Design of Automotive Battery Systems for the Circular Economy

Konstruktion von Traktionsbatteriesystemen für die Kreislaufwirtschaft

Von der Fakultät für Maschinenwesen
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Foreword

This work's content is the fruit of my time spent as a research associate at the Chair of Production Engineering of E-Mobility Components of RWTH-Aachen University. Accordingly, I must first thank Prof. Kampker for his strong commitment to topics surrounding sustainability in battery production and E-mobility in general, and Dr. Heimes, who believed in this project's feasibility and granted me access to the eLab facilities at RWTH.

I will never be thankful enough to my supervisors, Dr. Wessel and Dr. Offermanns, without whose precious guidance and attention to details and formalities this work would have never been completed. I also thank my predecessors, Mr. Lienemann and Dr. Hollah, who initiated the institute's research into the field of Re-X, and my colleagues who brought it forward: Dr. Fluchs, Dr. Kreisköther, and Mr. Klohs.

I should also extend acknowledgements to the very best thesis students, who helped me perform this work, including those who later became research associates: Mr. Ghandily, Mr. Gorsch, Mr. Kisseler, Mr. Vienenkötter and those who did not, namely, Mr. Biederbeck, Mr. Vacca, Mr. Alberti, and Mr. Wu.

Because tearing down and testing used batteries is dangerously practical, I am especially grateful to the eLab's management and its outstanding and helpful technicians, Mr. Frauenrath and Mr. Pelzer.

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Besides my parents, I am also very grateful to all the people who tolerated me under stressful conditions, especially Dr. Francesco Turoni, and to all those who helped me maintain a balanced, healthy, and positive lifestyle, especially my sailing partner, Mr. der Heijer, the staff and community of Crossfit Heerlen.

I want to express my gratitude to Lukas and all the young research associates who built my doctoral cap "Doktorhut," which is the most creative and advanced I have ever seen.

Summary

The urgent need to reduce greenhouse gas emissions across the economy has led to tremendous growth in electric mobility. Initially, the industry focused on scaling up production and infrastructure, but the adoption of electric mobility has been hampered by skepticism about the durability and environmental sustainability of battery systems. For many products, these can be improved by extending the life cycle, which includes maintenance. In the case of automotive battery systems, some challenges make this approach problematic, such as the aging and reliability characteristics, the non-reversible joining methods used in production, and the difficulty of automating a large number of assembly and disassembly operations. The objectives and results of this work are to understand the characteristics of battery systems in terms of life cycle engineering and to design a product development methodology for the design of products with similar characteristics capable of improved life cycles in terms of both durability and sustainability. This methodology covers the fields of reliability engineering, life-cycle engineering, and engineering design principles and addresses the maintenance of products that do not have easily predictable failure modes. In fact, most life-cycle engineering methodologies aim to facilitate the diagnosis and replacement of a few identifiable parts to extend the life of a larger system. This is not possible for battery systems because it is not known which cells will fail or age first. Therefore, a methodology has been designed to facilitate disassembly down to the cell level. The methodology starts with a preliminary product architecture and the collection of requirements for components, focusing on their reliability and life cycle characteristics. In the second module, possible life cycles and maintenance intervals are derived for each component, and components with compatible characteristics are clustered. In the third module, a product structure is derived that takes into account the interactions between components and their joining methods and prioritizes the clustering and accessibility of joints for components with similar maintenance intervals. The fourth and final module plans the detailed design in a concurrent engineering framework and evaluates the benefits of the proposed life cycle in economic and environmental terms. This methodology has been progressively applied to three use cases, and its potential has been validated. With the further development of industrial automation in disassembly using computer vision and adaptive algorithms, the present design methodology should contribute to the development of battery systems that can be economically refurbished many times during their lifetime, thus increasing the acceptance of electric mobility and facilitating the reuse of used but not completely spent battery systems.

Zusammenfassung

Die Notwendigkeit zur Reduktion der Treibhausgasemissionen, hat zu einem rasanten Wachstum der Elektromobilität geführt. Jedoch wurde die Akzeptanz der Elektromobilität durch die Skepsis hinsichtlich der Langlebigkeit und Umweltverträglichkeit von Batteriesystemen beeinträchtigt. Bei vielen Produkten können diese durch die Verlängerung des Lebenszyklus, verbessert werden. Im Fall von Kfz-Batteriesystemen ist dieser Ansatz jedoch aufgrund einiger Herausforderungen schwierig, z. B. wegen der Alterungseigenschaften, der nicht reversiblen Verbindungsmethoden und der Schwierigkeit, Montage- und Demontagevorgängen zu automatisieren. Die Ziele und Ergebnisse der vorliegenden Arbeit umfassen das Verständnis der Besonderheiten von Batteriesystemen im Hinblick auf deren Lebenszyklus sowie die Konzeption einer Produktentwicklungsmethodik für die Gestaltung von Produkten mit ähnlichen Besonderheiten. Diese Methodik deckt die Bereiche Zuverlässigkeitstechnik, Lebenszyklus-Engineering sowie Konstruktionsprinzipien ab und befasst sich mit der Instandhaltung von Produkten, deren Ausfallmodi nicht leicht vorhersehbar sind. Die meisten in der Literatur bestehenden Methodiken zielen darauf ab, die Diagnose und den Austausch von wenigen identifizierbaren Teilen zu erleichtern, um die Lebensdauer eines größeren Systems zu verlängern. Bei Batteriesystemen ist dies nicht möglich, da nicht bekannt ist, welche Zellen zuerst ausfallen oder verstärkt altern werden. Daher wurde eine Methodik entwickelt, die die Demontage bis auf Zellebene erleichtert. Innerhalb dieser erfolgt im ersten Modul zunächst die Erarbeitung einer vorläufigen Produktarchitektur sowie die Sammlung von Anforderungen an die Komponenten, mit Schwerpunkt auf ihrer Zuverlässigkeit und ihren Lebenszykluseigenschaften. Im zweiten Modul werden für jede Komponente mögliche Lebenszyklen und Wartungsintervalle abgeleitet, und die Komponenten mit kompatiblen Eigenschaften werden in Baugruppen zusammengefasst. Im dritten Modul wird eine Produktstruktur abgeleitet, die die Wechselwirkungen zwischen den Komponenten, berücksichtigt und die Verbindungszugänglichkeit für Komponenten mit ähnlichen Wartungsintervallen priorisiert. Das vierte und letzte Modul plant das Detaildesign im Rahmen des Concurrent Engineering und bewertet die Vorteilhaftigkeit des vorgeschlagenen Lebenszyklus in wirtschaftlicher und ökologischer Hinsicht. Die Methodik wurde schrittweise auf insgesamt drei Anwendungsfälle angewandt und validiert. Mit der Weiterentwicklung der Automatisierung der Demontage trägt die vorliegende Methodik zur Entwicklung von Batteriesystemen bei, die innerhalb ihrer Lebensdauer ökonomisch gewinnbringend überholt werden können, wodurch die Wiederverwendung gebrauchter Batteriesysteme erleichtert wird.

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Numbers

1R	reduce, as in ”lean manufacturing”
3R	reduce, reuse, recycle
6R	principles of ”sustainable manufacturing”

B

BEV	battery electric vehicle
BMC	battery management controller
BMS	battery management system
BoL	beginning of life
BOM	bill of materials

C

C2C	cradle to cradle
C2P	cell-to-pack
CAD	computer aided design
CAN	controller area network
CID	current interruption device
CSC	cells supervising circuit

D

DC	direct current
DCIR	direct current internal resistance
DCR	direct current resistance
DfA	design for assembly
DfC	design for cost
DfD	design for disassembly
DfE	design for environment
DfL	design for life-cycle
DfM	design for manufacturing
DfMA	design for manufacturing and assembly
DfR	design for recycling
DfRem	design for remanufacturing

DoD	depth of discharge
DPM	disassembly precedence matrix
DSM	design structure matrix

E

ECM	equivalent circuit model
EFRE	European regional development fund
EKF	extended Kalman filter
EMC	electromagnetic compatibility
EMF	electromagnetic field
EMI	electromagnetic interference
EoL	end of life
EPR	extended product responsibility
EV	electric vehicle

F

FCEV	fuel cell electric vehicle

G

GHG	greenhouse gas
GWP	global warming potential

H

HEV	hybrid electric vehicle
HRC	human-robot collaboration
HV	high voltage
HVIL	high voltage interlock circuit

I

ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IME	Institute of Process Metallurgy and Metal Recycling
IPPD	integrated product and process development
IPT	integrated product team
ISC	Institute for Silicate Research
IT	circuit with isolated ground (from French ”isolè terre”)

K

Kfz	Kraftfahrzeug

L

LCA	life-cycle assessment
LCC	life-cycle costing
LCO	lithium-cobalt oxide
LCSA	life-cycle sustainability assessment
LFP	lithium-iron-phosphate
LMO	lithium-manganese oxide
LV	low voltage

M

MIM	module indication matrix
MPA	modular product architecture
MTBF	mean time between failures
MTTF	mean time to failure

N

NCA	lithium-aluminum-cobalt oxide
NMC	lithium-nickel-manganese-cobalt oxide

O

OBD	on-board diagnostics
OBD2	on-board diagnostics on the CAN bus according to ISO 15765
OCV	open circuit voltage
OEM	original equipment manufacturer
OSR	overhaul, sort and repurpose

P

PA	polyamide
PA-6	polyamide-6
PCM	phase change materials
PE	polyethylene
PEM	Chair of Production Engineering E-mobility Components
PHEV	plug-in hybrid electric vehicle
PLM	product life-cycle management
PP	polypropylene
PST	post shredder recovery
PU	polyurethane
PVC	polyvinylchloride

Q

QFD	quality function deployment

R

RC	element of an electric circuit made of one resistor and one capacitor in parallel

S

SEI	solid-electrolyte interface
S-LCA	social life-cycle assessment
SoC	state of charge
SoF	state of function
SoH	state of health
SUV	sport utility vehicle

T

TIM	thermal interface material
TTM	time to market

U

UNECE	United Nations Economic Commission for Europe

X

XpYs	X cells connected in parallel and Y in series, where X and Y are natural numbers

1 Introduction

This chapter introduces the background for this work in section 1.1 and the relevance of the problem it aims to solve in section 1.2. Section 1.3 formulates the overarching objectives and the scope of the research before section 1.4 explains the methodological framework, with section 1.5 presenting the consequent structure of this work.

1.1 Initial situation

The year 2021 represented a major turning point in perceptions of the dangers of climate change and resource depletion, and efforts to bring human activity within the regenerative limits of the biosphere[1] started to be acknowledged in public discourse and politics.[2,3] To achieve a 50% chance of containing global warming under 1.5°C, global greenhouse gas emissions must reach net zero by 2035, including emissions caused by the mobility sector, which encapsulates the movement of both people and goods. Not only is a rapid shift to electric mobility far in advance of 2035 essential, but two other conditions must also be met: the reduction of private traffic by seamlessly integrating public transport using sharing services and the reduction of the exploitation of scale effects and synergies by decarbonizing the energy sector. Sharing platforms and logistics services are helping drive the change to electric mobility by exploiting the advantages of the electric powertrain, repositioning vehicles from a consumer-owner market to a paradigm dominated by efficiency and the minimization of the total cost of ownership. The switch to electric mobility cannot be separated from the switch to renewable electricity: Not only is more renewable electricity necessary to power electric mobility, but integrating vehicles into the power grid can help the energy transition by providing smart energy storage services.[4]

The decarbonization of vehicle fleets can be realized by achieving a majority of battery electric vehicles (BEVs), with the most efficient vehicles using renewable electricity and fuel cell electric vehicles (FCEVs) employed for long-range and high-power applications. However, these technologies present a further problem for the transition away from the internal combustion engine (ICE): They rely heavily on rare metals, not all of

1 Raworth (Doughnut economics) 2017, pp. 1-27.
2 Intergovernamental Panel on Climate Change (Sixth Assessment Report) 2021, p. 13.
3 International Emission Trading Association (COP26-Summary-Report) 2021, pp. 1-10.
4 Kobiela et al. (CO2-neutral bis 2035: Eckpunkte eines deutschen Beitrags zur Einhaltung der 1,5°C Grenze) 2020, pp. 74-88.

which can be recycled in satisfactory quantities while achieving suitable grades of purity at a large scale and viable cost.[5] Even if these raw materials are ultimately sufficient for a worldwide shift to electric mobility, temporary shortages, and substantial price fluctuations are possible. This is detrimental to the rapid scaling up of BEV production. Nevertheless, the mining and processing of large quantities of such materials cause enormous environmental damage in the exporting territories, often translating to social distress.[6] Moreover, electric mobility does not imply sustainability unless the electricity used is from renewable sources and stringent conditions are met in the life cycle of vehicles and, in particular, batteries. The extraction and processing of the necessary raw materials cause greenhouse gas (GHG) emissions, as do the manufacturing processes of the electric powertrains and (in particular) their batteries.[7]

The results of BEV life cycle analyses are disputed because every study depends on different assumptions, which are valid or were valid at different times and in different places. However, because life-cycle assessment (LCA) studies rely fundamentally on input factors that have changed significantly in recent years, such as the increasing share of renewable energy in the energy mix of battery cell production plants, the decreasing amount of cobalt in lithium-ion cell chemistries, and the overall improvements in cell manufacturing processes, researchers admit that past studies overestimated the global warming potential (GWP) of battery production and that the general trend is towards a significant reduction.[8] In addition to the trends highlighted in these studies, other trends can be expected, such as increased battery cell quality and lifetime and improvements in recycling technology at a large scale.[9]

Apart from these trends in the battery field, electric mobility could greatly improve its sustainability and accelerate adoption rates by adopting circular economy strategies. This would decrease costs for users by 25-40% and provide many other benefits to society and the environment.[10] The most effective circular business models revolve around the concept of "product as a service," which fits perfectly with the leasing of vehicle fleets within an integrated mobility offer and aims to facilitate the recovery of used products, which remain the property of the same entity across most of their life cycle. This strategy requires a shift in vehicle development priorities, with a focus on efficiency, durability, and maintenance. Furthermore, it emphasizes the role of prolonging the product's life via reusing, repairing, and refurbishing.[11] Although many aspects of the circular economy are already applied to ICE vehicles, which are usually maintained

5 Belmer et al. (Brennstoffzellen und Batteriefahrzeuge) 2019, pp. 40-43.
6 Öko-Institut (Strategien für die nachhaltige Rohstoffversorgung der Elektromobilität.) 2017, pp. 47-53.
7 Koch et al. (Ökobilanz von Pkws mit verschiedenen Antriebssystemen) 2020, pp. 28-29.
8 Emilsson et al. (Lithium-ion Vehicle Battery Production) 2019, p. 5, pp. 30-33.
9 Drabik et al. (Prospects for electric vehicle batteries in a circular economy) 2018, p. 3, pp. 15-22.
10 Ellen MacArthur Foundation (Growth within a circular economy vision for a competitive Europe) 2015, pp. 54-68.
11 Accenture Strategy (Chancen der Kreislaufwirtschaft für Deutschland) 2017, pp. 15-23.

and repaired within an extensive ecosystem that includes both official and independent spare parts and service providers, BEVs are well-suited for use in circular business models because of their robustness against misuse, the long life of many components, and their integration in data networks. One peculiarity of BEVs is that used automotive batteries can be reused in other applications after their use in a vehicle, allowing used automotive batteries to significantly help the electricity grid and other sectors incorporate an increasing share of renewable energy.[12]

In recent years, the market share of BEVs and the size of BEV fleets have increased exponentially, enabling disruptive mobility services[13] and cost savings in last-mile logistics[14], allowing for used batteries to be employed in the stabilization of electric power grids[15], and seeing some vehicles original equipment manufacturers (OEMs) offer remanufactured battery packs.[16,17] Nevertheless, the circular economy for automotive batteries remains in its infancy, with goals such as widespread public acceptance and the reduction of production costs and safety risks having a higher priority in this relatively early phase than optimizing the environmental footprint, which is generally reserved for a later stage of technological maturity. By analyzing the currently available options for automotive battery life cycles, three key facts clearly identify the advantages of designing battery systems with longer lifetimes. First, the state of battery recycling is not yet mature enough to allow most materials to be recovered at a quality sufficient to produce new batteries at an industrial scale and have a positive effect on the environment and subsidy-free profits. Relatively new processes have proven to be very efficient at the laboratory scale but have not been scaled up, and other industrial processes have demonstrated rather disappointing material recovery rates while also requiring high energy inputs. Certain more innovative approaches being developed and tested need more time to become industrially available. Second, the re-manufacture of batteries is only possible and profitable for certain battery designs. These designs are suboptimal from other perspectives, such as lightweight construction, power density, and manufacturing costs. Widely adopted best practices for other products (i.e., predictive maintenance) are not used for automotive batteries, not even in fleets. Third, reuse in second-life applications, even when possible and practicable, still has some optimization potential.

