on two categories, the technical possibility and the necessity of automating a given disassembly step. To score these different steps, which could range from a -100 to 100, an easy-to-use criteria catalog was developed and applied on these batteries. This criteria catalog consisted of a total of ten criteria, five criteria for the technical possibility to automate the step and five criteria for the necessity to automate that step. Disassembly steps that score above 50 for the technical ability to automate and had a positive necessity of automating score are steps that should be automated. The scores generated for both batteries showed that most of the unscrewing operations should be automated while most of the lifting operations should be performed by human workers. The results from the automation assessment of the *Audi Q5* battery compared similarly to approaches found in literature but was able to produce more extreme scorings because of the simplified criteria catalog. The work presented in this paper gives an approach to assess the automation potential of a given disassembly step in any EV battery.

Keywords: EV batteries, disassembly, automation.

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1. Introduction

Climate change is one of the biggest threats to the environment and humanity today, with transportation being one of the largest producers of greenhouse gases [1]. To reduce the emissions of greenhouse gases, many countries promote the use of electric vehicles (EVs). Compared to conventional cars, EVs use simpler electric motors instead of large internal combustion engines with many individual parts. Since vehicle range is an important indicator for the competitiveness of EVs, EV batteries are large and heavy to carry enough charge to provide that range. Additionally, EV batteries contain expensive materials such as lithium and cobalt that significantly contribute to their production costs [2]. The treatment of disposed EV batteries is an increasingly important field of research as the numbers of sales of EVs continue to rise [3] and their batteries have a lifespan of about 10-15 years [4].

Disposing EV batteries in landfills is the worst end-of-life treatment method because of the expensive materials wasted, and the negative environmental impact due to the hazardous materials contained in the EV batteries [5]-[6]. Manual disassembly is another disposal method used as the EV battery cells are treated with a pyro-metallurgical process in order to recover and extract valuable materials [7]. This manual disassembly process is very expensive due to high labor costs and workers' protection from high-voltage and chemical hazards. Many of the disassembly operations used in EV battery disassembly, such as unscrewing or grabbing, are very repetitive and could be automated. This automation is necessary for reducing costs and making EV battery recycling more attractive.

There are three types of EVs that use different types and sizes of EV batteries. Battery electric vehicles (BEV), which are typically the largest and heaviest, only use electric energy and do not have an internal combustion engine or a fuel tank. Hybrid electric vehicles (HEV) use both an internal combustion engine and an electric propulsion system with the goal of achieving better fuel economy. HEV batteries are much smaller, as they only provide a very short electric driving range. Plug-in hybrid electric vehicles (PHEV) use an internal combustion engine, as well as an electric motor and battery that can be plugged into external electricity sources. The goal of this combination is to provide a certain range of only electric driving as well as higher driving performance and efficiency. For example, with a PHEV, it is possible to drive inside cities using only electric power and then use the internal combustion engine for long-distance driving. The PHEV batteries have sizes and weights in between the BEV and HEV [8].

Most EV batteries use lithium-ion technology where battery cells are bracketed together in modules. Each EV battery contains a certain number of battery modules as well as a battery energy control module (BECM), cables, electrical connectors, and most include a cooling system and insulation. A housing cover around the battery usually consists of two parts, a lower tray and an upper cover. EV battery design is missing common standards as there is a very high number of variants due to the different types of EVs (PHEVs, BEVs and HEVs), all of which require different battery designs, sizes, weights, and structures [9]. For example, the *Tesla Model S* uses cylindrical cells with 16 modules in one battery pack, and 444 small battery cells in one module. The *Nissan Leaf* uses an EV battery design with 48 small modules but just 4 large cells while the *BMW i3* battery is composed of just 8 battery modules with 12 large cells in each module [10]. About two thirds of the costs for an EV battery originate from the cells raw materials and production [11].

To further illustrate the design of an EV battery, look at the *2017 Chevrolet Bolt* battery. The observations on this battery have been taken from the videos of Kelly [12], [13] who performed a disassembly and re-assembly of the *2017 Chevrolet Bolt* EV battery. Figure 1 shows the battery with the cover removed and the battery system exposed. The battery system is made up of five battery sections, with each section consisting of two battery modules. The two modules in the front are referred to as Battery Section 1, the next two modules moving towards the rear of the battery are Battery Section 2 and the next two are Battery Section 3. The lower two modules in the back are Battery Section 4, while Battery Section 5 is the raised section located above Battery Section 4. This two-level structure in the *2017 Chevrolet Bolt's* battery allow for more efficient use of the vehicles space for storing electric energy, thus providing a higher driving range. However, this geometry creates challenges for disassembly [12].

The *2017 Chevrolet Bolt* battery weighs approximately 435kg and has dimensions of approximately 1.6 m long by 1 m wide. Battery Sections 1-3 are approximately 15 cm high and the Battery Sections 4 and 5 have a combined height of about 30 cm. The battery has total of 288 cells with Battery Sections 1-3 having an equal number of cells while Battery Sections 4 and 5 containing slightly fewer cells. In the front, there is the relay assembly which is composed the main electrical components and has a cover over it with three screws. The long orange parts are busbars that connect the different battery modules together. All around the battery modules, just inside the tray, are orange and black cables, which are the high voltage sense lines and low voltage harness respectively. In the front of the EV battery there is an orange high voltage electrical connector that charges the battery if AC charging is used. On the top of Battery Section 5, the orange high voltage disconnect can be seen next to the black BECM. Between the modules and in front of the Battery Section one metal bracket, which fix the Battery Sections, is visible [12].

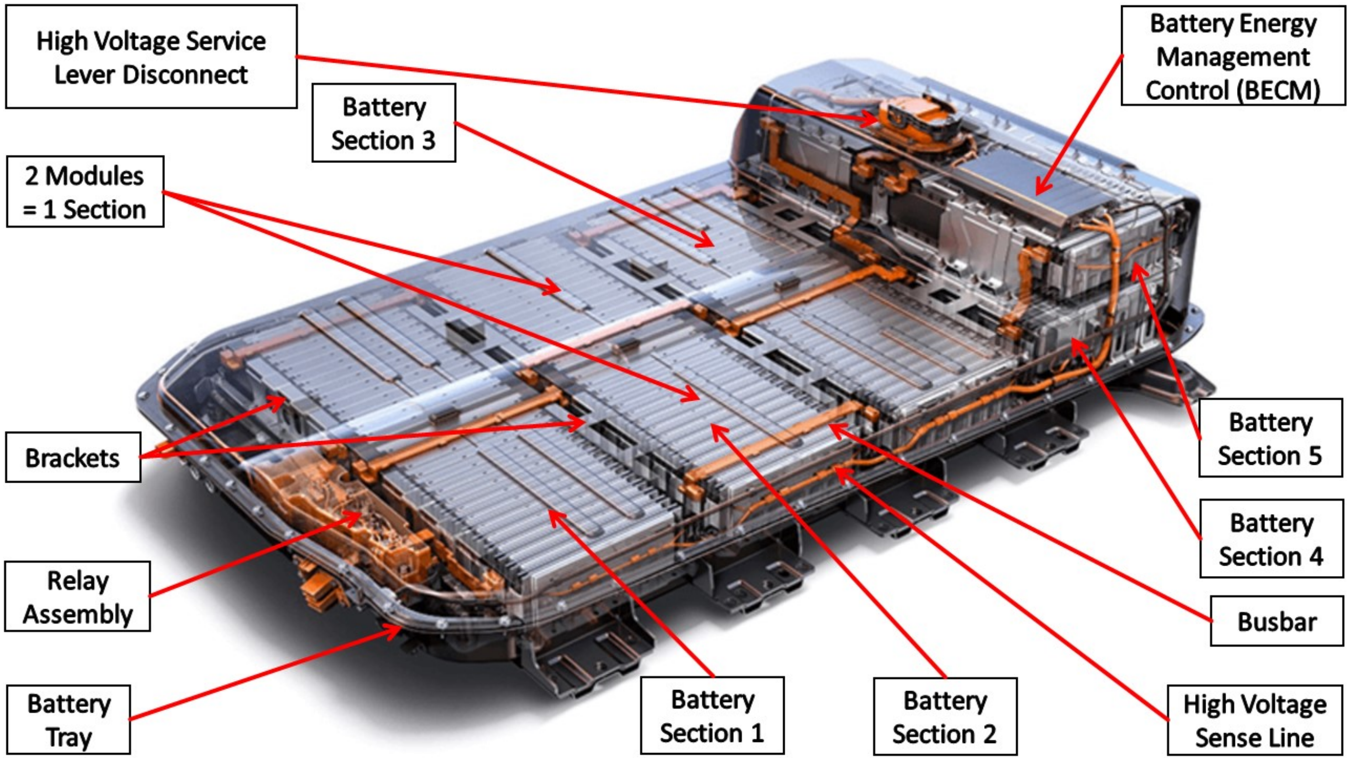

Figure 1: 2017 Chevrolet Bolt battery with removed cover, adapted from [14]. The annotations are added by the authors.

The remainder of this paper is structured as follows. The next section reviews previous studies on the disassembly of EV batteries. Section 3 covers the disassembly structure for an EV battery. In Section 4, the analysis and assessment of EV battery recycling is presented, while Section 5 presents a comparison of the assessment of different battery types. Concluding remarks are presented in the last section.

2. Previous Studies on the Disassembly of EV batteries

This section reviews recent studies on the analysis and assessment of automation potentials for disassembly steps in EV battery disassembly. It also reviews several concepts for battery disassembly.

2.1 Analysis and Automation Assessment in EV battery disassembly

Wegener *et. al* [15] investigated the disassembly of EV batteries using the *Audi Q5 hybrid* which has a relatively small HEV battery consisting of four battery modules and weighs 35kg. It was recommended to discharge the batteries prior to disassembling to sort the parts and materials. A shredding operation was suggested for the battery cells to regain valuable materials such as lithium and copper, and to reuse disposed electrical parts. Fourteen main parts were identified, and a table was created where each part was scored with the numbers of predecessors in disassembly to develop a disassembly order.

Each step was described with the corresponding tool for manual disassembly, then, a disassembly priority graph was developed that combined succeeding steps with the same tool.

Herrmann *et. al* [16] looked at the automation potentials of single disassembly step using a product analysis based on different battery systems (BEVs, PHEVs and HEVs) to develop a criteria catalog. A software tool collected the information about disassembly sequences, part costs, and disassembly times to develop a disassembly graph which stored information such as disassembly times for different steps. Fifteen main disassembly steps down to the level of battery cells were identified. The two indicators for the assessment are the "technical ability of a disassembly process to be automated" (TAA) and the "necessity to automate the corresponding disassembly operation" (NA) [16] which describes the economic feasibility. Twelve criteria for NA and eleven criteria for TAA were created for the scoring model and weighted differently based on the importance of each criterion. Based on the portfolio analysis, a scatter diagram was developed that visualized automation potentials and necessities. It was suggested to only automate the handling of the battery system to the disassembly area, the extraction or lifting out of single battery modules and the extraction of single lithium cells. This work proposed to only automate handling and repetitive grabbing operations and only count screws with a TAA score of zero. This differed from [11] which proposed loosening of fasteners as a main task for the robot because of the high repetition of the task.

Li, Barwood, and Rahimifard [17] presented an assessment for robotic disassembly using environmental, technological, and economic criteria. Formulas were developed for accessing the three categories, and the assessment validity was tested by assessing and disassembling with three different automotive electronic components. Each disassembly step was listed with the disassembly time, tool used, and if that step was carried out manually or automatically. Schwarz *et al*. [18] created a virtual disassembly tool to help to predict the disassembly time as well as calculate the material composition and weights. Theis et al. [2] presented a general study on the economics of EV battery disassembly and the feasibility of the LithoRec process to determine optimal investment plans and performance indicators. Li et al. [19] considered the economic aspects associated with the acquisition of remanufacturable products and pricing strategies, as well as the economic benefits to original equipment manufacturers resulting from remanufacturing products in addition to selling new products.

2.2 Disassembly Concepts for Electric Vehicle Batteries

Wegener *et al.* [20] suggested a human-robot workstation where the robot and human share the same workspace for reduction of transport time. The robot would perform the easier tasks, such as unscrewing, while the human would perform the more complex tasks, such as prying. The robotic end-effector could be positioned manually by the human to demonstrate the location of fasteners, or with the help of a vision system. They reported this human demonstration of fastener locations was time consuming and locating fastener positions with a vision system would be much faster. A bit changing mechanism was proposed that allowed the robot to unfasten different sizes and types (screws, nuts, bolts) of fasteners with the same robotic end-effector.

Schmitt et al. [21] stated that although the automation of EV disassembly needs to be highly flexible, a fully automated disassembly is unrealistic and not efficient due to the number of steps that are too challenging for automation. The barriers for automated disassembly such as product, process, environment, and logistics are also summarized. Product barriers could be fasteners or a design that is not disassembly friendly [22]-[23] and could originate from parts with an unstable form and location (e.g., cables that should be cut). Environment barriers can refer to usage and aging variance in the product while logistic barriers could include missing labeling and the high number of EV battery variants. Extracting a single disconnected battery cell from opened modules showed a high automation potential, which led to the development of a flexible gripper that could measure the state of charge of the cells to avoid high voltage (HV) dangers. Harper et al. [10] described challenges in EV battery disassembly and how automation could be performed. Some of these challenges include different component sizes in various battery designs and the need for qualified employees due to heavy battery weights and HV dangers. They described the Optisort system [24], which uses computer vision to read labels and sort batteries by identifying objects based on shape, size, and color as a potentially useful algorithm for pre-sorting batteries. Sensors, especially ones that incorporate tactility and force sensing are important to create intelligence robots. It was concluded that re-use is economically more feasible than direct disassembly, but any disassembly following the re-use should be automated as much as possible to reduce risks to human workers. Kampker et al. [25] compared different factory layouts (Linear, U-shape, S-shape, and L-shape) for a disassembly plant that remanufactures EV batteries to obtain and compare performance parameters such as needed-space and disassembly times. Kay et al. [26] investigated the automated disassembly of EV batteries. Technicians were observed on their manual disassembly performance and experiments on gripping and cutting operations were performed. While not explicitly targeting EV battery disassembly, Liu et al. [27] presented a service platform for robotic disassembly where a physical robot was integrated in the disassembly planning process to optimize disassembly solutions. Zhang et al. [28] introduced an evaluation method to determine the extent a product can be remanufactured using a fuzzy extension analytic hierarchy process.

Human-robot collaboration is a promising concept for disassembly, especially due to the complex and unpredictable nature of disassembling EV batteries. Goodrich and Schultz [29] described human-robot interaction (HRI) as robotic systems that are used by a human, or where a human and robot work together. The biggest distinguishing factor for HRI is how the robot and human communicate, and if there is close proximity between them. Murata [30] described human-robot collaboration as the opportunity to combine the advantages of humans and robots for accomplishing different tasks and compensating for each other's weaknesses. Shozo and Takeo [31] explained the advantages of hybrid assembly systems which are in-between manual and fully automated assembly. Automated assembly is good for high quality and high productivity but lacks flexibility while manual assembly has a lower quality and productivity but is more flexible and can handle a larger number of variants.

Another aspect in human-robot collaboration is robotic learning which implements algorithms that help robots learn and improve skills from processed data. Argall et al. [32] discussed learning by demonstration where the human showed the robot how to accomplish a task and the robot interpreted the human movements and developed its own actions for performing the task. Vongbunyong et al. [33] described how the expert knowledge of human workers can be transferred to the robot and performed a case study using LCD screens.

Collision prevention is also an important aspect in human-robot collaboration to prevent injuries and damage. A collision detection method without external sensors was presented by De Luca et al. [34] where they used proprioceptive sensors for collision detection and discussed different reaction strategies. Zhang et al. [35] showed how neural networks can be used in order to predict the human motions to achieve human-robot collaboration in performing a case study of an engine assembly.

3. Disassembly Structure for an EV battery

A BEV battery has been investigated in detail in this paper. First, a list of all parts and fasteners was created, the relations between the parts and fasteners was determined and these connections were shown using a graph structure. Based on the graph structure, one possible disassembly sequence was developed. Following that, an assessment on the technical possibilities and the economic needs for disassembly of each single disassembly step was performed.

3.1 Structuring of Parts and Disassembly steps

The structuring of the parts was developed using the *2017 Chevrolet Bolt* battery as an example based on the disassembly and reassembly video of Kelly [12] - [13]. In the first video [12], the EV battery was manually disassembled down to the level of the battery modules. The parts that remained in the tray after extracting the modules were also disassembled.

For the structuring of the parts, we differentiated between parts (numbered: P#) and fasteners (numbered F#). Based on the videos [12] - [13], all parts and fasteners were identified that were taken apart from the battery tray. The individual battery modules were not disassembled further. In total, 76 parts and 374 fasteners were identified and labeled. Table 1 shows an example of labeled fasteners. The IDs F1-50 correspond to the 50 bolts around the top cover which are further described, and the image shows the fastener or parts location. Typical identified fasteners are bolts, nuts and screws, but clips or covers are also labeled as fasteners if they must be opened or unclipped. There is a large number of different parts with many varieties in shape and size. Most typical parts are brackets, covers, and busbars due to the design of an EV battery. The parts and fasteners can also be labeled as active and passive components [36]. In that description active components refer to fasteners and passive ones to the parts connected by fasteners. In the *Chevy Bolt* EV battery, the passive parts "Top Cover (P1)" and "Battery Tray (P76)" are connected by the active parts "Bolts (F1-50)" and "Bolts (51-56)". This means all the active parts (56 bolts total) connecting the two passive parts must be unbolted before the passive parts can be removed.