[12] Fischhaber et al. (Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen) 2016, pp. 1-2.
[13] Sprei (Disrupting mobility) 2018, pp. 239-242.
[14] Ranieri et al. (A Review of Last Mile Logistics Innovations in an Externalities Cost Reduction Vision) 2018, p. 11.
[15] Bobba et al. (Sustainability assessment of second life application of automotive batteries (SASLAB)) 2018, pp. 12-60.
[16] Rematec (Nissan LEAF battery reman fact file) 2019, p. 1.
[17] Kiemel et al. (Kreislaufstrategien für Batteriesysteme in Baden-Württemberg) 2020, pp. 92.

1.2 Motivation

In general, prolonging battery life not only aligns with the goals of the circular economy but also is particularly beneficial during the current years of transition, having the potential to improve both the adoption of BEV and the environmental impact across the life cycles of those vehicles. In fact, the production of new batteries could be postponed to a time when production technology has a smaller environmental impact, making low-cost used batteries available to support the transition to renewable energy synergetically. In another cascade effect, the recycling at end of life (EoL) would be delayed by years and would happen using the more advanced (future) processes outlined in section 2.7.1.2.

Because automotive battery packs comprise many battery cells connected in a series, the aging of few cells determines the whole battery pack's lifespan. Mathew et al.[18] simulated the development of the state of health (SoH) over the lifespan of a battery pack and the effect of replacing single cells as they approach failure or at regular maintenance intervals. The authors simulated both lithium-iron-phosphate (LFP) and lithium-nickel-manganese-cobalt oxide (NMC) chemistries, modeling their equivalent circuit model (ECM) with stochastic variations of the parameters that affect capacity, internal resistance, and aging according to the measured variations on new cells due to manufacturing quality. They simulated load cycles with an average of 1C discharge and 80% to 20% depth of discharge (DoD), representing a fairly heavy-duty cycle. After each cycle, the simulation updated the ECM of each cell according to the aging model, such that after some cycles, the cells responded differently to the power demand, amplifying the differences between cells. At maintenance events, cells below a critical capacity value (SoH $<$ 85%) were replaced with new ones. They considered a battery pack made of 40 cells with a mean time to failure (MTTF) for cells of 4,000 cycles and different standard deviations of cell parameters (2%, which is plausible for the variation in capacity and 5%, which is plausible for resistance according to Paul et al.,[19] as well as 10%, which would correspond to a poor cell quality). The first key finding is that SoH can be maintained indefinitely at a certain level by replacing the cells at certain intervals. A lower cell variability would result longer maintenance intervals and in a higher number of cells being changed at maintenance events. With maintenance intervals of 2,000 cycles (equal to half of the MTTF), a variable number of cells between 3% and 30% are replaced, and the pack SoH drops below 80% shortly before maintenance events, at which it is brought up to above 85%. With a shorter maintenance interval of 1,000 cycles, the pack SoH oscillates between 82% and 85%. Differences in battery chemistry and reliability affect the maintenance intervals, but the general conclusion is that the lifetime of an automotive battery can be significantly increased a certain number of times by replacing relatively few cells.

[18] Mathew et al. (Simulation of lithium ion battery replacement in a battery pack for application in electric vehicles) 2017, p. 92.

[19] Paul et al. (Analysis of ageing inhomogeneities in lithium-ion battery systems) 2013, pp. 644-650.

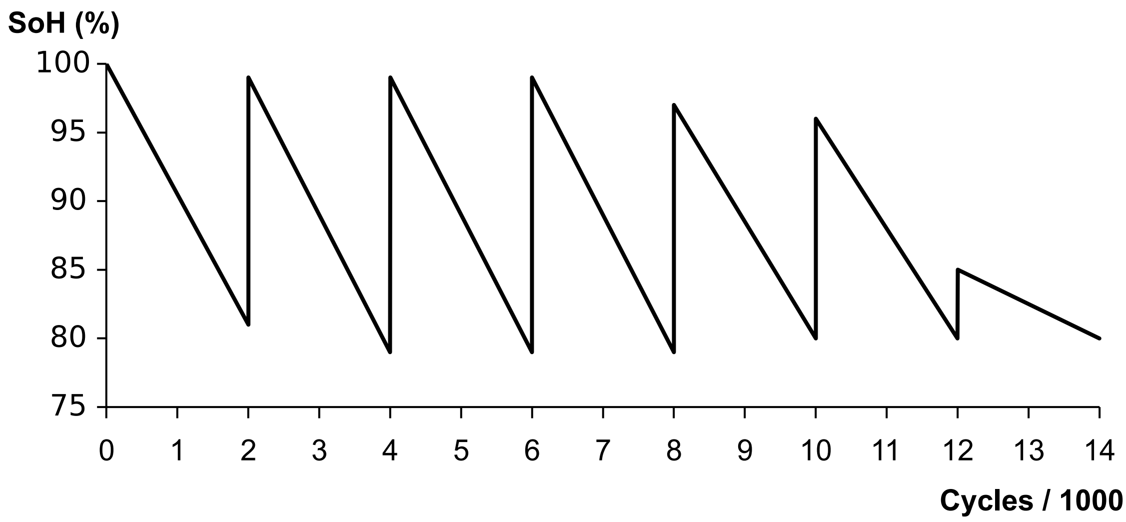


Figure 1.1: SoH of a battery pack made of 40 cells with a mean cyclical lifetime of 4,000 cycles and replacement of the cells with SoH < 85% (between 5% and 30% each time) every 2,000 cycles

As figure 1.2 shows, battery cells are responsible for most of the environmental impact caused by batteries,[20] as well as the costs.[21]

In suitable second-life applications, the maximization of the lifespan of each cell would be more beneficial than simply prolonging the lifespan of a battery pack. For that to be possible at a reasonable cost and without compromising performance, a new design strategy for battery packs and modules must be adopted.[22]

1.3 Objectives and scope of this work

Recognizing that the maintenance strategy proposed by Mathew et al. is only theoretical, the present work will outline a practicable design methodology for battery packs and modules. In addition to the use case of maintaining an automotive battery, the present work will focus on improving the reuse potential of single cells in automotive or other applications to minimize their environmental impact and decrease the battery pack's total operation costs. This work is valid under the assumption that cell properties have a certain spread that is determined by the quality of their manufacturing process. According to Mathew, if all cells had similar characteristics and aged similarly, an increasing number of cells would need to be replaced at each maintenance event, and

[20] Notter et al. (Contribution of Li-ion batteries to the environmental impact of electric vehicles) 2010, p. 6552.

[21] Kampker et al. (Elektromobilität) 2013, pp. 46-47.

[22] Kampker et al. (Evaluation of a Remanufacturing for Lithium Ion Batteries from Electric Cars) 2016, pp. 1392-1394.

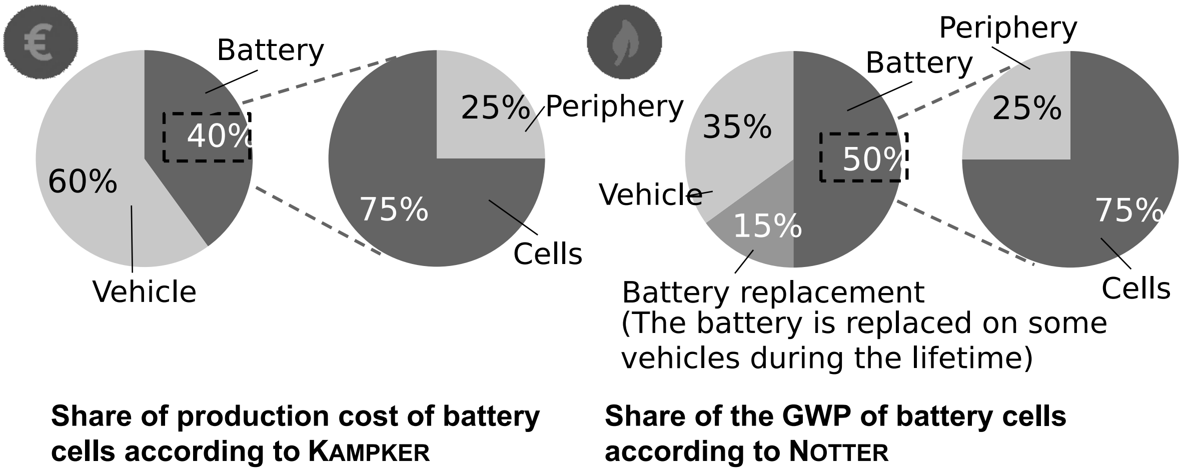


Figure 1.2: Share of GWP and production cost of battery cells with respect to a compact class EV battery

maintenance events could be performed less frequently, up to a point at which this strategy would become unnecessary. Improving cell manufacturing quality is a goal of cell manufacturing process design and quality control, and it is expected to improve as long as production technologies mature. Nevertheless, a very high grade of technological maturity is not anticipated soon because of the expectation that emerging technologies will frequently disrupt battery materials and formats.[23]

Thus, for the foreseeable future, battery production lines will continue to switch to new technologies before the older processes reach maturity. Therefore, this work does not focus on a particular chemistry but on a design methodology that can work consistently in response to the frequent changes in the specific requirements regarding materials and cell formats.

Thus, broadly speaking, this work intends to develop a design method for automotive battery packs that allows the residual value of each used cell to be exploited under the assumption that cells age differently within the same pack.

The proposed method must answer the following research questions:

- How can a life cycle maximize the residual value of depreciating cells instead of a durable product core?
- What does a product design workflow that enables multitudinous automatic assembly and disassembly up to the cell level look like?

First, the currently available approaches will be explained and their limitations will be analyzed. Then, a novel life cycle concept will be introduced that allows more value to be reaped and resources to be used more efficiently in products with architectures similar to that of automotive battery systems. A design method derived to fulfill the requirements

[23] Weber et al. (Roadmap integrierte Zell- und Batterieproduktion Deutschland) 2016, pp. 19-24.

of this life cycle will give way to small-scale demonstrations of the practical applications of this method. Finally, the need for further research will be outlined, especially in fields related to enabler technologies.

1.4 Epistemological framework

According to the schemata developed by Ulrich and Hill, this work exists within the framework of engineering sciences, which is positioned between the natural sciences (which explain empirical facts) and the social sciences (which consider human actions).[24] The integration of automotive batteries into a circular economy depends on solving technical problems and guiding the actions of economic actors and regulatory bodies.

Notably, the framework of the circular economy considers criteria, methods, and metrics that differ from those used by the linear economy. That is, according to Kuhn[25], because it has a different "locus of commitment," it can be considered a new paradigm. The present work must fulfill two criteria to contribute to a paradigm shift:

1. Use coherent methods and sources within the paradigm of the circular economy.
2. Produce results applicable to achieving solutions to problems other than those related to batteries.

The present work aims to constitute a "progressive problem shift" within the research program of ecodesign—in the Lakatos sense[26]— as applied to electric vehicle (EV) batteries, such that it follows a set of negative and positive heuristics to ensure coherence within that program.[27]

Negative heuristics must restrict the validity of theories to the widest defensible field. In this work, the core must be applicable to all possible EV battery architectures (i.e., made of many single cells, independent of their joining technologies), provided that they fulfill some core requirements, and independent of their performance, aging, and chemistry, such that they avoid making exceptions for these characteristics. These characteristics will be accounted for as generalizations in the fields of product architecture, reliability, joining technologies, and engineering design.

The positive heuristics are derived from the systems theory proposed by Ulrich[28],

1. The problems of applied sciences are generated not by the validity of the underlying explanatory theories but by the applicability of their models to practical problems.

[24] P. Ulrich et al. (Wissenschaftstheoretische Grundlagen der Betriebswirtschaftslehre) 1976, p. 305.
[25] Kuhn (The Structure of scientific revolutions) 1962, pp. 3-9.
[26] Lakatos (Falsification and the Methodology of Scientific Research Programmes) 1970, pp. 185-191.
[27] Lakatos (Falsification and the Methodology of Scientific Research Programmes) 1970, pp. 191-194.
[28] H. Ulrich (Anwendungsorientierte Wissenschaft) 1982, p. 8.

2. These kinds of practical problems do not necessarily belong to any scientific discipline but are often interdisciplinary.

3. The purpose of applied sciences is not to explain reality but to realize a new reality.

4. The measure of the success of applied sciences is not found in the truth of its theories but in their utility in practical applications.

5. Because of the last point, the applied sciences are not free of ethical value, with the criteria describing their success corresponding to ethical judgments.

If these heuristics are met without exception, the present work should aid proposals for alternative designs, which are neither inherently more expensive nor representative of performance or safety issues, because these proposals would run contrary to recent developments.

1.5 Structure of this work

This work's structure derives from the applied research methodology developed by ULRICH. In chapter 2, the process begins with a description of the function and properties of batteries and the current state of industrial practice. This inductive phase of knowledge aggregation is guided by noting extant products and relevant project experience in the industry and in research. This serves the function of identifying potential problems or areas of improvement, which would further the research objectives, the solution of which would ensure the practical relevance of the progress shift achieved by the research effort. After identifying the practical problems, they should be formulated within a theoretical framework that facilitates their solution. This phase is deductive and begins with a review of the literature in the relevant fields of life cycle engineering and engineering design (in chapter 3) to define the limitations of current models, which are designed to solve practical problems and define the requirements of appropriate theories and models. According to the heuristics of LAKATOS, this ensures robustness and applicability. Building on those heuristics and the specific requirements of automotive batteries, an extended design methodology is outlined in chapter 4 and then detailed in chapter 5, which also presents the proposed methodology's steps in detail. The proposed methodology is then applied to the practical problem in the context of examples drawn from battery designs in chapter 6. Chapter 6.4 comprises a critical discussion of the results obtained and the identification of the work's limitations and the implications for future work. Chapter 7 summarizes the key results and assesses their significance for the practical problem of interest. This structure is summarized in figure 1.3.