Table 1: Description and image of a fastener

ID	**Name**	**Description**	**Image**
F1-50	Bolts 1-50	Bolts for the top cover (P1) to Battery Tray (P81)	 F1-50 Around Top Cover

3.2 Development of a Disassembly Graph

Next, a disassembly graph was developed, and for every part and fastener, it was verified which parts and fasteners needed to be disassembled first. As discussed, before the "Top Cover" can be removed, the 56 bolts connecting it to the battery tray must be unfastened. Figures 2-4 show the developed disassembly graph where the parts are displayed with grey boxes and the fasteners with blue boxes. All boxes with a dashed outline are accessible/visible at the beginning of the disassembly process and the orange boxes are used as continuations (C#). The graph shows the direct predecessors and successors for each individual fastener (or group of fasteners) and part. The presented graph is a similar to the "graph model of the environment" [36], however, the presented graph clearly points out which parts are passive (P#) or active (F#). Furthermore, the arrows show the direction of disassembly and dashed lines are used to indicate when two lines cross for visual clarity. Our presented graph combines the arc structure for a disassembly graph [37] with the idea of the model of the environment with active and passive components [36] (fasteners and parts), while showing the direction of disassembly and differentiating between the different kinds of components.

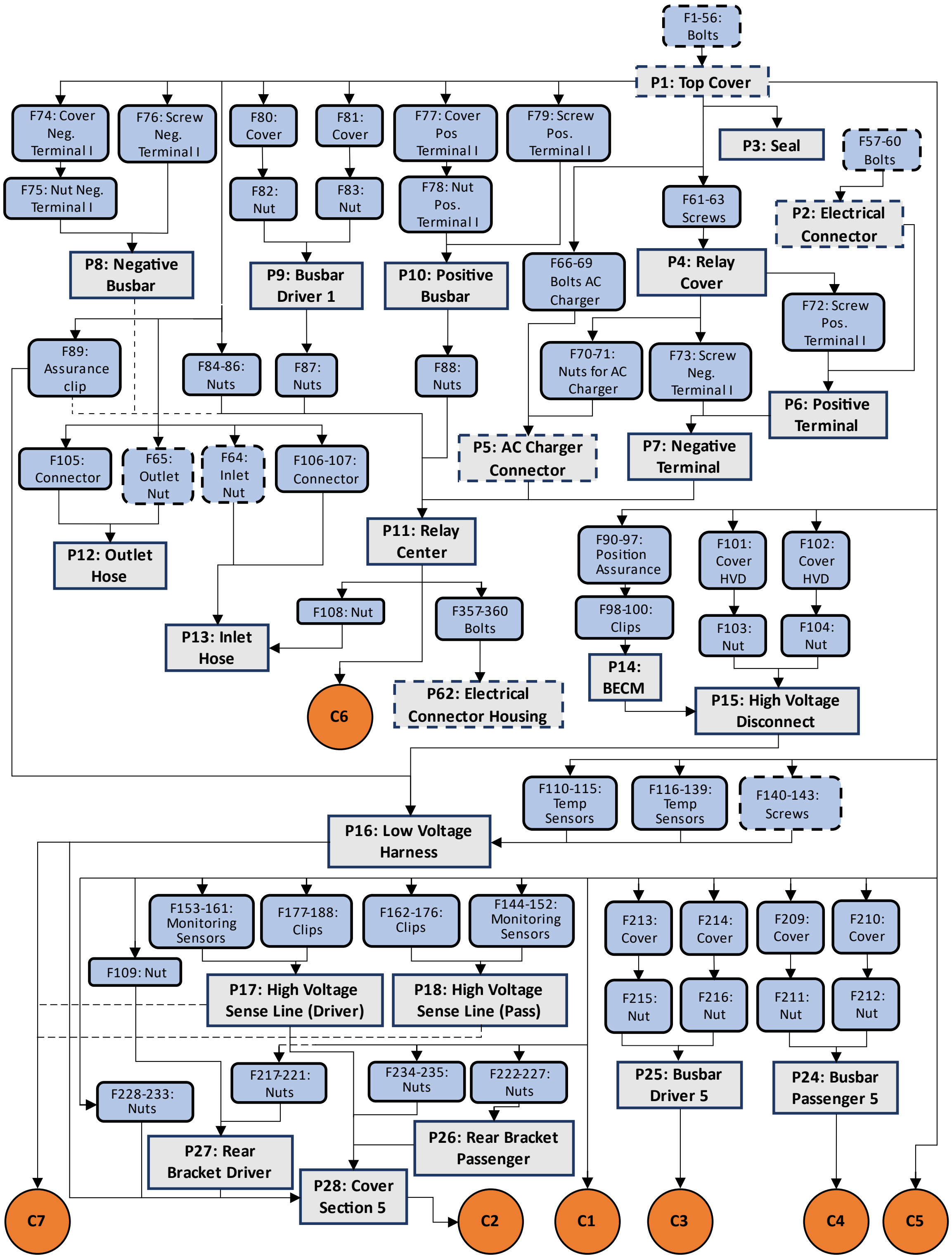

Figure 2: Disassembly graph of 2017 Chevy Bolt EV battery (page 1)

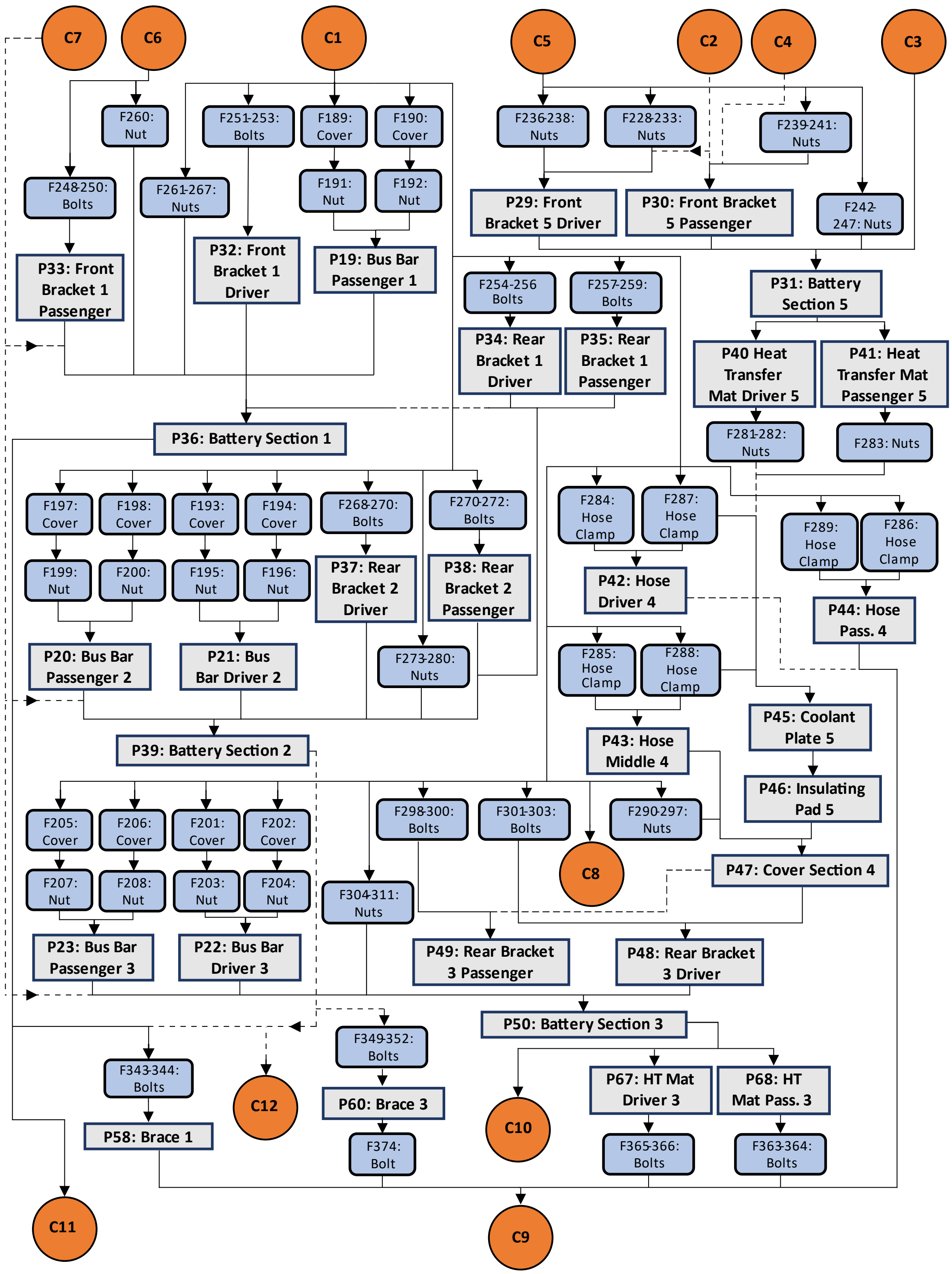

Figure 3: Disassembly graph of 2017 Chevy Bolt EV battery (page 2)

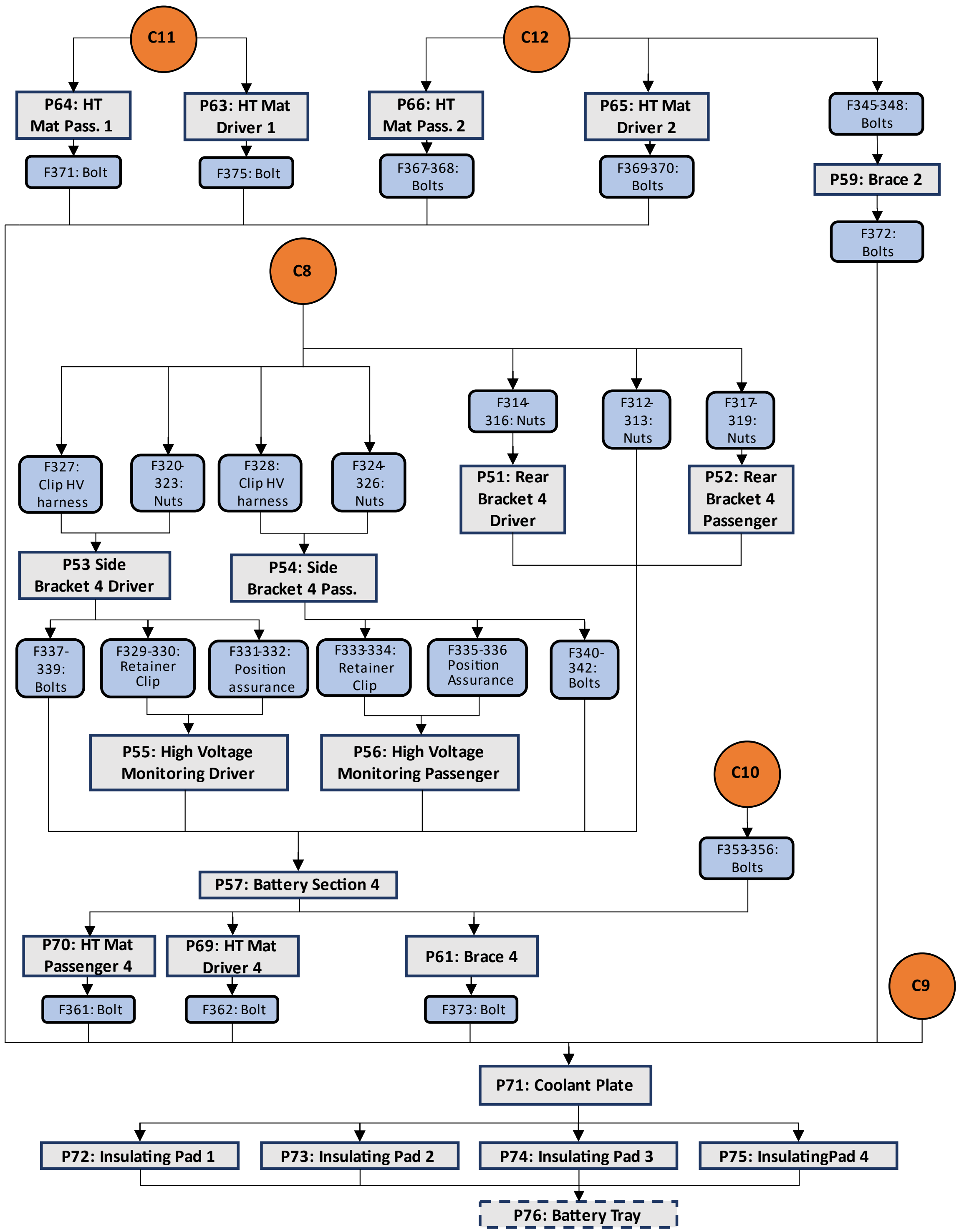

Figure 4: Disassembly graph of 2017 Chevy Bolt EV battery (page 3)

3.3 Suggested Disassembly Sequence

Although there are several approaches [38]–[44] for finding an optimized disassembly sequence with the help of operations research algorithms, it was decided to just find one exemplarily, manually optimized disassembly sequence. For that purpose, based on the disassembly graph, similar parts or fasteners that could be disassembled in one step have been combined, thus significantly reducing the number of disassembly steps. The reasons for grouping these parts are the reduction of tool changes, reduction of traveling distance for the robot or human worker, the possibility of parallel working of several robots or the human worker and sorting of disassembled parts for further recycling.

Table 2 shows partial listening of the 46 disassembly steps (see Appendix for full listing). In this table, the steps are numerated with the ID "D#", the parts or fasteners ID of each disassembly step are listed in the column "*Parts and Fasteners"*. The next column, "*Connector type and quantity or removable part*" shows the quantity of the different parts or fasteners which helps for later assessment to determine the number of necessary tool changes. In the column labeled "*Access",* the way the part of fastener can be accessed is noted (such as from the top or from the side), and the necessary tools to remove the part or fasteners are listed in the column "*Tools"*. Those can be compared to previous automation approaches for electric and hybrid vehicle batteries [15]-[16], [20]-[21], [45]. The column "*Comments"* is filled with further information or predicted difficulties while the "*Approximate Size"* column lists the size of parts, or general working space to approach the disassembly step. The last column lists a first estimation about the difficulty of automation for that step that could be used later in assessments. These first estimations were projected based on existing approaches for tooling, accessibility, and further singular properties of one disassembly step.

The first disassembly step is "D1" which describes the unfastening of the 56 hexagonal bolts around the top cover and service plug connector (F1-56). Besides the bolts for the electrical connector, removing these hexagonal bolts is the only possibility to start the disassembly process. Open access from the top is possible and simplifies detection (see Figure *5*). The disassembly tool required for this step is a screwdriver for the bolts. It is noted in the comment that the work area is large (approximately one meter in width and two meters in length) meaning more than one robot or one large robot may be needed to perform the task. Additionally, the six bolts around the service plug connector are 20cm higher which must be considered for detection and access. The first estimation for automation suggests an easy automation of disassembly because there are several approaches for unscrewing bolts [20], [46] and the access and detection seem feasible because there are no hidden bolts and the bolts are a different color than the top cover.

Table 2: Examples of disassembly step descriptions

Step #	Details						
	Parts and Fasteners	**Connector type and quantity, or removable part**	**Access**	**Tools**	**Comments**	**Approx. Size**	**Automation Difficulty? Easy/Difficult/ Challenging (First estimation)**
D1	F1-56	56 hexagonal Bolts,	Top, open	Screwdriver for bolts	6 bolts around service plug connector (higher in z-direction) Difficulties due to large area.	2m x 1m	Easy
D6	F74, F77, F80, F81	4 Covers	Top	Prying tool for opening covers	Need for a prying tool, that can open covers	50cm x 50cm	Difficult
D12	F64-65	2 Large Nuts	Side, inside	Nutrunner Screwdriver, to hold it from the inside	Hold it fixed from inside and unscrew nut from outside, very difficult to automate, large screwdriver needed, grabbing would also be difficult.	10cm x 10cm x 10cm	Challenging
D19	F103-104, F109, F140-143, F191-192, F195-196, F199-200, F203-204, F207-208, F211-212, F215-280, F290-326	88 Nuts, 24 Bolts, 4 Screws	Top (some are partly hidden)	Screwdriver/ Nutrunner	Tool change needed, some of the nuts and bolts are more difficult to detect, because those are below the brackets or in between the sections at the bottom. Extended screwdriver/ nutrunner needed	180cm x 90cm x 40cm	Easy
D39	P36, P39, P50, P57	4 Battery Sections	Top	Battery Lifting Tool for Battery Sections	Special lifting tool needed, lifter must get adjusted on the battery, slow lifting encouraged. Balance whole EV battery while lifting	40cm x 80cm x 15cm	Difficult


Figure 5: Disassembly step D1, the Top Cover [12].

An example for combining different disassembly steps is “D6: Covers for Busbars (Front)” (see Table *2*). The four covers (F74, F77, F80, F81) shown in Figure 6, could be opened in one step because they are similar and also located in the same area of the EV battery. These parts are accessible from the top and a prying tool would be needed to open them. A first estimation implies that automation is difficult because of the difficulty of the prying process and it also could be hard for a vision system to find the spot to place the prying tool.

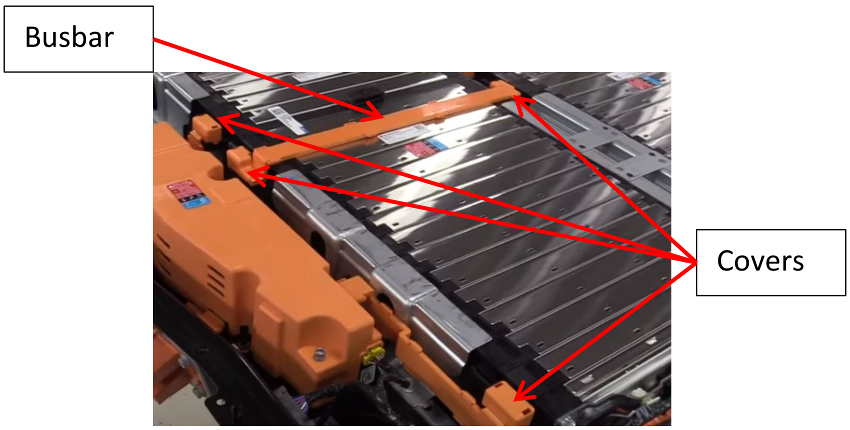

Figure 6: Disassembly step D6, the four covers for the busbars in the front [12].