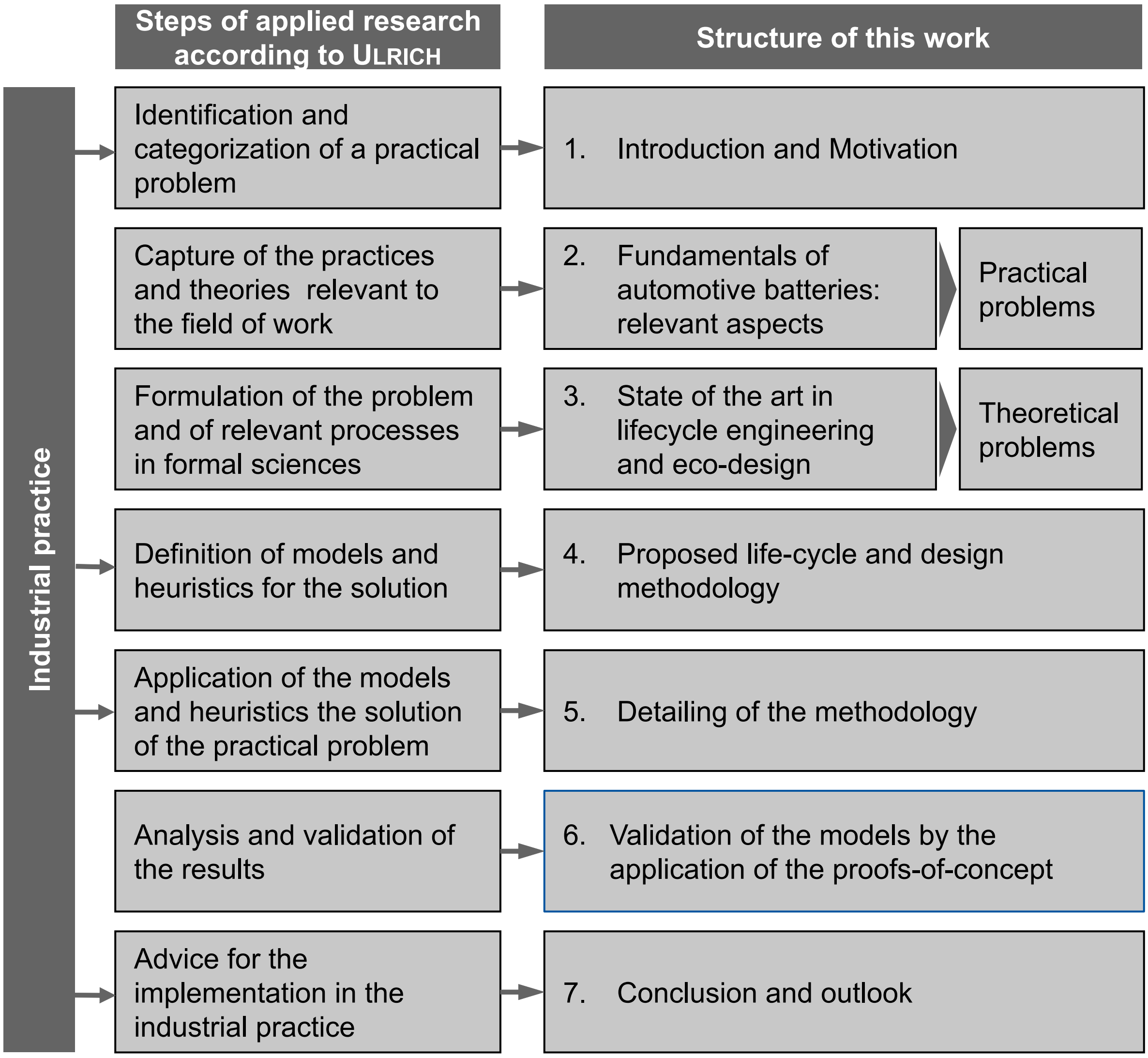


Figure 1.3: The structure of this work in relation to the applied-research methodology developed by Ulrich

2 Fundamentals of the life cycle of automotive batteries

This chapter provides an overview of automotive battery systems, beginning by detailing the working principles, common cell designs, reliability properties, battery pack designs, and life-cycle options. Given the focus on understanding how the properties of batteries influence their life cycle, the processes at the EoL are also reviewed. The analysis of the key functions and the components that perform those functions, shown in table 2.1, follow the framework of PAHL-BEITZ[29].

Automotive battery systems generally comprise numerous single cells, a structural and sealed housing, several high voltage (HV) connections, control electronics with the necessary wiring harness and sensors, and (often) a thermal management system.[30,31] Because the cells perform the core function of the batteries, the next sections will summarize the most relevant aspects of cell chemistry to understand their influence on battery system design, reliability, and life cycle. The other components will be analyzed with respect to practical implementations in the context of battery designs.

2.1 Cell chemistry

Generally, lithium-ion battery cells are constituted by metallic current collectors that are coated with active materials. Active materials are classified primarily by how they interact with lithium ions: Either the ions bind inside an existing material structure (intercalation) or they react with the active materials, completely changing their structure (conversion).[32]

$$A^{n+} + ze^{-} + mX \rightleftharpoons AX_m \tag{2.1}$$

Equation 2.1 represents the general formula of an intercalation reaction, where A is a working ion (e.g., Li^{+}, Na^{+}, or Mg^{2+}), che is an electron, X is an anion, such as an oxide of one or more transition metals (e.g., CoO_2 or $Ni_{0.8}Mn_{0.1}Co_{0.1}$, in the case of a NMC811 cathode) and z is a number required for charge balance.

[29] Feldhusen et al. (Pahl/Beitz Konstruktionslehre) 2013, p. 297.
[30] Kampker et al. (Elektromobilität) 2018, p. 58.
[31] Köhler (Lithium-ion battery system design) 2018, pp. 93-99.
[32] Hannah et al. (On the Balance of Intercalation and Conversion Reactions in Battery Cathodes) 2018, pp. 4-7.

Functions	**Components**
Convert chemical into electrical energy and vice versa	Battery cells
Collect current from cells	HV busbars
Contain the cells and provide necessary pressure on cells	Module structure
Compensate stack tolerance and cell expansion	Gap pad
Isolate cell housings from one another	Gap pad or isolation foil
Collect current from cells	HV busbars
Connect busbars to cells	Module terminals
Provide ingress protection	Housing
Compensate pressure and humidity inside the housing	Compensation membrane
Provide exit for venting gases	Venting valve
Provide protection against touching HV parts	Safety covers
Detect opening of housing and safety covers	High voltage interlock circuit (HVIL)
Collect voltage and temperature measurements from cells	Low voltage (LV) wiring harness
Measure cells voltage and temperature	Cells supervising circuit (CSC)
Measure current at terminals	Current sensors
Measure isolation resistance	Isolation monitor
Provide active disconnection	Contactors
Provide passive over-current protection	Fuses
Avoid over-current during connection and disconnection	Pre-load circuit
Monitor sensors and enact control logic	Battery management controller (BMC)
Transfer heat from or to the cells	Cold plate
Ensure heat conductivity between cells and cold plate	Thermal interface material (TIM)

Table 2.1: Functions of the components of a battery system

The case of a lithium polymer battery is the simplest to illustrate: During the discharge process, Li^+ ions are released from the layered structure of graphite, causing its volume to slightly decrease:

$$LiC_m \rightleftharpoons Li^+ + ze^- + C_m \tag{2.2}$$

At the cathode, the Li^+ ions intercalate inside the crystalline structure of cobalt oxide, causing a slight volume increase:

$$Li^+ + e^- + CoO_2 \rightleftharpoons LiCoO_2 \tag{2.3}$$

In conversion chemistry, the reaction products have completely different properties from the reaction components:

$$A^{n+} + ze^- + mX \rightleftharpoons \sum_i A_p^i X_q^i \tag{2.4}$$

Equation 2.4 represents the general formula of a conversion, where the working ion A (e.g., Li^+, Na^+, or Mg^{2+}) is oxidized by an anion X (e.g., O or S) and forms a series of compounds. A special example of the conversion reaction happens with metallic lithium anodes, where lithium is decomposed into ions and the active material is consumed during discharge and deposited during the charge.

$$Li \rightleftharpoons Li^+ + e^- \tag{2.5}$$

Two examples of conversion reactions happen at the cathode of a lithium-oxygen battery, where metallic lithium is oxidized by atmospheric oxygen and becomes a passivization lithium oxide layer, limiting capacity and power at a low state of charge (SoC):[33]

$$2\,Li^+ + 2\,e^- + O_2 \rightleftharpoons Li_2O_2 \tag{2.6}$$

In a Li-S cathode, an increasing amount of lithium is oxidized by the same quantity of sulfur, and the material structure changes completely from S_8 to Li_2S_8, Li_2S_6, Li_2S_4, Li_2S_2, all the way to Li_2S, causing a major change in volume:

$$16\,Li^+ + 16\,e^- + S_8 \rightleftharpoons 8\,Li_2S \tag{2.7}$$

To summarize, on the one hand, conversion chemistry allows for more energy density and is subject to shorter lifespans because the structure of the active materials is not stable. Hence, its application is confined to non-rechargeable batteries and high-performance batteries with shorter numbers of cycles. On the other hand, intercalation materials demonstrate smaller volume changes, connoting stability over a longer number of cycles at the expense of the extra cost and weight of the materials.[34]

[33] Wunderlich et al. (Anomalous Discharge Behavior of Graphite Nanosheet Electrodes in Lithium-Oxygen Batteries) 2019, pp. 6-11.

[34] Yu et al. (Understanding Conversion-Type Electrodes for Lithium Rechargeable Batteries) 2018, p. 273, pp. 279-280.

Conversion chemistry has been briefly explained because it will be present in the upcoming generation of batteries with solid electrolytes and metallic lithium at the anode[35]. This will have a limited effect on the overall battery life cycle, only impacting chemical processes involving new materials.

The presence of cobalt and the evolution of intercalation materials to increase lifespan are necessary because of the mechanical stress at the micro-scale due to the volume change of the crystalline structure of active materials: the state of the crystalline structures influence the entropy of the chemical reactions.[36,37,38,39,40,41,42,43,44]

To summarize, in cell design, it is critical that active materials have a large area and limited thickness, ideally applied as a coating for metallic current collectors, which must be stable within the potential windows of the cathode and the anode.[45,46] Usually, the positive terminal is called the "cathode," and the negative terminal is called the "anode," even if this is true only during the discharge process, during which electrons leave the anode, such that the current conventionally flows from the cathode (plus pole) to the anode (minus pole). Because of their good electrical conductivity and electrochemical potential, aluminum is used at the cathode while copper is used at the anode.[47]

The intrinsic need to perform a chemical reaction with high power density requires that the electrodes be at a close distance and facing each other in large areas. Accordingly, different materials must be packaged into a limited space, which has implications for the life cycle, as explained in later sections.

35 Hatzell et al. (Challenges in Lithium Metal Anodes for Solid-State Batteries) 2020, p. 929.

36 J. H. Lee et al. (Battery dimensional changes occurring during charge/discharge cycles - thin rectangular lithium ion and polymer cells) 2003, pp. 834-837.

37 H. Li (Is Cobalt Needed in Ni-Rich Positive Electrode Materials for Lithium Ion Batteries?) 2019, p. A429, p. A437.

38 U. H. Kim et al. (Pushing the limit of layered transition metal oxide cathodes for high-energy density rechargeable Li ion batteries) 2018, pp. 1-2.

39 U. H. Kim et al. (Quaternary Layered Ni-Rich NCMA Cathode for Lithium-Ion Batteries) 2019, p. 2.

40 W. Li et al. (High-Nickel NMA: A Cobalt-Free Alternative to NMC and NCA Cathodes for Lithium-Ion Batteries) 2020, p. 1.

41 Park et al. (Improved Cycling Stability of $Li[Ni_{0.90}Co_{0.05}Mn_{0.05}]O_2$ through Microstructure Modification by Boron Doping for Li-Ion Batteries) 2018, p. 1.

42 Ryu et al. (Suppressing detrimental phase transitions via tungsten doping of $LiNiO_2$ cathode for next-generation lithium-ion batteries) 2019, p. 2, p.9.

43 Ryu et al. ($Li[Ni_{0.9}Co_{0.09}W_{0.01}]O_2$: A New Type of Layered Oxide Cathode with High Cycling Stability) 2019, p. 1, pp. 5-6.

44 Sun et al. (Beyond Doping and Coating: Prospective Strategies for Stable High-Capacity Layered Ni-Rich Cathodes) 2020, pp. 1137-1143.

45 Lain et al. (Design Strategies for High Power vs. High Energy Lithium Ion Cells) 2019, pp. 9-10.

46 Korthauer (Lithium-ion batteries) 2018, p. 57.

47 Korthauer (Lithium-ion batteries) 2018, pp. 104-106.

2.2 Cell design and formats

Even though cells alone can store electrochemical energy, it remains impracticable to use a single huge cell to store the necessary energy, and the size of cells is limited by physical factors and production processes.[48]

In production terms, current collectors are coated with active materials and then stacked in pairs of anodes and cathodes with a separator placed in between them before they are put into cell housing such that the battery poles are externally accessible.[49,50] Moreover, some mechanical pressure must be exerted on the stack to maintain contact between the components and prevent deformation and delamination.[51] Cells are differently classified according to the type of housing: cylindrical, prismatic, and pouch, each of which is available in different formats.[52]

In round cells, the current collectors and separators are rolled around a cylindrical core, usually made of plastic, in what is called an electrode assembly or jelly roll.[53]

The jelly roll is then inserted into cylindrical housing, usually made of deep-drawn stainless steel or (less frequently) nickel-plated steel. However, other metals, such as aluminum alloys, can be used, provided appropriate strategies to avoid galvanic corrosion are adopted.[54]

The negative current collector is then welded to the housing while the plus pole is welded to a cap, which contains a current interruption device (CID) that melts in the case of over-current to deactivate the cell in the event of a short circuit.[55]

The plus and minus poles are separated by a plastic element contained in the cap that mostly comprises polypropylene (PP) or polyethylene (PE) or (less often) polyamide-6 (PA-6) or polyvinylchloride (PVC).[56]

The electrode sheets and the housing are usually connected by metal strips called tabs, which can cause thermal non-homogeneity and failure in high-power batteries.[57] For this reason, Tesla proposed a tab-less cell design in their 4680 cell format with an estimated capacity of 9,000 mAh.[58]

The manufacturing process for round cells with a single tab per electrode appears in figure 2.1.

48 Chu et al. (Battery cell design and method of its construction) 2007, p. 1.
49 Heimes et al. (Produktionsprozess einer Lithium-Ionen-Batteriezelle) 2018.
50 Korthauer (Lithium-ion batteries) 2018, pp. 105-111.
51 Cannarella et al. (Stress evolution and capacity fade in constrained lithium-ion pouch cells) 2014, p. 750.
52 Korthauer (Handbuch Lithium-Ionen-Batterien) 2013, pp. 112-116.
53 Korthauer (Handbuch Lithium-Ionen-Batterien) 2013, pp. 113-114.
54 Vargel (Galvanic corrosion) 2020, pp. 296-298, pp. 306-307, pp. 310-312.
55 W. Li et al. (Comparison of current interrupt device and vent design for 18650 format lithium-ion battery caps: New findings) 2022.
56 M. Herrmann (Packaging - Materials review) 2014, pp. 123-132.
57 Yao et al. (Tab Design and Failures in Cylindrical Li-ion Batteries) 2019, p. 24082.
58 Evannex (An Up-Close Look At Tesla's 4680 Battery Cell Production) 2021, p. 1.

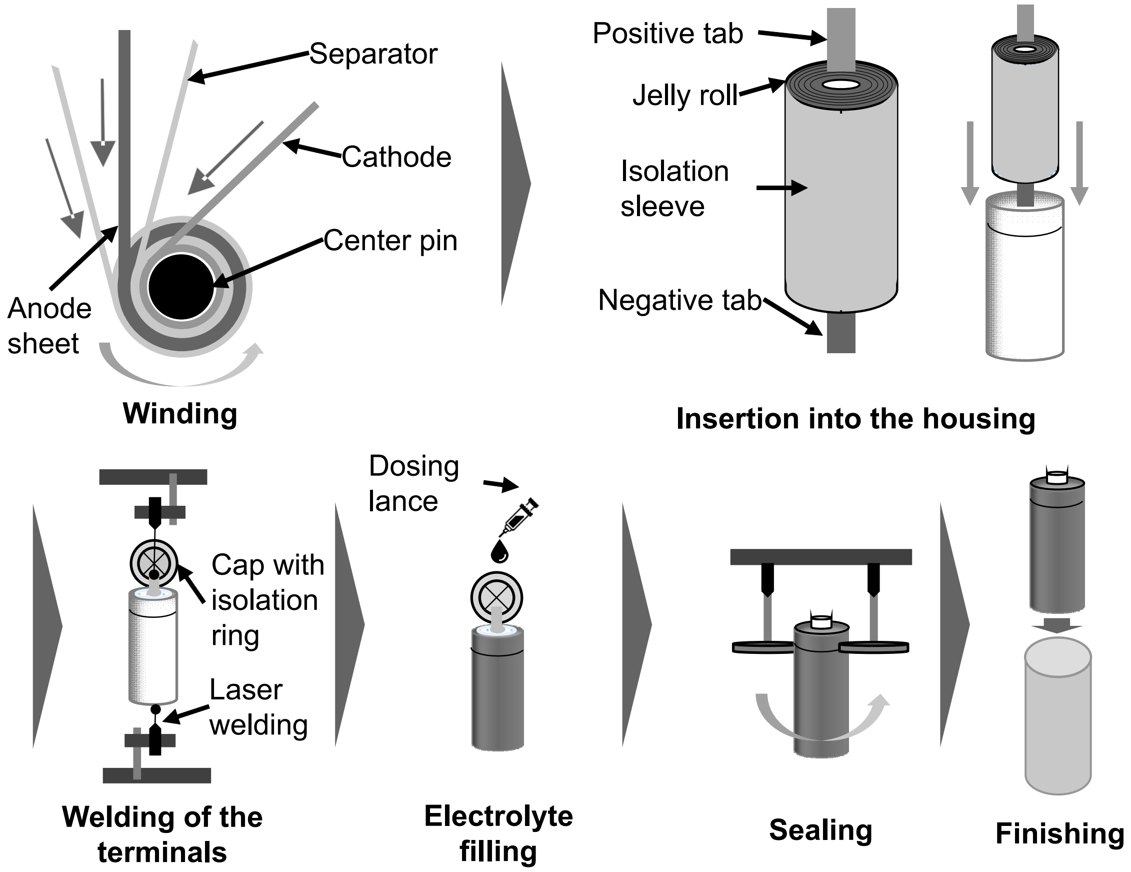


Figure 2.1: Manufacturing process of round cells

	HEV	PHEV1	PHEV2	BEV1	BEV2
Capacity (Ah)	>5	>20	>20	>40	>60
Height (mm)	85	85	91	115	115
Width (mm)	120	173	148	173	173
Thickness (mm)	12.5	21	26.5	32	45

Table 2.2: Standard formats of prismatic cells

Round cell formats are standardized: Most are 18650 (18 mm in diameter and 65 mm in height, with a capacity between 3,000 and 3,600 mAh) or 21700 (21 mm in diameter and 70 mm in height, with a capacity between 4,000 and 5,000 mAh), and the tendency toward bigger formats is limited by the thermal dissipation. The thickness of the electrode coating is limited to avoid delamination during the winding process.[59] Structurally, the cylindrical housing reacts symmetrically against the internal pressure, making the structure very stable.[60,61] From a thermal perspective, the safety device at the plus pole acts as an insulator, such that the cells can be cooled on the side surface and best from the minus pole.[62]

Prismatic cells were designed to address the size limitation of round cells and improve packaging. The traditional design sees the current collectors and separator wound in a large jelly roll that is then flattened and inserted into the rectangular stainless-steel case. Both poles are on the top and connected by tabs to the current collectors, with a safety device present at the plus pole. Because the winding process increases the mechanical stress at the bending radii and the current distribution, heat production is not uniform. This has life-cycle repercussions in high-power applications, so prismatic cells are most often used in high-energy contexts.[63]

To overcome these limitations, a stacking process has been developed as an alternative to winding, where the current collectors are cut to the size of the housing and subsequently stacked with the separator, as in the Grepow design.[64]

The manufacturing process of prismatic cells in a wound jelly roll appears in figure 2.2.

Prismatic cells are available in standardized formats tailored to the specific requirements of the high-power applications typical of hybrid electric vehicles (HEVs), the high-energy applications typical of BEVs, or the intermediate applications associated with plug-in hybrid electric vehicles (PHEVs), as shown in table 2.2.[65] On the basis of an

[59] Musk (Tesla Battery Day) 2020.
[60] Waldmann et al. (18650 vs. 21700 Li-ion cells – A direct comparison of electrochemical, thermal, and geometrical properties) 2020, pp. 4-8.
[61] Darcy (Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells) 2018, p. 53.
[62] Jeon et al. (Thermal modeling of cylindrical lithium ion battery during discharge cycle) 2011, p. 2977.
[63] Korthauer (Lithium-ion batteries) 2018, p. 220.
[64] Grepow (What is Cell Stacking Technology?) 2019, p. 1.
[65] Deutsches Institut für Normung (DIN 91252-11) 2016.

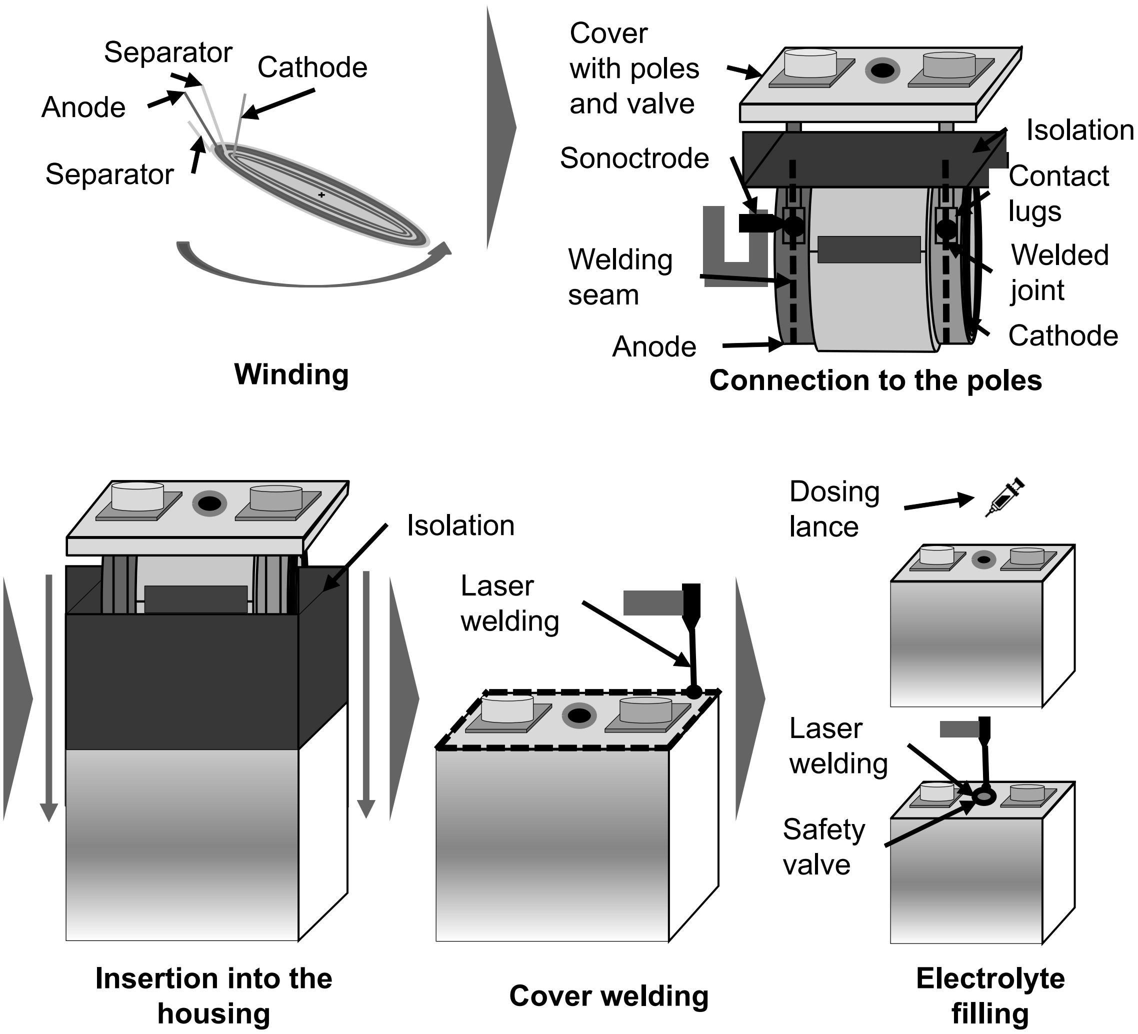


Figure 2.2: Manufacturing process of prismatic cells

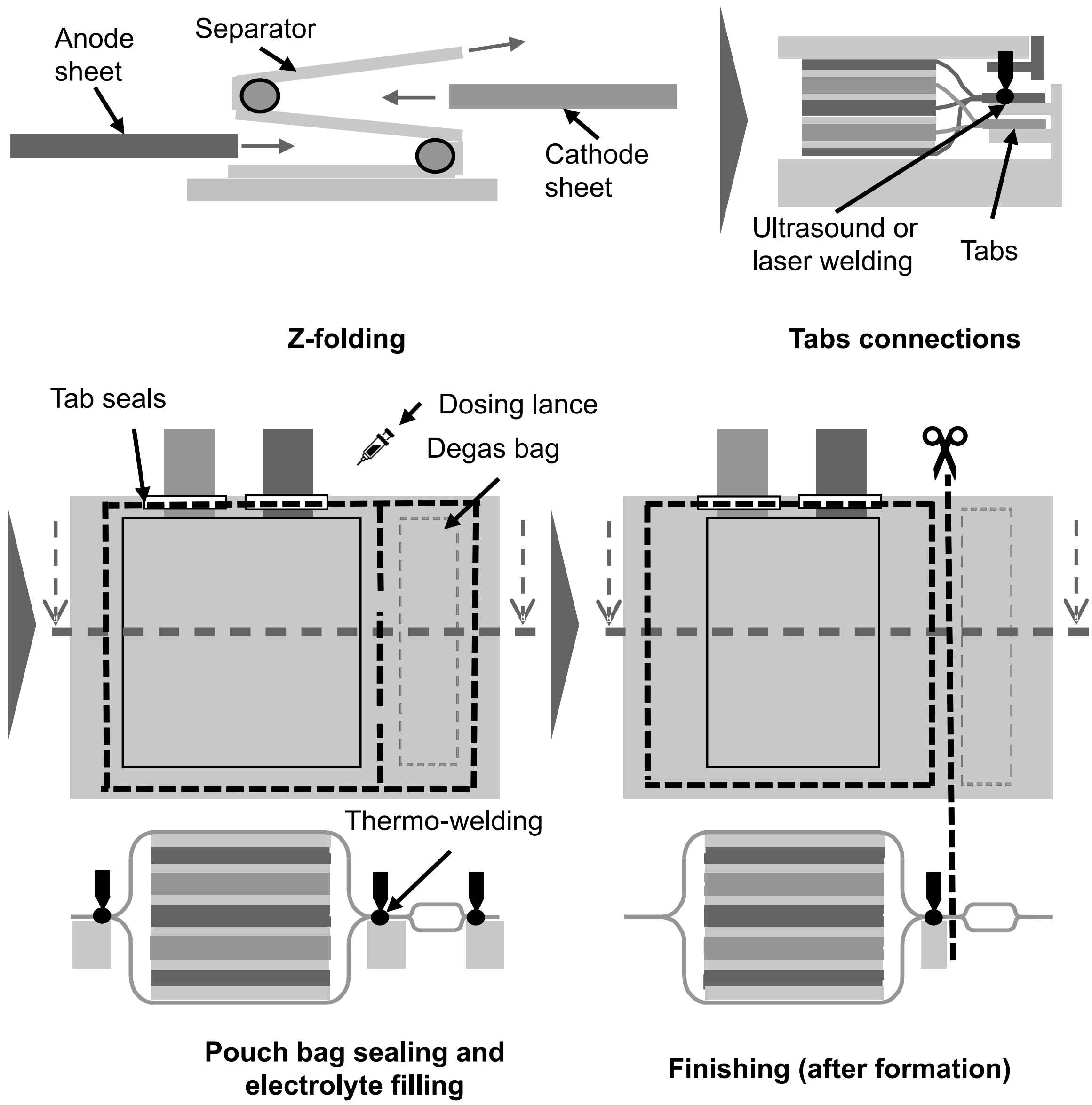


Figure 2.3: Manufacturing process of pouch cells

evaluation by the Fraunhofer Institute's Battery Alliance—based on production costs, energy density, and safety aspects—the BEV2 format shown in table 2.2 represents the best and also most widespread tradeoff. According to the same study, the same criteria are met slightly better by pouch cells.[66]

In pouch cells, the electrode sheets are flat and stacked together, and internal short circuits are prevented by a separator folded on both sides of each sheet.

All electrodes are connected in parallel at the cell terminals, also called tabs.

The electrode stack is contained in a pouch bag made of plastic-coated aluminum foils. The aluminum acts as a moisture barrier and the plastic, PP, PE, or polyamide

[66] Hettesheimer et al. (Entwicklungsperspektiven für Zellformate von Lithium-Ionen-Batterien in der Elektromobilität) 2017, pp. 14-16.

(PA), adds resistance to tears, serves as insulation, and protects against corrosion.[67,68]

The pouch bag is thermo-welded along the perimeter and sealed around the tabs by thermo-welded plastic strips.

The manufacturing process of pouch cells is shown in figure 2.3.

The pouch bag material is resistant to corrosion even in unusual cell designs with aqueous electrolytes, where the electrodes are not connected in parallel but stacked in series as bipolar plates to achieve higher per-cell voltage.[69,70] The bipolar plates designs most commonly features solid-state electrolytes.[71]

2.3 Aging of battery cells

Battery cells are subject to degradation because of various mechanisms, some of which depend on battery usage (referred to as ”cyclic aging”) and some of which depend on the time since manufacture and the storage conditions (referred to as ”calendar aging”).[72] These mechanisms are at the root of battery failures, they need to be understood to predict and increase battery lifespans and devise strategies best utilize the residual matter of spent batteries in circular economies.