Disassembly step D12 “Big Nuts for Coolant Hoses” (see Table *2*) shown in Figure 7, represents an example of a challenging step. It is unique and needs special tools because of the size of the nuts holding the coolant hoses to the frame. It must be accessed from the side, which is also very difficult, so a first estimation suggests D12 has a very low automation potential.

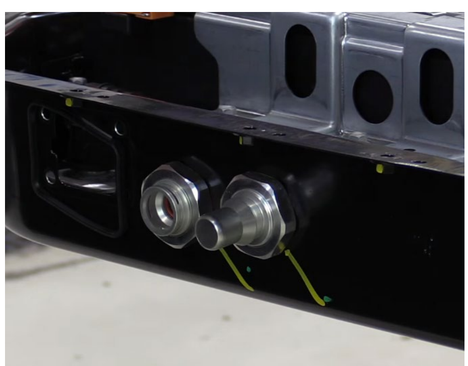

Figure 7: Disassembly step D12, the Big Nuts for Coolant Hoses [12].

The step D19 “Nuts, Bolts and Screws for Busbars and Brackets, High Voltage Disconnect and Battery Sections” (see Table *2*), is an example where multiple of fasteners have been combined. This disassembly step combines the unfastening of 88 nuts, 24 bolts and 4 screws since the operations are very similar and repetitive and only require a few tool changes. While some of the fasteners are partly hidden below brackets, most of the fasteners are relatively easy to detect and approach (Figure 8), therefore, an extended screwdriver or nutrunner could be used. The noted workspace is very large, because the fasteners are spread over the whole battery. Finally, this step is considered easy because of the high automation potential of using unscrewing tools.

Figure 8: Example for screws in disassembly step D19 [12].

Step D39 “Battery Sections 1-4 Lifting” is when four of the five battery sections are separated from the remaining battery parts and is one of the most important steps. Figure 9 shows the lifting of one of the battery sections. While this part is large and relatively easy to detect, it is more difficult to find the spots on the part to place the lifting tool. The handling of heavy parts is another challenge, so a special lifting tool or crane is needed. Due to the glued heat transfer mats below the battery section the lifting must also be down slowly. Also, the lifting tool must be adjusted to balance the battery sections while lifting which is why this step is ranked as difficult.

Figure 9: Disassembly step D39, the lifting of four battery modules [12].

4. Analysis and Assessment of EV battery Recycling

4.1 Assessment of the Automation Potential of Disassembly steps

Based on the developed 46 disassembly steps and the collected information about every step, an assessment of automation potential for each step has been realized. A criteria catalog was created for this task which provides criteria for the technical possibilities and the necessities for automation. This catalog was applied to an example of one PHEV and one BEV battery.

The results for the hybrid vehicle and EV battery have been compared to results from literature, and the differences and similarities are discussed.

Herrmann et al. [16] proposed a catalog with 23 criteria for the assessment of hybrid vehicle and EV batteries. Some similar criteria have been aggregated to get a simpler catalog with 10 criteria, five for the TAA, and five for the NA. This is done to simplify the assessment as the weaker criteria are combined to come up with five equally important criteria for each category (NA and TAA). For example, the different criteria of "direct involvement of hazardous material", "disconnecting of current carrying cables", and "distance to electric potential" were combined to form NA3: Danger. In comparison to [16], each criterion was assigned the same weighting factor as they were all equally important.

Table 3 shows the list of criteria and for each criterion a scoring between -2 and 2 is possible. The scoring range is finer than that used in [16], which only ranged from -1 to 1, and is chosen for assessing more accurately. With a weighting factor of 10, the range of possible scorings is from -100 to 100 for each NA and TAA. The equation used to obtain these values for NA and TAA are shown with Eq. 1-2 where NA_i and TAA_i are derived from the assessment of each criterion for each disassembly step from Table 3.

$$NA = 10 \times \sum_{i=1}^{5} NA_i \quad \text{Eq. 1}$$

$$TAA = 10 \times \sum_{i=1}^{5} TAA_i \quad \text{Eq. 2}$$

For the NA the time a human worker needs is the most important aspect which is accounted for in the first two criteria (NA1 and NA2) as the number of motions are relatively easy to count. For the disassembly time, approximations have been made on the basis of the Methods-Time Measurements (MTM) [47]. This technique is well used in industrial settings, where standard times for certain movements are fixed. Kroll and Hanft [48] applied that method on disassembly tasks for electronic devices. They combined that approach with guidelines for the Design for disassembly (DFD) [22], and provided examples of times for different tasks.

Table 3: Assessment criteria

Category	Criterion Number	Criterion Description
NA	1	Number of Motions (human)
	2	Duration of manual disassembly time in seconds
	3	Danger (High voltage protection, hazardous materials)
	4	Weight
	5	Priority (value)
TAA	1	Complexity of motion (for robot, number of different motions)
	2	Access for end effector
	3	Possible detection
	4	Automation potential for robotic end effector
	5	Material handling

Danger for the human worker (NA3) is another criterion where the dangers range from sharp edges and chemicals to the danger of high voltage which is present in EV batteries. The necessary protection for a human worker and its costs and longer working times must be considered.

The weight of a part (NA4) is another important factor. Due to health considerations, human workers cannot handle heavy weights for a long time or perform many repetitions. Steinberg and Windberg [49] documented weights and posture criteria such as bending and twisting and provided rankings. For the disassembly assessment we used a combination of both posture and weights. The documented time criterion was not considered, as it was already included in the time criterion discussed earlier.

Table 4 shows the scorings for the weight criterion. Heavy weights or when human workers need to perform lots of bending operations tend to show a preference for automation, while light weights suggest manual disassembly.

Table 4: Criterion scorings on part weights and ergonomics (NA4)

Scoring Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	≥25 kg or strong bending/twisting and weight far away from body	<25 kg, or far away or strong bending/ twisting	<15 kg or medium bending of body, part far away from body	<10 kg or little bending of body	<5 kg, straight upper body, part near to body

The scoring values for the priority criterion (NA5) are shown in Table 5. As discussed before, the battery modules and cells contain a high amount of valuable materials. Additionally, there are valuable materials in other parts, such as aluminum or recyclable expensive components like the BECM. The highest rating (two) will be given if the step separates a valuable recyclable part and is necessary to reach the battery modules. A score of one will be given if it is a necessary step in order to achieve access to the battery modules, while a score of zero corresponds to just relatively valuable parts. If the step only leads to sort of different materials for further recycling, it will score minus one while a scoring of minus two will be given if only unrecyclable low-cost parts are removed. In summary, NA5 is the most economically driven criterion.

Table 5: Criterion scorings on the priority for disassembly (NA5)

Scoring Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	Necessary in order to reach cells and other valuable materials	Necessary in order to reach cells	Not necessary to reach cells, but other valuable materials	Not very valuable materials but sorting different materials for further recycling	Low-cost materials, not necessary for cells

The first TAA criterion (TAA1) assesses the complexity of the robotic motion. The number and difficulty of the motions are combined. Standard movements such as translational or rotational movements are simple. More complex operations or necessary tool changes lower the scoring while special types of motion such as unplugging yield a score of -2. .

Table *6* summarizes the requirements for the different scorings.

Table 6: Criterion scorings for the complexity of robotic motion (TAA1)

Score Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	Few simple standard movements (only translational and rotational) e.g. simple screws, simple grabbing	Medium number of standard movements (two tool changings allowed) e.g., different screws	More complex movements (max 1) or more tool changings e.g., prying, cutting, or larger grabbing	Complex movements and many tool changings	Very complex operations, e.g., special unplugging

The access (TAA2) and detection (TAA3) are two further criteria which are strongly related to each other. For a successful automation of disassembly, it is desired that a given end effector can easily access the part or fastener. Additionally, a vision system must be able to detect the spot to place the disassembly tool precisely preferably in an open view and with open access. Size limitations or the need for extended or angled end-effectors diminish that scoring. Shadows, bad contrast, or small part sizes lower also the detection scorings.

Table 7 indicates the scorings on how a robotic end-effector could access the parts or fasteners. Table 8 summarizes the scorings on the challenges to a vision system for part detection and localization.

Table 7: Criterion scorings for the access (TAA2)

Score Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	Completely open, any end-effector could approach it	Open, but size limitations for end effector, or side access	Extended end effector needed (e.g. extended screwdriver)	Small tool or angled screw-driver needed	No access at all for robotic end effector

Table 8: Criterion scorings for the detection (TAA3)

Score Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	Open view, no shadows, good color contrast and relatively large part	Open view, shadows, or bad contrast possible or medium size part	Partly hidden or bad contrast and shadows or smaller size part	Partly hidden and bad contrast or shadows and/or small part	Completely hidden, no chance to detect part

The automation potential for the robotic end-effector (TAA4) has been taken as another criterion for the assessment. The rating depends on the number of studies or choices about different automation tools and is influenced on the level of realization and reliability of the proposed systems. Additionally, it is considered how suitable such concepts are for a disassembly step. The requirements for each scoring are listed in Table 9.