2.3.1 Modeling battery aging

According to a review by Barre et al.[73], battery aging can be modeled in different ways. Molecular and electrochemical models are the most detailed and rely on solving partial differential equations of physical phenomena across the electrode plane. Aging mechanisms are modeled on normal functions, connoting high complexity, meaning that these models require the most computing power and largest numbers of parameters to be identified by means of complex experimental methods.[74] These models are used for scientific purposes[75], with those created for online use in battery management systems (BMSs) using simplified differential equations and correct prediction errors against

[67] Korthauer (Lithium-ion batteries) 2018, p. 27, p.217.
[68] Svens et al. (Li-Ion Pouch Cells for Vehicle Applications — Studies of Water Transmission and Packing Materials) 2013, p. 408.
[69] Korthauer (Lithium-ion batteries) 2018, p. 221.
[70] Evanko et al. (Stackable bipolar pouch cells with corrosion-resistant current collectors enable high-power aqueous electrochemical energy storage) 2018, pp. 1-3.
[71] Quantumscape (Solid-State Battery Landscape) 2021, p. 1.
[72] Barré et al. (A review on lithium-ion battery ageing mechanisms and estimations for automotive applications) 2013.
[73] Barré et al. (A review on lithium-ion battery ageing mechanisms and estimations for automotive applications) 2013, pp. 682-683.
[74] Waldmann et al. (Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study) 2014, pp. 134-135.
[75] Hariharan et al. (Mathematical Modeling of Lithium Batteries) 2018, p. 63.

frequent measurements of state variables.[76] Less-detailed models based on equivalent electrical circuits[77] have their parameters identified by empirical laws and electrical, non-destructive tests.[78,79] These models are based on fitting general electro-chemistry laws with measured parameters,[80] with these parameters dependent on many variables, including temperature[81,82] and change over the battery's lifespan, such that the evolution of such parameters can hint at the SoH.[83]

For models based on lifespan prediction and diagnostics, which can be performed onboard vehicles, the initial values of the parameters of each cell must be known, and certain other parameters must be estimated by the speed of degradation of the relevant measures. For example, the time response to current pulses depends on the SoH, among many other variables.[84]

2.3.2 Calendar aging

Calendar aging is caused by the chemical degradation of cell materials during storage. It is modeled most simply as a kinetic reaction approximated by the Arrhenius equation 2.8, where t is the reaction rate, E_a is a parameter that needs to be determined experimentally for each cell type, R is the universal gas constant, and T is the cell temperature:

$$t = A \exp\left(\frac{-E_a}{RT}\right) \tag{2.8}$$

This equation is appropriate for describing an experimental setup in which the lifespan is defined by the decay of a relevant characteristic (e.g., the capacity) and the temperature is constant. To estimate calendar aging under real conditions, E_a must be determined experimentally and then the equation must be integrated over time to account for variations in temperature across the observation time.[85,86] This presents two

76 J. Lee et al. (Li-ion battery SOC estimation method based on the reduced order extended Kalman filtering) 2007, p. 9.
77 Kutluay et al. (A New Online State-of-Charge Estimation and Monitoring System for Sealed Lead–Acid Batteries in Telecommunication Power Supplies) 2005, p. 1315.
78 Rong et al. (An analytical model for predicting the remaining battery capacity of lithium-ion batteries) 2006, p. 451.
79 Jongerden et al. (Battery Aging, Battery Charging and the Kinetic Battery Model: A First Exploration) 2017, p. 88.
80 Hariharan et al. (Mathematical Modeling of Lithium Batteries) 2018, pp. 124-125, p. 128.
81 Lin et al. (A lumped-parameter electro-thermal model for cylindrical batteries) 2014, pp. 2-3.
82 Huria et al. (High fidelity electrical model with thermal dependence for characterization and simulation of high power lithium battery cells) 2012, p. 1.
83 S. Li et al. (Model-in-the-Loop Testing of SOC and SOH Estimation Algorithms in Battery Management Systems) 2017, p. 1.
84 Bernardi et al. (Analysis of pulse and relaxation behavior in lithium-ion batteries) 2011, p. 426.
85 Bloom et al. (An accelerated calendar and cycle life study of Li-ion cells) 2001, p. 246.
86 Thomas et al. (Rate-based degradation modeling of lithium-ion cells) 2012, pp. 379-380.

problems for the diagnostics of used cells. On the one hand, the variability of E_a over single cells—because of differences in manufacturing quality—produces calculation errors; on the other hand, the residual lifespan of a cell subject to calendar aging cannot be computed without knowing the temperature history since the cell was manufactured.

2.3.3 Cyclical aging

Cyclical aging is more complex, dependent not only on external factors but also on battery usage. The main factors considered are typically temperature, the number of equivalent cycles, the DoD, and the voltage, current, and mechanical stress.[87] In particular, the mechanical pressure on the stack varies during a battery's lifespan and fluctuates at every cycle. High-energy cell design with thicker active material coating, as used in EVs, shows higher volume expansion and, therefore, higher fluctuations in mechanical stress. Experiments have shown that high mechanical pressure leads to higher pressure fluctuations and accelerated cyclical aging, further accelerating mechanical pressure.[88] Pinson et al. proposed a model that considers the growth of the solid-electrolyte interface (SEI) as the main cause of cyclical aging, as observed by Zhang et al..[89] Pinson et al. predicted the effects of mechanical stresses on anodes with high levels of mechanical stress, such as silicon-rich materials. In this case, the SEI fractures under substantial mechanical stress, and a new SEI layer grows on the newly exposed regions.[90] Another cyclical aging mechanism of concern is lithium plating, which describes metallic lithium deposition at the anode during charging (instead of intercalation). This happens when the necessary over-potential for the intercalation reaction is outside the intended boundaries because of a combination of high requested current and low temperature.[91,92,93] Cordoba-Arenas et al. developed an aging model that considers SEI growth and other mechanisms in PHEV batteries for online use in BMSs.[94] The models for cyclic aging generally assume damage accumulation for each charge-discharge cycle, which is computed by gain factors that depend on the correct parameter identification. If an error is present in the parameters, the lifespan prediction

[87] Sarre et al. (Aging of lithium-ion batteries) 2004, pp. 67-71.

[88] Cannarella et al. (Stress evolution and capacity fade in constrained lithium-ion pouch cells) 2014, p. 745.

[89] Y. Zhang et al. (Cycling degradation of an automotive LiFePO4 lithium-ion battery) 2011, p. 1513.

[90] Pinson et al. (Theory of SEI Formation in Rechargeable Batteries: Capacity Fade, Accelerated Aging and Lifetime Prediction) 2013, pp. A248-249.

[91] Petzl et al. (Lithium plating in a commercial lithium-ion battery – A low-temperature aging study) 2015, pp. 804-807.

[92] Ecker (Lithium plating in lithium-ion batteries) 2016, pp. 137-140.

[93] Legrand et al. (Physical characterization of the charging process of a Li-ion battery and prediction of Li plating by electrochemical modelling) 2014, pp. 208-209.

[94] Cordoba-Arenas et al. (Capacity and power fade cycle-life model for plug-in hybrid electric vehicle lithium-ion battery cells containing blended spinel and layered-oxide positive electrodes) 2015, p. 482.

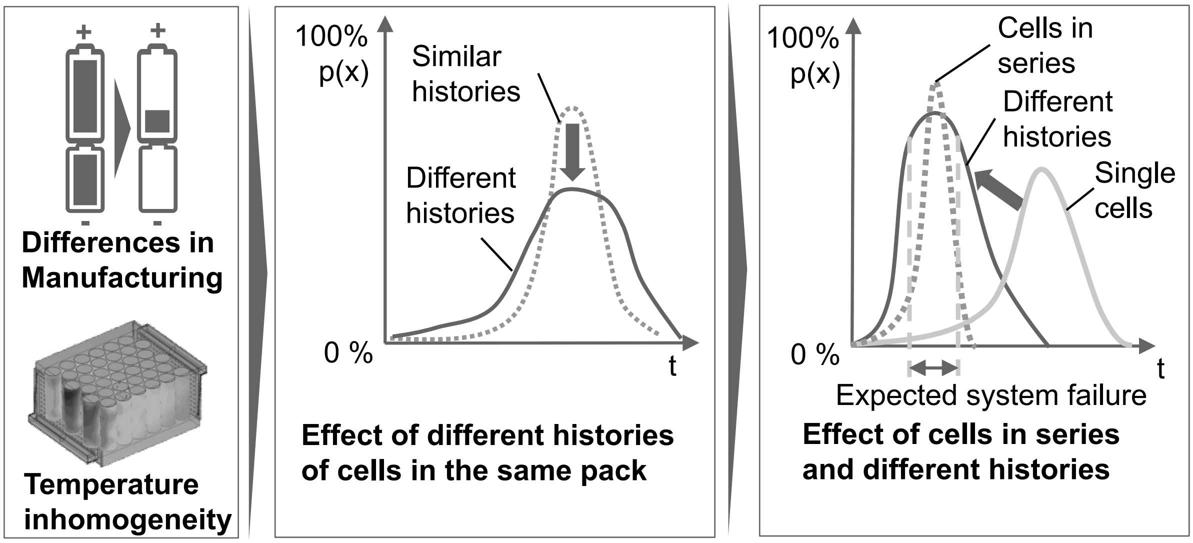


Figure 2.4: Effect of differences in cell quality, use history, and number of cells on the reliability of a battery system

will become increasingly less accurate over the battery's lifespan.[95] Accordingly, algorithms such as extended Kalman filter (EKF) and artificial neural networks have been applied to correctly identify model parameters. However, as in the case of calendar aging, the lifespan of a battery cell can only be predicted if its complete history has been recorded.[96]

2.3.4 Aging non-homogeneity between cells

Some factors that affect aging are not homogeneous either within a single cell or between different cells, as represented in figure 2.4. This is due to differences in cell manufacturing quality, how cells are connected, and the position of cells inside the battery pack. Notably, in a battery pack where all cells are connected in series and therefore cycled between the same voltages, the differences in capacity between cells results in a higher DoD for cells with less capacity, which would then age faster.[97] The other factors are mechanical stress and temperature.[98] Paul et al. considered the thermal effects of differences in new cells due to manufacturing process fluctuations on both calendar and cyclic aging (independent of each other). The authors used empirical laws from cell

95 C. Chen et al. (Prognostics of lithium-ion batteries using model-based and data-driven methods) 2012, p. 1.

96 S. Li et al. (Model-in-the-Loop Testing of SOC and SOH Estimation Algorithms in Battery Management Systems) 2017, p. 3.

97 Dubarry et al. (Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations) 2019, p. 19.

98 Hunt et al. (Surface Cooling Causes Accelerated Degradation Compared to Tab Cooling for Lithium-Ion Pouch Cells) 2016, pp. A1846.

manufacturers in a dual-polarization[99] equivalent circuit.[100] They simulated the battery lifespan of a battery pack made of 96 cells with relatively small differences in parameters (1.3% deviation in capacity, 5.8% deviation in direct current resistance (DCR), and a spread of aging parameters based on empirical measurements) and found that the consequent temperature differences (4-7°K) and load differences caused significantly faster aging in some cells during a simulation of the driving cycle with only 10% DoD of an HEV. The difference in capacity across cells increased to 11%.[101] BAUMHOFER ET AL. confirmed experimentally the substantial impact on aging behavior of between-cell differences caused by manufacturing.[102]

2.4 Reliability engineering

The aging and failure mechanisms of battery cells determine the reliability of battery systems. To understand the life cycle of battery systems, this section explains the basis of reliability and discusses how the EoL of a battery system is defined.

2.4.1 Reliability of physical systems

All physical systems are subject to failure, traditionally defined as "the termination of a system's capability to perform its function."[103] After a failure has occurred, the system is in a fault state, incapable of performing its function. DEL FRATE introduced this definition to the context of life cycles, measuring performance degradation and loss of function against the user's expectations.[104] Failures occur at different probabilities over the lifespan of a system or product:

- Soon after manufacturing, certain common types of failures are caused by evident manufacturing defects that might not have been detected at the end of the production process.

- During the product's lifespan, certain random failures occur with the same probability due to undetected small defects with effects resulting in failure at a later, unpredictable time.

[99] Stroe et al. (Generalized Characterization Methodology for Performance Modelling of Lithium-Ion Batteries) 2016, p. 1.
[100] Paul et al. (Analysis of ageing inhomogeneities in lithium-ion battery systems) 2013, p. 650.
[101] Paul et al. (Analysis of ageing inhomogeneities in lithium-ion battery systems) 2013, pp. 644-650.
[102] Baumhöfer et al. (Production caused variation in capacity aging trend and correlation to initial cell performance) 2014, p. 332.
[103] Prasad et al. (Dependability terminology: similarities and differences) 1996, pp. 17-18.
[104] Del Frate (Failure of engineering artifacts: a life cycle approach) 2013, pp. 922-925.

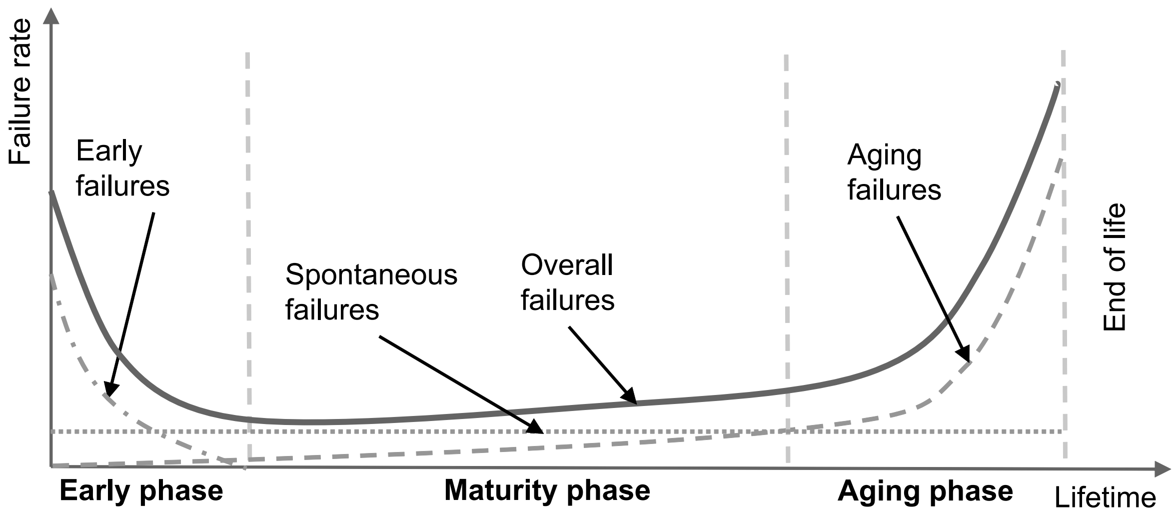


Figure 2.5: Probability of failure during the lifespan of a generic system

- As a system ages, the effects of time and usage mean that system damage accumulates, making the system more susceptible to failure.[105]

The proportions of the types of failures depicted in figure 2.5 vary according to the type of system and the damage accumulation to which it is subjected. For instance, electronic systems are especially susceptible to early and spontaneous failures, while mechanical systems subject to fatigue and wear are mostly susceptible to aging failures.[106] A system's lifespan is defined in terms of either time or load cycles, depending on the application. The variable t is used in both cases.

The probability of failure is modeled in reliability engineering as statistical distributions over the system's lifespan:

- f(t) is the failure rate, that is, the probability of a failure occurring at time 4t.
- F(t) is the cumulative failure distribution, that is, the probability of the system being in a fault state at time t.
- S(t) is the survivability, that is, the probability of the system having not failed at time t.[107] By definition:

$$S(x) = 1 - F(x) \tag{2.9}$$

Spontaneous failures can be modeled by an exponential distribution, where λ is the failure rate:

[105] Klutke et al. (A critical look at the bathtub curve) 2003, p. 125.
[106] Jiang et al. (Bayesian inference method for stochastic damage accumulation modeling) 2013, p. 127.
[107] Smith (Reliability, Maintainability and Risk) 2022.

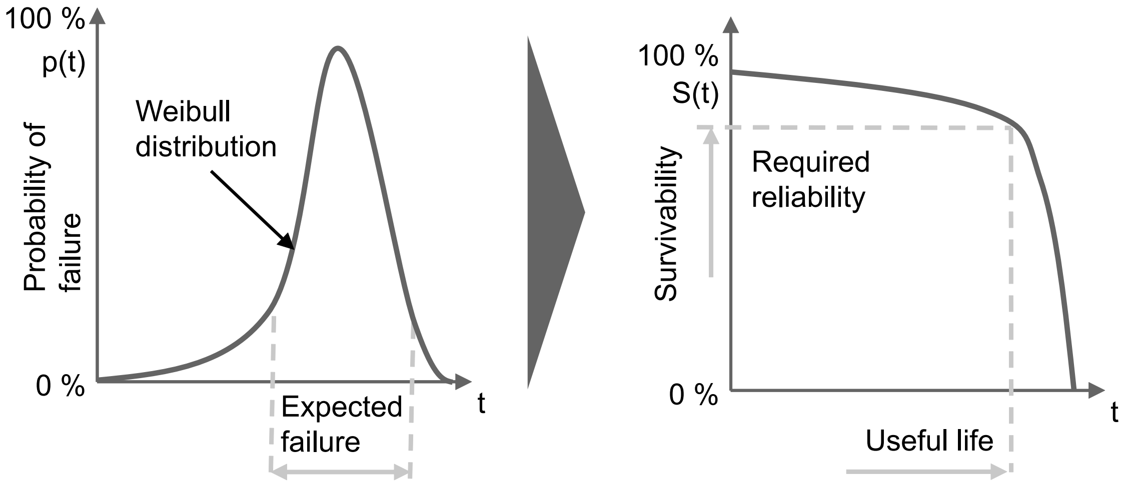


Figure 2.6: Probability of failure and survivability of a system subject to aging

$$f(t) = \lambda e^{-\lambda t} \tag{2.10}$$

$$F(t) = 1 - e^{-\lambda t} \tag{2.11}$$

This model is commonly used to estimate the reliability of electronics, such as the BMS.

Aging failures can be modeled by a Weibull distribution of the failure probability, where the shape parameter β affects the failure rate over time, and the scale parameter η affects the MTTF:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta - 1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2.12}$$

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2.13}$$

If $0 < \beta < 1$, the failure rate decreases with t; if $\beta > 1$, the failure rate increases, as is the case for aging. In the special case of $\beta = 1$, the distribution is exponential.

Aging failure is common in mechanical systems where:

- Damage accumulation depends on the load applied to some weak spot.
- The load on the weak spot increases as damage accumulation progresses.
- At a certain time, the weak spot is overloaded, and the component fails.

Under these conditions, failure occurs at a rather predictable overload level, and damage accumulation can be modeled accurately because most failures occur in a restricted, predictable time window. This makes it possible to estimate the lifespan at which a desired reliability is guaranteed on the basis of the probability of failure, as figure 2.6 shows.[108] A desired level of reliability can be obtained by restricting the useful life to a value that corresponds to the desired survivability and performing preventive and predictive maintenance, as is often the case in the aerospace industry for systems subject to damage accumulation due to mechanical fatigue.[109] More complex but similar conclusions can be made for systems with multiple causes of damage accumulation.[110] The biggest obstacle to predicting a system's useful life in advance is the variability of parts, implying the importance of quality management in the approach to designing for lifespan.[111]

Theoretically, every failure mechanism should be modeled separately with a distribution, and the overall failure rate probability should be a weighted combination of the distribution of each failure mode.

If a system comprises multiple components, the combination of its reliability characteristics can be modeled using Boolean networks under the following assumptions:

- The state of each component is either functional or failed.
- The state of each component is independent of the other components.
- The lifespan of each component starts at the same time.

These assumptions allow the probability of failure and survival to combine according to the laws of probabilities.

Under this assumption, the survival probability of a system in series at time t is the product of the survival probabilities S_i of its components C_i, because a system fails because of a single failed component:

$$S(t) = \prod_{i=1}^{n} (S_i(t)) \tag{2.14}$$

The failure probability of a system in parallel at time t is the product of the failure probabilities F_i of its components C_k, with the system surviving if a single component survives:

$$F(t) = \prod_{k=1}^{m} (F_i(t)) \tag{2.15}$$

108 Zhu et al. (Probabilistic modeling of damage accumulation for fatigue reliability analysis) 2012, p. 922.

109 Yue et al. (A fatigue damage accumulation model for reliability analysis of engine components under combined cycle loadings) 2020, p. 1.

110 Y. Chen et al. (Reliability analysis of PMS with failure mechanism accumulation rules and a hierarchical method) 2020, p. 12.

111 Matsuoka (Electronic componebnts reliability testing for quality assurance), p. 68.

The simplification of considering systems in parallel and in series concerns the probability of failure and not necessarily how the components are connected.[112]

2.4.2 Reliability of battery cells

Battery cells have three properties that distinguish them in terms of this model:

- They are subject to both calendar and cyclic aging, such that their lifespan can be defined in terms of time or equivalent cycles according to the prevalent damage accumulation mechanism.
- Damage accumulation depends on cell conditions at a given time and on the time history of multiple aging parameters.
- Some failure modes are interdependent, such that the progress of one aging mechanism accelerates other aging mechanisms. It is very difficult to measure the reliability of these mixed failure modes.[113]
- The fault state is defined by the application: Usually, a minimum capacity and a maximum internal resistance are allowed for a specific application. Sometimes battery cells cannot perform their function, and sometimes they reach a safety-critical state. However, they usually continue to work at a reduced level of performance after a failure.

Because early defects are usually detected during the first cycles in the formation process,[114] these are more relevant to quality management, with battery reliability referring to increasing failure rates over the system's lifespan.

Aging failure is conventionally defined as $SoH < 80$% for automotive applications on the grounds that the gravimetric energy density decreases with the SoH, and a higher percentage of the battery's capacity is used to accelerate an "unnecessarily" high battery mass. However, this definition does not match the reality of automotive use, where vehicles or batteries are replaced when they can no longer perform their function or be upgraded.[115]

A common model used to describe the reliability behavior of aging failures in battery cells is the Weibull distribution, whose parameters must be fitted according to experimental data regarding the particular cell type and manufacturing process.[116]

112 Bertsche et al. (Zuverlässigkeit mechatronischer Systeme) 2009, p. 49, p. 60.
113 Klein (Numerische Analyse von gemischten Ausfallverteilungen in der Zuverlässigkeitstechnik) 2013, pp. 130-132.
114 Placke et al. (Assessment of Surface Heterogeneity: a Route to Correlate and Quantify the 1 st Cycle Irreversible Capacity Caused by SEI Formation to the Various Surfaces of Graphite Anodes for Lithium Ion Cells) 2015, p. 18.
115 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, p. 11.
116 Lehner (Reliability assessment of lithium-ion battery systems with special emphasis on cell performance distribution) 2016, p. 110.

2.4.3 Reliability of battery modules and packs

In battery modules and packs, cells electrically connected in series behave as components in series in a Boolean network. The same is not necessarily true for cells electrically connected in parallel because, although they offer an alternative path for the electrical current, losing some cells in parallel causes a loss of system capacity and an increase in internal resistance, potentially causing the system requirements to not be met, resulting in system failure.[117]

In comparison to a mechanical system with a predictable load that fails at any given point of failure (weak spot), battery systems can fail because of the failure of any number of cells because various aging mechanisms depend on the particular conditions of each cell. Moreover, the use history of each cell, which includes the temperature and the DoD, depends on cell properties such as internal resistance and capacity, which depend on manufacturing quality.[118]

The combination of more cells in parallel increases reliability only up to a point of diminishing returns.[119] In general, combining more cells with differences in manufacturing quality and the use history of each cell should move the peak of the failure probability of a battery system toward shorter lifespans, in comparison to single cells. Therefore, many cells should remain functional when a battery system fails, confirming the assumptions underlying the simulations of MATHEW ET AL.

2.4.4 Experimental validation of the hypotheses justifying cell replacement

The simulations by MATHEW conclude that a cell replacement strategy can beneficially prolong a battery's lifespan if the cells have aged at different rates at the time of replacement.[120] The present work tests this hypothesis' validity in two cases of real vehicles with different use cases: One vehicle was part of a fleet subject to heavy-duty use and regular maintenance; The other was a private vehicle driven for only a fraction of its lengthy life. The first vehicle's battery should be representative of prevalent cyclic aging, and the second vehicle's battery should be representative of prevalent calendar aging. This work was conducted in the context of the European regional development fund (EFRE) funded project BatteReMan, in which several automotive batteries have been disassembled and analyzed to assess re-manufacturing possibilities.

[117] Neupert et al. (Inhomogeneities in Battery Packs) 2018, pp. 13-14.

[118] Schindler et al. (Analyzing the Aging Behavior of Lithium-Ion Cells Connected in Parallel Considering Varying Charging Profiles and Initial Cell-to-Cell Variations) 2021, p. 2.

[119] Ivan et al. (Reliability Analysis of Different Cell Configurations of Lithium ion battery Pack) 2019, p. 49.

[120] Mathew et al. (Simulation of lithium ion battery replacement in a battery pack for application in electric vehicles) 2017, pp. 100-101.

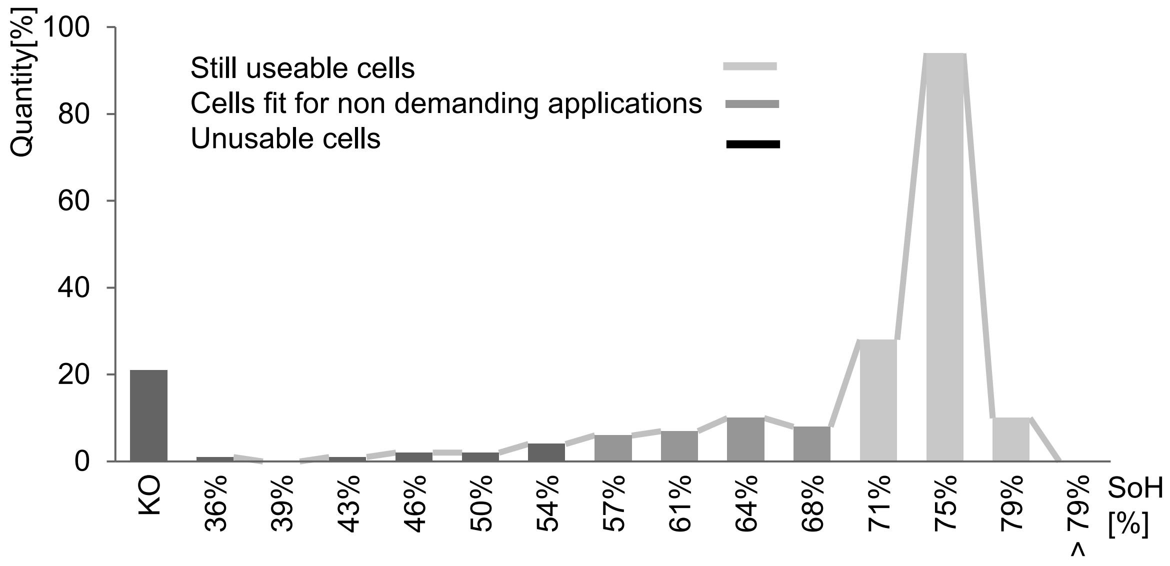


Figure 2.7: SoH of 2,800 Ah 18650 round cells from the same battery module of a light delivery truck used intensively for three years

2.4.4.1 Delivery fleet vehicle

A light delivery truck was used for three years for two shifts per day, six days a week, and was fast-charged during loading operations between shifts and slow-charged overnight, making it representative of a use case where cyclic aging predominates over calendar aging. After the use phase, the truck was retired because it could no longer fulfill its daily functions.

The SoH of the 18,650 cells taken from one module, in figure 2.7, show how a small number of cells failed (the CID opened, so there was no continuity between the poles), and a certain number of cells deviated from the average SoH, significantly compromising the battery life.

2.4.4.2 Private vehicle

The opposite case, where calendar aging prevailed over cyclic aging, was tested with three returned compact-car batteries that were used privately for 100,000 to 300,000 km over a period of about six to eight years. Their modules comprise four cells, connected two in parallel and two in series (2p2s). Because it was not possible to test the single cells, the smallest possible modules had to be taken as a proxy for cell-to-cell variability to confirm the working hypothesis.

As figure 2.8 shows, the dispersion of cell SoH is more pronounced in the batteries with lower overall SoH. However, the overall dispersion is definitely lower than in the cyclically aged battery. The parallel connections between cell pairs inside the modules might partially hide the absence of badly damaged or aged cells. However, theoreti-

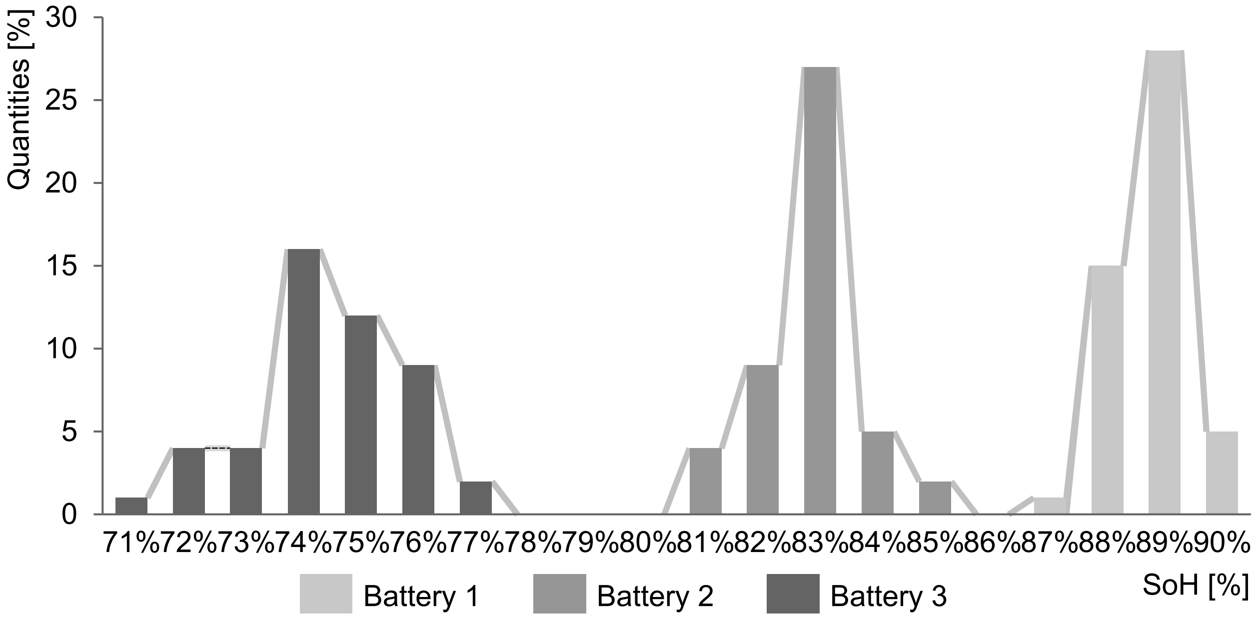


Figure 2.8: SoH modules from three used Nissan Leaf batteries, mostly subject to calendar aging

cal calendar aging models are less dependent on each cell's different load and initial conditions, making the conclusion appear plausible.

2.4.4.3 The need for a cell replacement strategy for lifespan extension

The possibility of changing cells during the life cycle to prolong the lifespan, as proposed by Mathew et al., seems far more effective in heavy-duty vehicles, where cyclic aging prevails over calendar aging, meaning that the different initial and boundary conditions of each cell cause greater dispersion of the SoH and, therefore, the lifespan. This conclusion fits well with battery use in vehicle fleets, where batteries are frequently monitored and vehicles subject to frequent, scheduled maintenance.