Table 9: Criterion scorings for the automation potentials of the robotic end-effector (TAA4)

Score Value	**2**	**1**	**0**	**-1**	**-2**
Meaning	Many choices for automated tool	Some existing choices for automated tool	At least one existing choice for automation (not fully tested)	Proposed concept for automation, not fully realized	No proposed concepts to automate, uncertainty about automation possibility in future

The last TAA criterion is the material handling (TAA5). It combines the handling of the removed parts or fasteners and threads for further processing. The collection of simple fasteners into a metal bin for simple further recycling, such as screws gets a rating of two. If the parts are just metallic but small or medium size parts, such as brackets, the rating is one. A rating of zero would be given if different materials are involved that can’t be sorted such as cables with sensors, or if the parts are very large. For large parts like the battery sections or large covers, a crane or lifting tool could be necessary. If the parts are large and there are different materials involved recycling is more difficult. Those parts get a rating of minus one. If parts are very large, have an unwieldy shape or if hazardous materials are involved then the rating would be minus two. An example would be a cooling plate that contains an easy flammable coolant such as R1234yf.

4.2 Assessment for Hybrid Vehicle Battery

The ten criteria outlined in the above section have been applied on the 18 out of the 19 steps for disassembly of the Audi Q5 HEV battery [15] (19 disassembly steps were described, but one step did not provide enough information to assess). All 19 disassembly steps and their scores are shown in the appendix. For each criterion the calculations and assumptions have been documented. Table 10 shows the assessment on the first step of the Audi Q5 hybrid vehicle battery disassembly.

Table 10: Assessment on the unscrewing of covers for the Audi Q5 hybrid vehicle battery

Criterion	**Comments**	**Scorings**
NA 1	Move, position, unscrew, move, grasp, bring, release for every bolt/nut + tool change approx. 7*20 = 140 movements	2
NA 2	5 seconds for every bolt/nut, approx. 120s in total with screwdriver grabbing/tool change	2
NA 3	No high voltage or chemical dangers at that point, only sharp edges possible	-1
NA 4	Very low weights, just screws/bolts and nuts, some bending to reach screws	-1
NA 5	Necessary to reach cells because no other possibilities to get to cells/modules	2
TAA 1	Tool changing seems necessary, but only translational und rotational. Simple standard movements	1
TAA 2	Access form sides and bottom needed, more difficult, but open	-1
TAA 3	Also, detection on sides and bottom needed	0
TAA 4	Some choices e.g., R. Li *et al.*, "Unfastening of Hexagonal Headed Screws by a Collaborative Robot," *IEEE Trans. Autom. Sci. Eng.*, pp. 1–14, 2020 [46]	1
TAA 5	Just collection of nuts/bolts	2

During this battery disassembly, approximately 20 bolts or nuts must be loosened and collected. Due to the high number of fasteners, the scoring on the movements (NA1) and time criteria (NA2) is high. There is no danger of chemical hazards or electrical shocks on the first step, so the scoring on danger is low (NA3) with the only possible danger being certain parts may have sharp edges present. The weights of the parts are also low (NA4) and there are only some steps in which bending seems necessary. In order of reach the most valuable parts, this step is very important (NA5). The NA scoring adds up to 40 $(10 \times (2 + 2 - 1 - 1 + 2))$ which recommends automating that step.

The movements required are standard unscrewing movements, however, it is necessary to perform a tool change which leads to a high score (TAA1). The scoring on the access is low (TAA2 and TAA3) since the fasteners are also located on the side and bottom which complicates detection. The scoring automation potential is higher (TAA4) as there have been some approaches on locating and unfastening bolts or nuts [20], [50]–[52]. Finally, the material handling (TAA5) is easy since fasteners are light parts that are collected in a bin for further recycling. A scoring of 30 $(10 \times (1 - 1 + 0 + 1 + 2))$ for TAA suggests the possibility that there is a high chance automate this step even if the access and detection below the battery are more difficult to achieve.

Figure 10 shows the result for 18 of the disassembly steps and most of the steps seem necessary and technically possible to automate since they are in the first quadrant of the graph. The shaded area of this figure shows the steps that should be automated. Steps in this shaded region have a positive NA score, so it necessary to automate them, and a TAA score above 50, so it is technologically possible to do so. Some extreme examples need further explanation such as Step 16 (Figure 10 [90,40]) "Unscrewing of nuts on the cell contacts", which has a TAA of 90. That high scoring refers to a relatively simple unscrewing operation where the fasteners are accessible from the top. There is a good contrast in color and shape of the fasteners for detection, while there are choices for automation of unscrewing operations. As discussed before the material handling of fasteners is simple.

Another example is Step 5 (Figure 10, [-10, -10]) "disassembly of the plug connection between the cell controllers and the BMS" the scoring shows it is neither necessary, nor possible to automate this step. In the framework of a human-robot workstation [20], this would be a typical task for the human worker. The low NA scoring results from the low part weights and little amount of movements. The low TAA scoring is caused by difficult access and detection as well as uncertainty about automation potentials for the robotic end-effector.

Steps 2 (Figure 10, [50, -10]) and 8 (Figure 10, [50, -20]) score negative on NA because these steps are fast cover removal operations however these relatively simple grabbing operations score relatively high on TAA because there are several automation approaches. If a gripper is installed it could be adjusted for such steps to save some extra worker's time, even if it is not as necessary as for other steps.

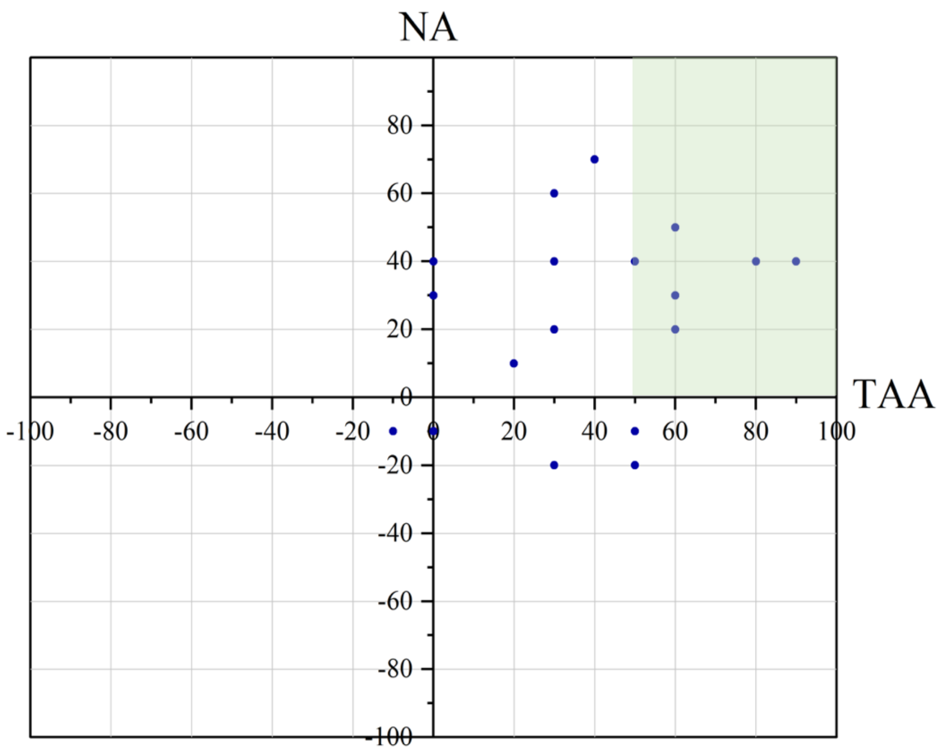

Figure 10: Assessments of disassembly steps for Audi Q5 hybrid vehicle battery (see Appendix)

4.3 Assessment for Battery Electric Vehicle Battery

Similar to the assessment of the steps for the hybrid electric vehicle, the assessment has also been applied on the 46 steps for the disassembly of the EV battery (see Figure 11 and table with all results in Appendix). The results (Figure *11*) look similar to those of the hybrid vehicle battery (Figure 10). However, there are some differences because the BEV battery is larger in size and more complex. Some disassembly steps will be discussed in detail.

A relatively extreme example in the assessment is step D39 (Figure 11, [30, 90]). This step has an NA scoring of 90 because of the importance of separating the Battery Sections and the high weight of the battery sections. However, the TAA scoring is lower but still positive as it is more difficult to automate a complex lifting operation for heavy parts.

D1 (Figure 11, [90, 40]) is an example for a step with an extremely high automation potential since the TAA scoring is 90. As discussed before, there are several approaches to automate unscrewing operations with open view and access. The NA scoring of 40 is lower because in the first step, there are no hazards due to high-voltage or chemicals, however it is possible these hazards may occur in later steps.