2.5 Design of automotive battery systems

This section explains the common features of automotive battery design and describes the challenges of designing such systems for circular economies that maximize the residual value of battery cells.

Common design features are described in reference to the literature and integrated with observations resulting from practical battery tear-downs performed within the BatteReMan project and other projects at the Chair of Production Engineering E-mobility Components (PEM). Batteries from the Renault Fluence, Nissan Leaf, and Audi e-Tron BEVs and HEVs based on the VW MQB platform have been disassembled and analyzed. To distinguish between the state-of-the-art knowledge and the knowledge produced for this work, pictures of the aforementioned batteries and related observations without citations have been obtained by the author on the basis of his experience of those battery tear-downs.

While some automotive battery systems feature an integral design, the architecture of most automotive battery systems is modular, with cells connected in parallel or in series by busbars and encased together in modules such that each module is a separate electrical system.[121] This means that each module contains the sensors to monitor cell status, with these sensors most often connected to a cells supervising circuit that provides a LV interface for the battery management controller. Each module voltage is usually limited to 60V to avoid being considered an HV battery according to Regulation 100 of the United Nations Economic Commission for Europe (UNECE).[122] Furthermore, it features mechanical mounting interfaces with the pack housing and interfaces for the thermal management system.[123]

2.5.1 Pack design

A modular battery system is assembled by mounting multiple modules in the pack housing, connecting their HV terminals together in series or in parallel, connecting the whole to the battery management and thermal management systems, and then closing the housing so that it fits into specific EVs, communicates with on-board electronics and fulfills homologation requirements. One example is the battery of the BMW i3.[125]

Integral designs have mostly been used where build space and weight-saving are prioritized over serviceability, as in the case of smaller HEVs batteries, such as those of the Toyota Prius[126] and high-performance brands (e.g., the Mercedes S400). These designs can be understood to comprise a single module with pack housing. These HEV batteries are so small that they can be easily replaced and serviced at a central location, as in the case of the Prius,[127] or they are not deemed sufficiently valuable to be repaired in the case of fault.[128]

More modern approaches to integral design are observed in the CATL Cell-to-Pack

[121] Kwade et al. (Current status and challenges for automotive battery production technologies) 2018, pp. 291, 295.
[122] United Nations Economic Commission for Europe (Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train [2015/ 505]) 2015, p. L87/3.
[123] Korthauer (Handbuch Lithium-Ionen-Batterien) 2013, pp. 14-15.
[124] Köhler (Lithium-ion battery system design) 2018, p. 104.
[125] Schoewel et al. (The high voltage batteries of the BMW i3 and BMW i8) 2014, pp. 9-12.
[126] Kelly (2016 - 2022 Toyota Prius Li-Ion Battery) 2017.
[127] Goreham (Don’t Buy A New Toyota Prius Hybrid Battery - Have It Repaired Instead) 2019, p. 1.
[128] Mckeever et al. (Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV) 2000, pp. 5-7.

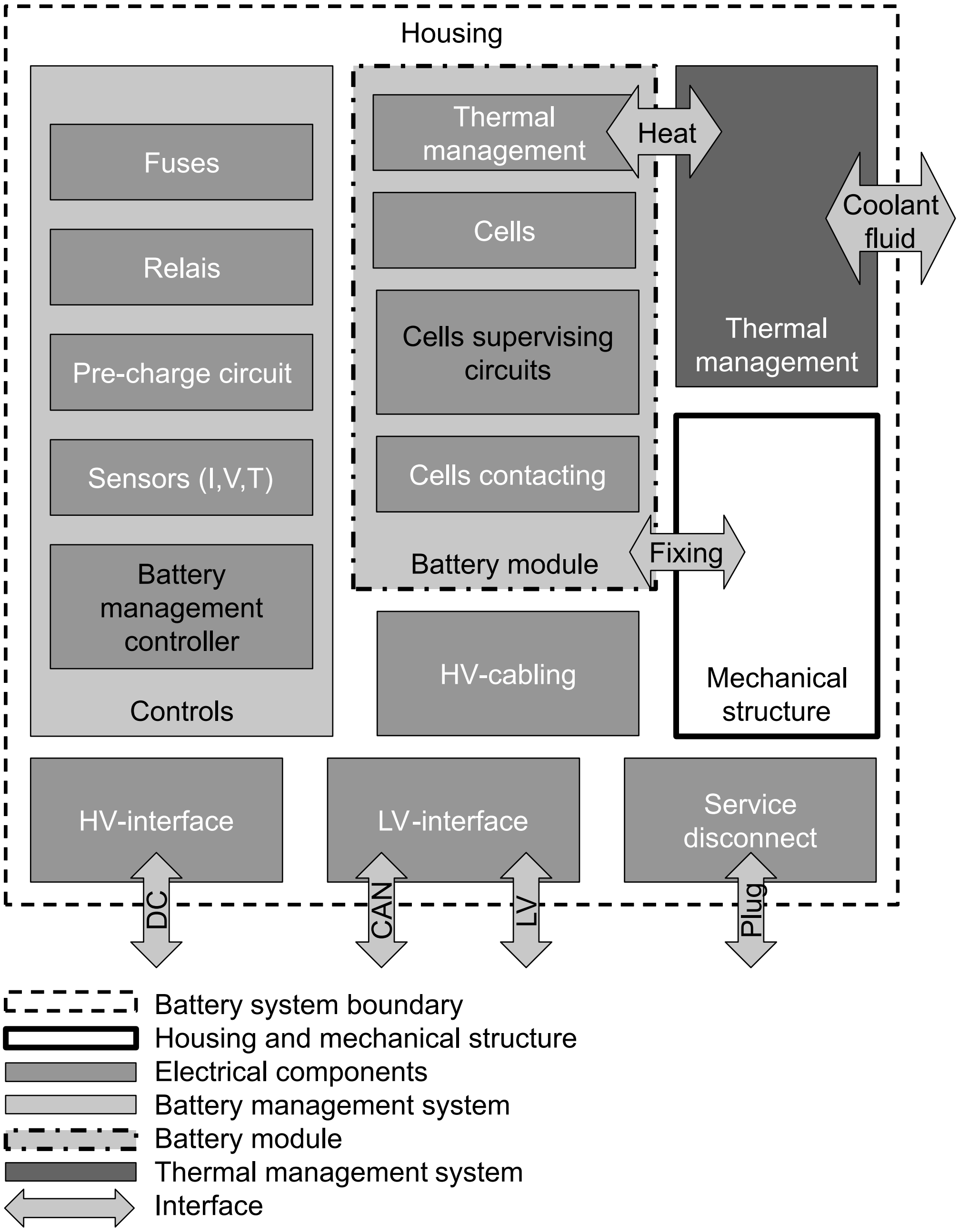


Figure 2.9: Architecture of an automotive battery pack[124]

technology[129] and the BYD Blade Battery[130,131], where internal space utilization claims to be improved by 50%. Such solutions skip the module level completely and utilize advanced handling automation during assembly to overcome the safety risks associated with positioning and contacting many cells in an open battery pack. BYD addresses the problem using very large battery cells, simplifying cell contact by avoiding cables between modules, and using the inherently safer LFP chemistry, with the energy-density disadvantages overcome by better packaging efficiency[132]

Tesla is pursuing similar efforts to avoid modules, filing the patent US20190312251A1, which describes round cells in contact in parallel in blocks that are then simply connected into large arrays of cells without modules.[133]

2.5.1.1 Differences in pack design because of different cell types

There is currently no consensus regarding what cell format is most advantageous at the system level. Although round cells arguably feature (volumetric) higher energy density, this is offset at the system level by lower packaging efficiency. In terms of (gravimetric) specific energy, the difference between cell formats is less pronounced, making a focus on space-saving more technically challenging than a focus on weight-saving because this involves the problem of densely packaging highly energy-dense round cells while providing enough safety, as indicated by Darcy.[134] In particular, the energy density at the cell level for round cells often does not result in high energy densities at the module level.[135]

Cell sizes cannot be chosen independently of the specific application because of the need to consider packaging, pack design, and temperature-limit non-homogeneity within cells.[136,137] As such, not only are pack designs different for every application but there exist various modules with different cell formats[138]. The choice of cells has a significant impact on application-specific performance, investment costs, system layout, and control strategies.[139]

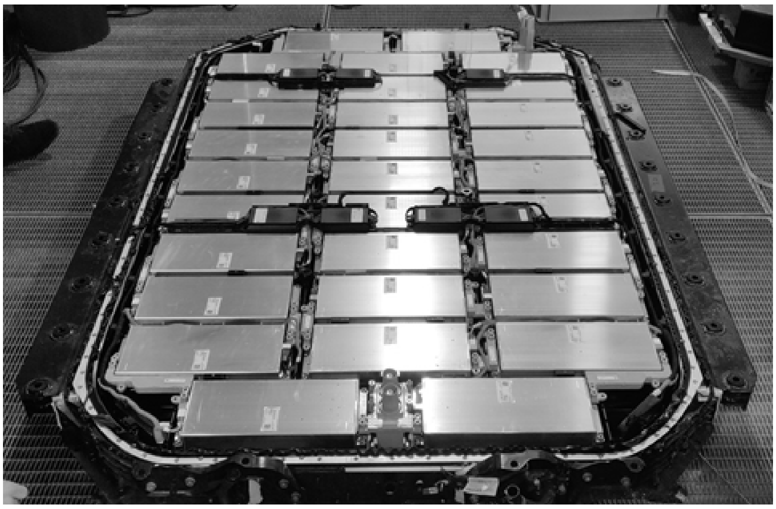
[129] CATL (China's CATL unveils cell-to-pack battery platform) 2019, p.1.
[130] BYD (BYD's New Blade Battery Set to Redefine EV Safety Standards), p. 1.
[131] Marques (CATL Confirms Battery Systems Without Modules That Will Allow the Design of Electric Cars with 500 Miles of Autonomy) 2020, p. 1.
[132] Kane (BYD Shows Off New Blade Battery Factory In Chongqing) 2020, p. 1.
[133] Matthews (Aggregated battery system) 2019, pp. 1-3.
[134] Darcy (Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells) 2018, pp. 13-41.
[135] Löbberding et al. (From Cell to Battery System in BEVs: Analysis of System Packing Efficiency and Cell Types) 2020, p. 11.
[136] M. M. Kerler (Eine Methode zur Bestimmung der optimalen Zellgrösse für Elektrofahrzeuge) 2019.
[137] M. Kerler et al. (A concept of a high-energy, low-voltage EV battery pack) 2014, p. 1.
[138] Sarovic (Gestaltung variantenrobuster Produkt-Produktionssysteme am Beispiel des Lithium-Ionen-Batteriemoduls) 2018.
[139] Becker et al. (Dimensioning and Optimization of Hybrid Li-Ion Battery Systems for EVs) 2018, p. 1.

Within the same application, efforts are being made to improve the commonality between cell and module formats. Even if an upgraded pack design is not fully implemented in a circular economy framework, BMW did upgrade the battery pack of its i3 EVs, incorporating higher-capacity cells while maintaining the same pack and module design.[140] Large manufacturers, such as VW and Audi, have adopted a modular kit product strategy in which standard modules are used in different vehicle-specific packs. Sometimes, different modules comprise different cells, but they are mechanically interchangeable to use the same pack design for versions of the same vehicle, which differ according to certain battery specifications (e.g., range, power).

Different variants usually feature common housing and the same packaging, as exemplified by figures 2.10a and 2.10a. This ensures expensive casting and sheet metal parts can be identical. Moreover, using the same sealing of the cover and the pressure compensation can save costs via scale effects[141].

140 Brunckhorst (Technische Daten BMW i3 (120Ah)) 2018, pp. 2, 4–5.
141 Kritzer et al. (Dichtungs- und Elastomerkomponenten für Lithium-Batteriesysteme) 2013, pp. 120-121.
142 Audi (Technical data - Audi e-tron 50 quattro 230 kW) 2021, p. 1.
143 Audi (Audi e-tron battery), p. 1.
144 Audi (Technical data - Audi e-tron 55 quattro 300 kW) 2021, p. 1.
145 Audi (Audi e-tron battery), p. 1.

(a) Audi E-Tron 50 71 KWh battery during teardown, with 60 Ah Samsung SDI prismatic cells[142,143]



(b) Lower level of the Audi E-Tron 55 95 KWh battery, with 60 Ah LG Chem pouch cells[144,145]

Figure 2.10: Battery pack variants with cells of different format and performance, using common module interfaces and housing

2.5.1.2 Arrangement of modules and fixtures in relation to the housing

In designs that consider the use of different modules and upgradeability, all modules are bolted by identical bolt patterns to the housing or a sub-frame, which is itself fixed to the housing, as figure 2.11 shows in the two top pictures 2.11a and 2.11b. If the battery build space cannot be flat, two or more tiers of modules can be used and fixed by holding brackets, as figure 2.11 shows in the bottom left picture 2.11c. A similar use of sub-frames is common in conversion designs from internal combustion engine vehicles (ICEVs), in which the build space must be the same as that of an ICE, as figure 2.11 shows in the bottom right picture 2.11d. Sub-frames are also used in small HEVs batteries to allow the preassembly of some modules and their cold plates into sub-assemblies fixed to the sub-frame in an automated production line. This is followed by the assembly of the piping and wiring harnesses and fitting of the pre-assembled battery inside the housing, which has a shape that might not allow some assembly steps to be performed inside, as figure 2.11 shows in the top right picture 2.11b.

As the ”skateboard” chassis design becomes established as the standard[146], the use of sub-frames loses importance because it necessarily decreases the system's energy density and requires more assembly steps and heavy-weight handling.[147]

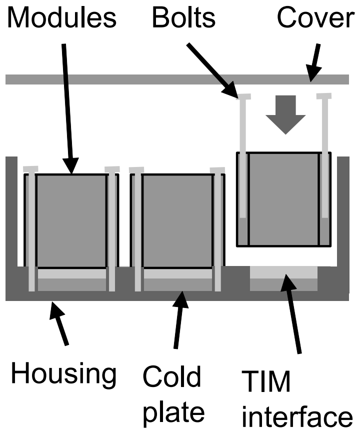
The designs in figures 2.11a and 2.11b feature a thermal management system with an interface that determines the assembly direction because the modules must be pressed against the cold plate with a TIM interface between them to facilitate heat conduction. Because the heat transfer must not be prevented by air gaps, a thermally conductive paste or gap pad is inserted between the module and the cold plate. Notably, the configuration in the top left figure is possible and relatively common without a cold plate (with modules made of any cell type).

The configuration in figure 2.11b requires some flexible piping, as in the case of the MQB HEV battery by VW, because the seals must be perpendicular to the assembly direction, as figure 2.12 shows.[148]

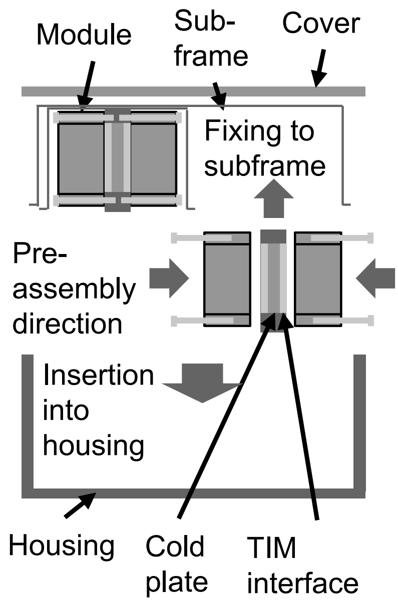
The Nissan-Renault group uses the same modules for both a purpose-design EV car (see figure 2.13a) and a conversion-design EV car (see figure 2.13b). Both variants have the same number of cells and system architecture but fit in different package spaces. The small module size enables the variable height of the battery pack to utilize the room under the seats in the purpose-design car and a narrow and deep battery to fit into the engine bay of the conversion-design car.