The two previous steps discussed both scored positive on NA and TAA scales, so those could and should be automated. D10 (Figure 11, [-40, 30]) should be automated because it is necessary to reach the valuable battery cells and the relay center which could be reused. However, this operation is very difficult to automate as there is not much space for a robotic end-effector and the parts are difficult to detect and would require multiple grabbing tools. Overall, it would probably be easier for a human worker to perform this step.

D42 (Figure 11, [70, -30]) "grabbing of the braces" is an example of a step that is possible to automate but is not necessary to automate. The high TAA is based on the relatively simple grabbing operation with just a little larger part and open access to it. The low NA is because the Battery Sections are already taken out, there are no HV or chemical hazards. Furthermore, this step is not necessary to get access to the battery modules. Those are already taken out and no more expensive materials can be disassembled with this step. Depending on the requirements for further processing the remaining materials in the battery tray could also be separated. For the braces, the separating could be done relatively easy by a robot (comparable to the unscrewing tasks done before).

The disassembly of the nuts for the coolant hoses are described with D12 (Figure 11, [-30, -20]). Performing this step is not necessary to gain access to the battery cells and it could be done quickly by a human worker which leads to an NA score of -20. From a technical point of view, it is difficult to automate this step due to the need for special tools and the lack of previous studies on such automation. The TAA scoring is -30 which indicates this step should still be performed by a human worker or left out completely.

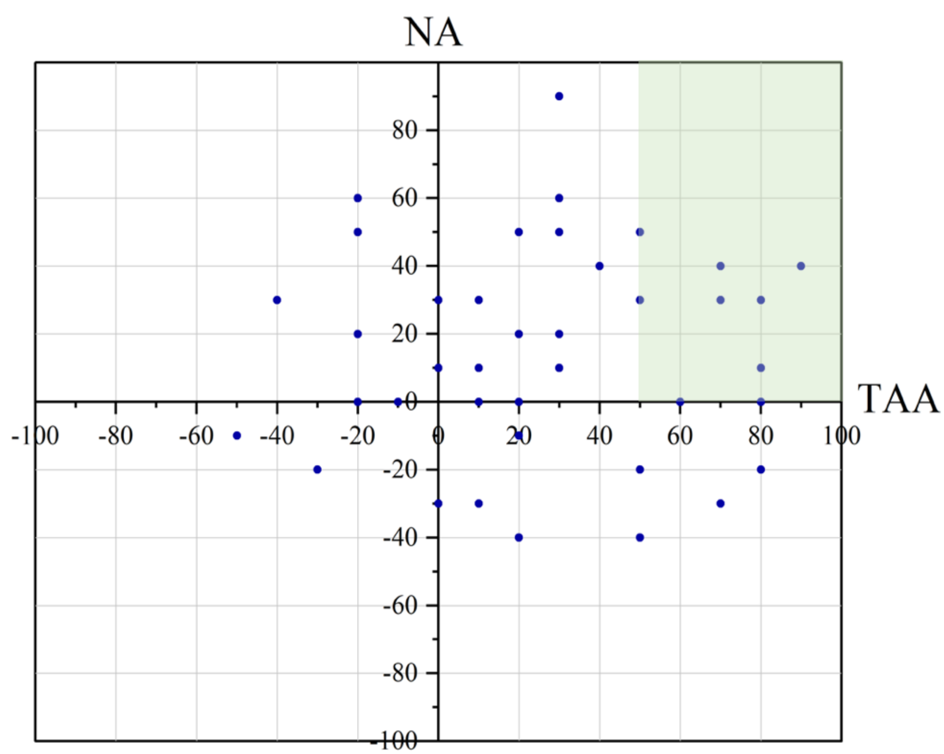

Figure 11: Assessment of disassembly steps for 2017 Chevrolet Bolt battery

5. Comparison of the Assessment of Different Battery Types

In this section the results from the analysis on the HEV and the BEV battery will be compared with the results from Herrmann et al. [16] who performed analysis on several different kinds of EV batteries. Figure 12 shows the results of that study.

First, comparing the analysis on the BEV battery (Figure 11) to the HEV battery (Figure 10), there are a higher number of necessary disassembly steps for the BEV battery resulting from the larger number of parts and higher complexity of the BEV battery. Another factor is the *Chevrolet Bolt* BEV battery has a more complex design; the fifth Battery Section is placed above the fourth one which requires a second cooling plate below the fifth Battery Section and several more parts. Methodologically there is also an important difference. Wegener et al. [20] analyzed the disassembly down to the level of modules and then continued the disassembly of the modules down the level of battery cells. The disassembly steps of the Chevrolet Bolt battery describe the disassembly just down to the level of Battery Sections (1 Section = 2 Modules). The subsequent steps describe the further disassembly of the remaining part in the battery tray. Because of that, the last steps of the BEV battery score lower on NA and are not needed to reach the battery cells. However, for the hybrid vehicle battery all proposed steps are necessary to reach the cells.

Another difference is the size since BEV batteries are much larger than HEV batteries. As previously discussed, the larger size and higher number of parts in the BEV battery leads to an increased number of disassembly steps, which in turn leads to an increased number of motions for each step. For example, there are 56 bolts around the top cover for the BEV battery, but just 20 fasteners for the covers surrounding the *Audi Q5 hybrid battery*. This leads to comparable higher NA scoring for the BEV battery due to a higher number of motions and a longer manual disassembly time (NA1 and NA2).

The results of the investigations by Herrmann et al. [16] for many different BEV, PHEV and HEV batteries (Figure 12) do not score a NA above 50 for any disassembly step. Those investigations were executed with a more detailed criteria catalog. The results of our investigation (Figure 11) score a NA of 50 or higher for several disassembly steps. From this, it can be concluded that the simplified criteria catalog produces more extreme scorings, especially higher results in TAA and NA. There are more disassembly steps with TAA or NA above 50 or with negative values for the BEV assessment with the simplified catalog. The higher NA scorings could be a caused by the focus on disassembly time and potential dangers. There are many repetitive disassembly steps in the BEV disassembly that score high on NA1 and NA2 because of the disassembly time and number of motions. High scorings on NA3 result from the HV dangers for all nearly all steps in between the "Top Cover" removal and the extraction of the battery modules. NA5 receives high scorings for many steps because those are necessary for reaching the most valuable materials, the battery modules and cells. Because of the high scorings in those four categories there are high NA scorings for many disassembly steps. Furthermore, the TAA scorings are lower in the study with the detailed criteria catalog. It is also suggested to only automated the three steps with a TAA above 50 and positive NA. These operations are the handling of the battery, the extraction of the cells and the extraction of the modules [16]. With our simplified criteria catalog those operations are rated worse in TAA because lifting operations are categorized as more complex, but in comparison to that previous study [16] our assessment strongly recommends automating unscrewing operations. Most of those have a very high TAA and high NA. Technical progress in automation of unscrewing and other operations is another reason for different TAA scorings. The investigations by Wegener et al. [20] also suggest the automation of unscrewing operations but that study did not provide ratings for single disassembly steps.

Our results (Figure 11) show that the ratings of the disassembly steps are placed into all four quadrants of TAA and NA combinations. This underlines the need for human-robot collaboration because some disassembly steps are very difficult to automate, so the human must perform these disassembly steps or at least teach the robot how to perform the steps. Those disassembly steps that score high in TAA and NA are possible to automate and should be automated. Disassembly steps with a high TAA rating but low NA rating could easily be automated but it is not necessary to automate those. An example for such a step is D42, the unscrewing of the screws for the braces. It should be decided on a case-by-case basis, if such a step should be automated with economic considerations being the most important for such decisions. In the case of D42, an automated screwdriver is already included in the robotic end-effector for several more important disassembly steps. Keeping this in mind, D42 should be automated because it does not require a lot of effort to do so. For disassembly steps that score low on both TAA and NA, a human worker is the better choice for performing these steps because automation will be difficult and is not necessary. For disassembly steps that score high on NA but low on TAA, it is recommended to automate the steps although it may be difficult to do. An example is D10 which is a very complicated grabbing operation. For such a disassembly step a human worker is still the better choice. Investigations on technical realization of such steps are necessary.

There is an even higher need for automation in EV battery disassembly in comparison to HEV/PHEV batteries due to the larger size, higher weight and the resulting expected higher disassembly time for manual disassembly. The higher repetition in many steps strongly recommends these steps be automated. From a technical point of view some disassembly operations are more difficult because of the weight, size and complexity, which include the handling of the battery and battery modules. Strong efforts on designing reliable automated systems for such steps are required because those operations with heavy weights are also not suited for human workers. There are still some non-repetitive or difficult disassembly operations in BEV battery disassembly were humans are superior compared to robots. With the large variety of assessed disassembly steps, a human-robot workstation is a suitable concept for the disassembly BEV and HEV/PHEV batteries [20]. The similarities between BEV and HEV/PHEV disassembly suggest disassembling all types in the same factory, but there should a larger sized disassembly station for the disassembly of the BEV batteries and a smaller station for PHEV/ HEV batteries. The extracted battery modules of all battery types could be disassembled at the same disassembly station.

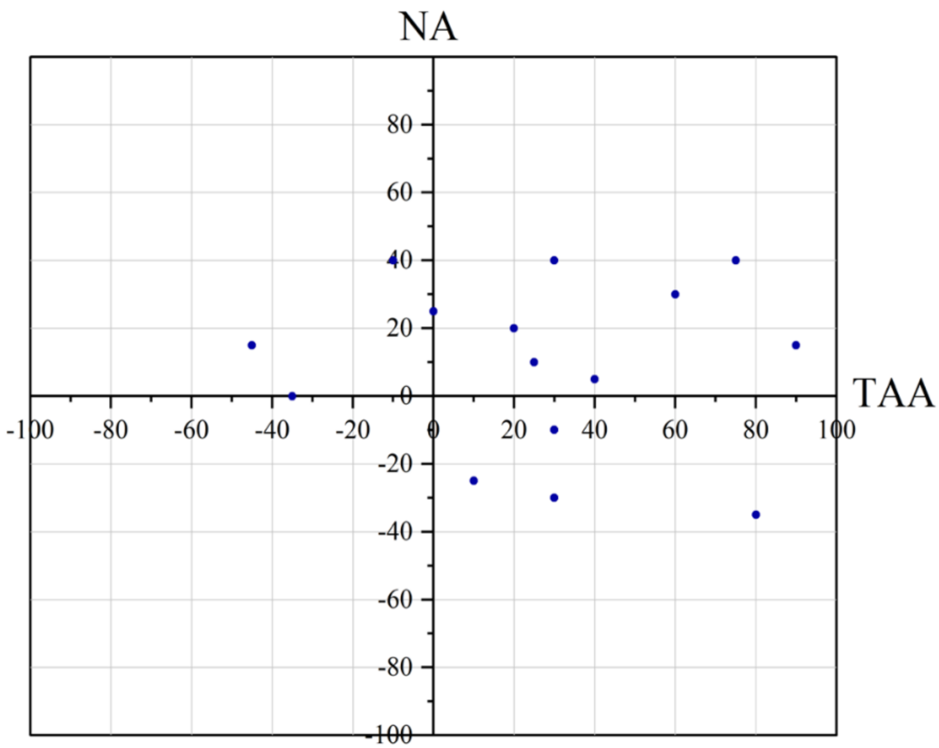

Figure 12: Assessment of disassembly steps for several BEV and HEV/PHEV batteries, adapted from [16]

6. Conclusions

This paper presented an overview of previous studies related to the disassembly of EV batteries which included topics such as the analysis of automation assessments for disassembly operations and disassembly approaches for EV batteries. It also presented a simplified easy-to-use catalog of criteria for calculating automation potentials of different disassembly steps used to generate a TAA and NA score. Each of these scores could range from -100 to 100 and when plotted against each other can be used to visualize which of the disassembly steps should be automated (positive NA value and a TAA value greater than 50). Negative TAA scores indicate that this step should either be left out completely or performed by a human worker.

The *2017 Chevrolet Bolt BEV* and *Audi Q5 HEV* batteries were used to test the automation assessment with simplified criteria for different disassembly steps. The disassembly steps for the *2017 Chevrolet Bolt* were determined based on disassembly and reassembly videos [12]-[13] and a disassembly graph was constructed which shows the relationship between all the fasteners and parts. From this disassembly graph, a disassembly sequence was generated with the individual disassembly steps. The steps for the *Audi Q5 HEV* battery were taken from a previous study [16] and the scores between the different methods were compared. The scores generated for both batteries showed that most of the unscrewing operations should be automated while most of the lifting operations should be performed by human workers. The scores produced with the simplified criteria generated more extreme scores than scores produced with more detailed criteria and as a result recommend more steps for automation. These higher scores for NA could be due to criteria that focus on disassembly time and potential dangers. The simplified catalog presented in this paper provides a finer scale that allows for more accurate assessments. Furthermore, the simpler assessment catalog attempts to allow for quicker assessments and easier comparisons of different battery models than in previous literature. This paper also presented a detailed assessment of a very large and complicated BEV example (2017 Chevrolet Bolt).

The work presented in this paper gives an approach to assess the automation potential of a given disassembly step in any EV battery. As newer EV batteries are being developed, the next step will be to apply the approach developed in this paper to these new batteries. This tool could help designers create EV batteries that are more efficient in disassembly.

Conflict of interest

The authors declare that they have no competing interests.

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Appendix

Table 11: Disassembly steps for BEV battery (2017 Chevrolet Bolt)

Step	Involved Parts or Fasteners	Description	NA	TAA
D1	F1-56	Bolts for Top Cover	40	90
D2	P1	Lifting of Top Cover	10	30
D3	F57-60	Bolts for Electrical Connector	30	70
D4	P2	Electrical Connector	-20	50
D5	P3	Seal	-30	0
D6	F74, F77, F80, F81	Covers for Busbars (Front)	20	20
D7	F61-63, F66-69, F75-76, F78-79, F82-83	Nuts/ Screws for Busbars (Front) and Relay Cover	60	30
D8	P4, P8-10	Relay Cover, Busbars	30	50
D9	F70-73, F84-88	Nuts, Screws below Relay Cover	50	30
D10	P5-7, P11	Grabbing of Relay Center, Terminals, AC-Charger	30	-40
D11	F105-108	Connectors and Nut for Coolant Hoses	-10	-50
D12	F64-65	Big Nuts for Coolant Hoses	-20	-30
D13	P12, P13	Grabbing of Coolant Hoses	-40	50
D14	F357-360	Nuts for Electrical Connector	0	60
D15	P62	Electrical Connector	-40	20
D16	F89-100, F110-139,	Assurance Clips, Temp. Sensors, BECM clips	60	-20
D17	P14	BECM	0	80
D18	F101-102, F189-190, F193-194, F197-198, F201-202, F205-206 F209-210, F213-214	Covers for Busbars, High Voltage Disconnect	50	20
D19	F103-104, F109, F140-143, F191-192, F195-196, F199-200, F203-204, F207-208, F211-212, F215-280, F290-326	Nuts, Bolts and Screws for Busbars and Brackets, High Voltage Disconnect and Battery Sections	50	50
D20	P15	High Voltage Disconnect	0	60
D21	P16	Low Voltage Harness	0	-20
D22	F144-188	Clips and Temp. Sensors for HV Sense Lines	50	-20
D23	P17, P18	HV Sense Lines	20	-20

D24	P26-27	Rear Brackets	0	60
D25	P28	Cover Battery Section 5	20	30
D26	P19-25, P29-30, P32-35, P37-38, P51-52, P53-54	Busbars and Brackets	50	30
D27	P40-41	HT Mats Battery Section 5	10	10
D28	F284-289	Hose Champs	10	0
D29	P42-44	Hoses	-30	10
D30	F281-283	Nuts for Coolant Plate	30	80
D31	P45	Coolant Plate Section 5	30	10
D32	P46	Insulating Pad Battery Section 5	0	20
D33	P47	Cover Battery Section 4	20	30
D34	F327-328	Clips HV Harness Battery Section 4	0	-10
D35	P48-49	Side Brackets Battery Section 4	0	60
D36	F337-342	Bolts Battery Section 4	40	70
D37	F329-336	Retainers, Position Assurance Battery Section 4	30	0
D38	P55-56	HV Monitoring Circuit Battery Section 4	0	60
D39	P36, P39, P50, P57	Battery Sections 1-4 Lifting	90	30
D40	P63-70	Heat Transfer Mats	10	10
D41	F343-356, F361-371, F375	Bolts for Braces, Coolant Plate	10	80
D42	P58-61	Braces	-30	70
D43	F372-374	Bolts for Coolant Plate	-20	80
D44	P71	Coolant Plate	0	10
D45	P72-75	Insulating Pads	-10	20
D46	P76	Handling of Battery Tray	40	40

Table 12: Disassembly steps for HEV battery (Audi Q5 hybrid) [15]

Step #	**NA**	**TAA**
Step I: Unscrew covers and casing bottom:	30	20
Step II: Removal of power electronics cover and side covering:	-10	50
Step III: Disassembly of the live lines from the modules/ stacks:	Not enough information to assess	Not enough information to assess
Step IV: Cutting of cable ties:	10	20
Step V: Disassembly of the plug connection between the cell controllers and the BMS:	-10	-10
Step VI: Removal of BMS and power electronics:	20	30
Step VII: Cutting of the bus for the thermo sensors:	-10	0
Step VIII: Disassembly and removal of system cover:	-20	50
Step IX: Unscrew and removing of cable guiding:	40	50
Step X: Removal of gas venting and the cover of the stacks:	20	60
Step XI: Disassembly and removal of the connector between the stacks:	30	0
Step XII: Unscrew and removal of stack holders:	50	60
Step XIII: Removal of casing bottom:	-20	30
Step XIV: Unscrew and removal of stack fastener:	40	80
Step XV: Removal of stacks:	70	40
Steps for the disassembly of the battery modules:		
Step I: Unscrewing of nuts on the cell contacts	40	100
Step II: Removal of cables and cell connectors	40	0
Step III: Unscrewing and removal of the side covers:	30	60
Step IV: Removal of battery cells:	60	30