As figure 2.14 shows, the modules are air-cooled for flexible stacking. The connections are by means of large busbar carriers, with some mirrored modules employed to avoid busbar crossing. The BMS is a central unit with a plug interface to the busbar

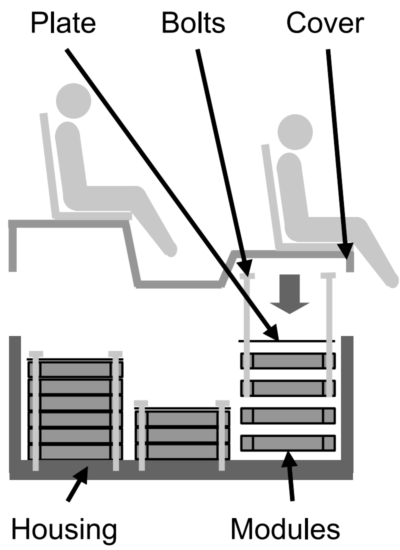
[146] Chernoff (A reinvented industry) 2018, p. 1.
[147] Chernoff (Reinventing the automobile) 2018, p. 1.
[148] Kritzer et al. (Dichtungs- und Elastomerkomponenten für Lithium-Batteriesysteme) 2013, pp. 123-125.
[149] Kane (Nissan Introduces $2,850 Refabricated Batteries For Older Leaf) 2018, p. 1.



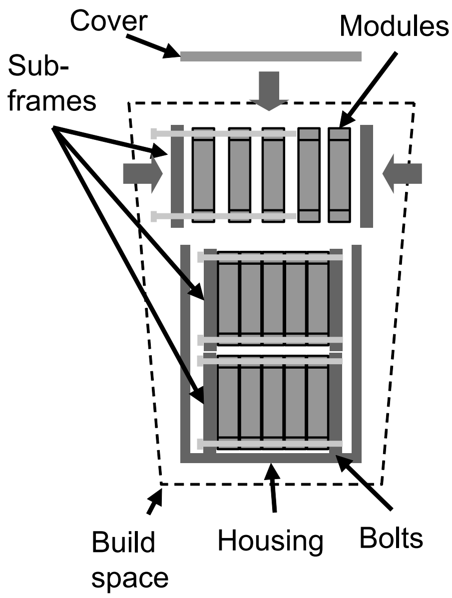
(a) Flat design



(b) Assembly sub-frames



(c) Packaging sub-frames (purpose design)



(d) Packaging sub-frames (conversion design)

Figure 2.11: Arrangements of modules in battery packs according to build space constraints and assembly sequence

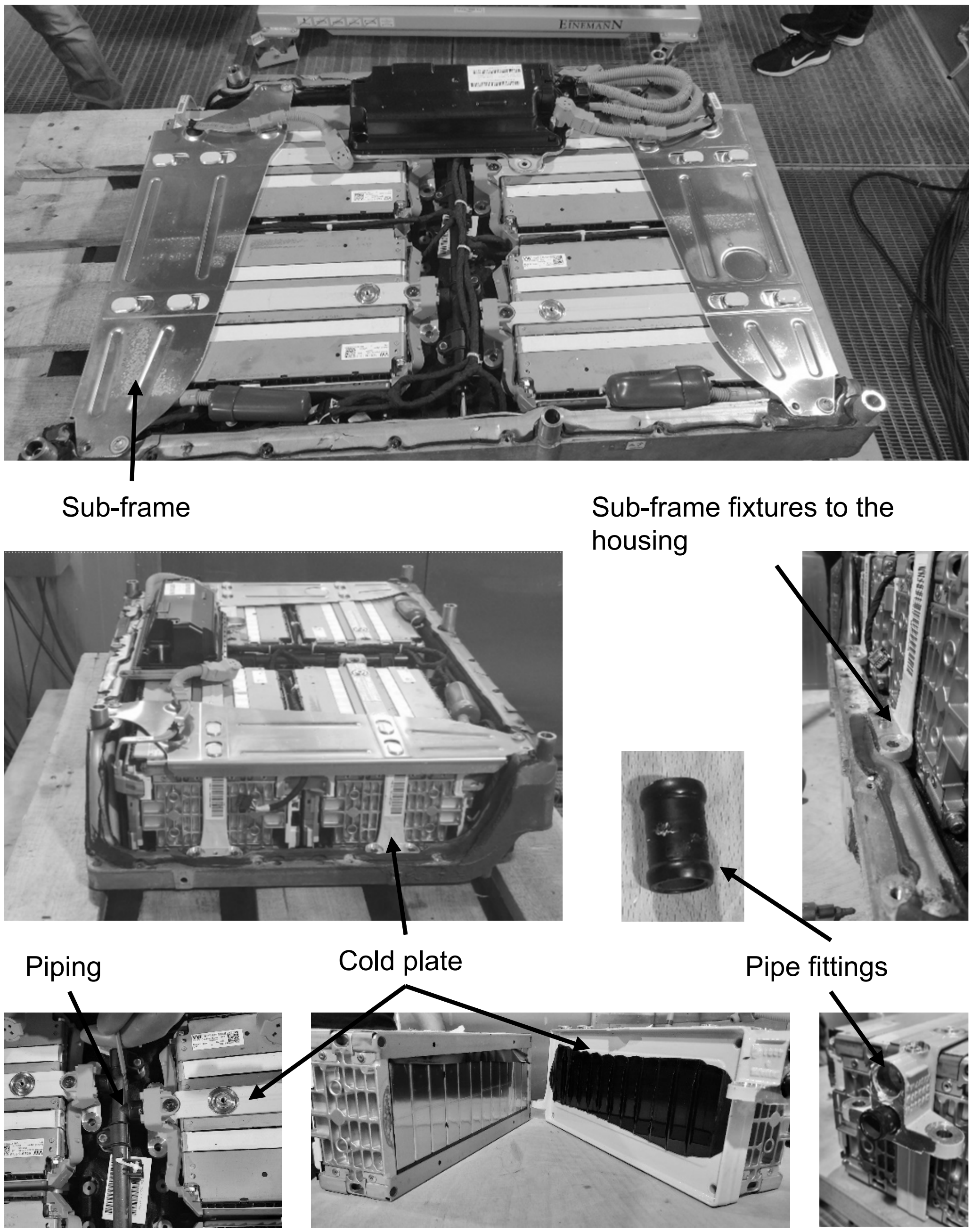


Figure 2.12: The teardown of VW MQB HEV battery pack. The modules are mounted sideways onto the cold plates, so they are mounted on a sub-frame that is inserted into the housing in a subsequent assembly step. The thermal management piping is external to the housing, and its fittings tolerate variations in module position and alignment

(a) Nissan Leaf battery[149]

(b) Renault Fluence Battery during teardown

Figure 2.13: Battery pack variants with different package common cells and modules, as well as standardized design for structural elements, electronics and wiring

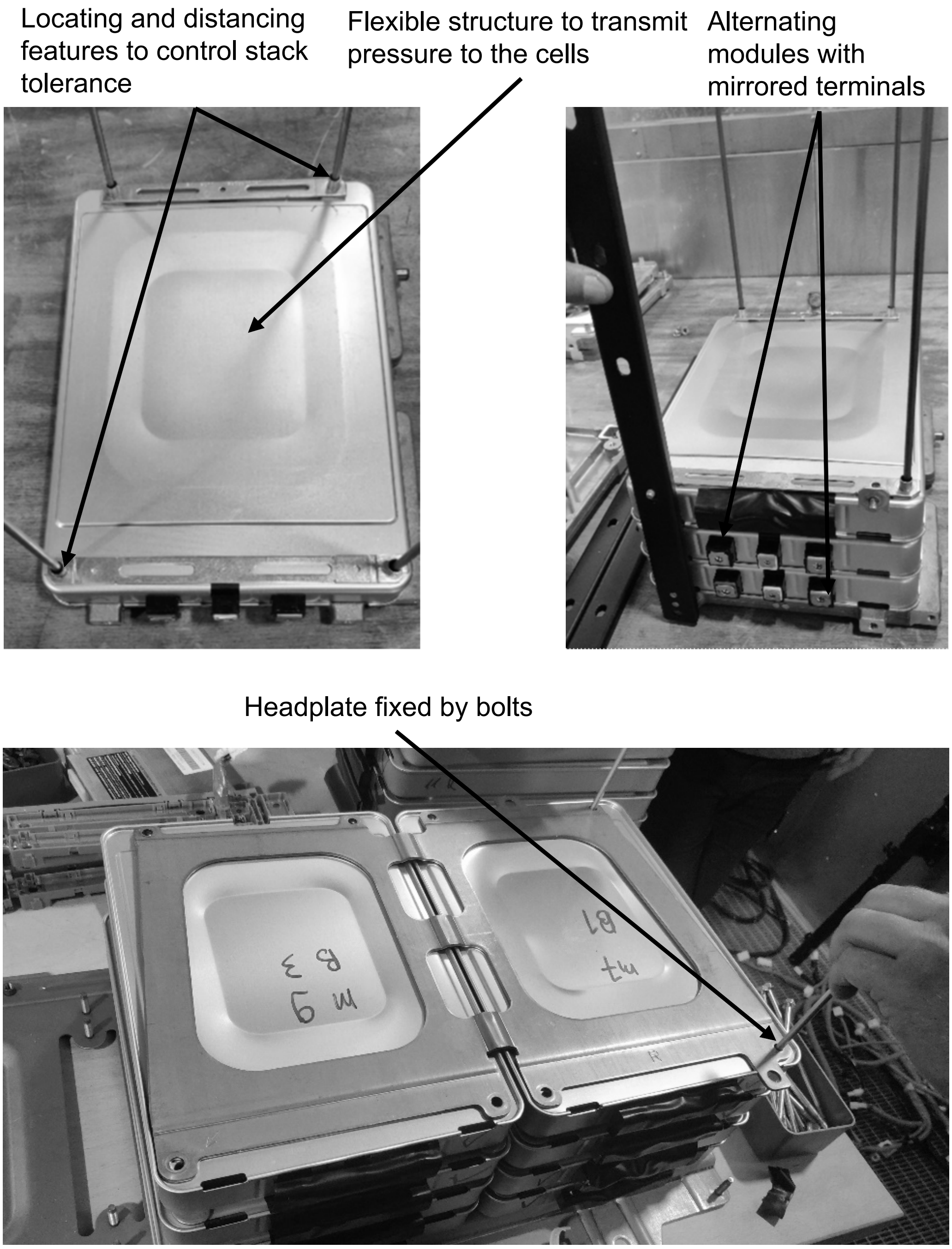


Figure 2.14: Nissan Leaf module housing and interfaces during teardown

carriers for the voltage sensors. Instead, the temperature sensors are fit into holes in certain modules that are not specially marked.

In general, automotive battery packs are designed with specifications based on specific vehicle versions. The OEMs attempt to leverage economies of scale by standardizing some modules and/or cells to varying extents. However, this is possible only to a certain extent, meaning different cell formats and sizes will continue to be used in the future.

The tendency toward cell-to-pack (C2P) designs will increase energy density at the pack level and increase the requirements for battery repair and disassembly because all handling and contacting must happen under HV. The general trend in cell size is toward larger cells with greater capacities, increasing the importance of their recovery.

2.5.1.3 HV connections between modules

The most intuitive way to connect the HV module terminals is to use isolated copper cables.[150,151,152] Cables compensate for tolerances, thermal expansion, and structural deformation. Nevertheless, they mostly need to be assembled manually. For this reason, copper busbars have been more common in recent years and are shaped to allow some deformation.[153,154] The most recent versions are made of ultrasound-welded thin plates or contain a braided flexible element.[155,156] Aluminum is an interesting option because it saves weight when the build space allows for more cross-sections.[157,158,159]

Busbars and cables are usually fixed on modules and onto connectors by bolts, with the joint requiring a defined contact pressure and cross-section to prevent electrical contact resistance from being too high and causing overheating.[160,161] For this reason, a loose bolt could pose a danger, causing a busbar to overheat, the thermal runaway of one module, or the failure of a thermally sensitive component such as a fuse. Therefore, the joints must be dimensioned carefully, and their tightening moment must be

[150] Deutsches Institut für Normung (DIN VDE 0276-603) 2005, pp. 1-3.
[151] Deutsches Institut für Normung (DIN EN 13602) 2013, p. 4.
[152] BMW (BMW I3 Battery Module) 2016, p. 1.
[153] Deutsches Institut für Normung (DIN 43671) 1975.
[154] Deutsches Institut für Normung (DIN EN 13599), p. 8.
[155] Deutsches Institut für Normung (DIN 46276 - 1) 1991, p. 1.
[156] Deutsches Institut für Normung (DIN 46276 - 2) 1975, p. 1.
[157] Deutsches Institut für Normung (DIN 43670) 1975, p. 3.
[158] Deutsches Institut für Normung (DIN EN 14121) 2009, p. 6.
[159] Mellor et al. (Comparative Study of Copper and Aluminium Conductors - Future Cost Effective PM Machines) 2014, p. 1.
[160] Deutsches Institut für Normung (DIN 43673 - 1) 1982, p. 1.
[161] Deutsches Institut für Normung (DIN 43673 - 2) 1982, p. 1.

checked.[162,163,164,165] Electrical contact resistance is reduced by coating the busbars with a soft electrically conductive coating such as silver plating[166] or, more commonly, nickel plating,[167] which spreads under the mechanical pressure and increases the effective contact cross-section.[168] Because these coatings experience a compression load cycle in bolted contacts for every thermal cycle, they might be damaged after disassembly. Hence, there is a limit to the number of times a busbar can be reused, and its surface must be checked before reuse because its state influences its contact resistance.[169,170] Contacts in plugs are subject to sheer during plugging and unplugging, meaning that the coating can peel off if a plug contact is plugged and unplugged many times. This is especially true when the contact force is higher, as is the case for HV power cabling.

The operation of HV connections among modules and to the HV terminals of the battery pack happens in a series environment and must be subject to technical, organizational, and personal safety measures to avoid injury, especially from electrical hazards. Because the battery is a circuit with isolated ground (from French ”isolè terre”) (IT) according to the IEC 60364, it is double fault-tolerant, meaning that accidental contact between two parts does not generate a dangerous error in the current flow.[171] If the assembly workers and the battery are isolated from the ground and if the workers wear protective isolating equipment, accidental contact between two points at different voltages (e.g., two modules or one module and housing) does not cause current flow because the circuit is not closed. From a design standpoint, this means that a system of covers that allows a maximum of two points to connect at one time and avoids accidental contact with a third conductive body (with the others covered) is safe for assembly, rework, and repair operations. Usually, such covers are rated IPXXB or IP2X according to IEC 60529 to prevent the entrance of both fingers and tools.[172] The opening and closing of these safety covers require substantial time during both assembly and rework and represent a considerable challenge in the context of disassembly automation

[162] Verein Deutscher Ingenieure (VDI 2230 - 1) 2015, pp. 21-22.

[163] Gatherer et al. (A Multi-Variable Parametric Study on the Performance of Bolted Busbar Contacts) 2015, p. 1.

[164] Xin et al. (Characteristics of Overheated Electrical Joints due to Loose Connection) 2011, p. 1.

[165] Braunovic (Overheating of flexible tinned copper connectors) 2001, pp. 386-388.

[166] Risdiyanto et al. (Study on Temperature Distribution at Busbar Connection Based on Contact Resistance of Different Plating Contact Surface) 2013, p. 4.

[167] Frey (Grundmaterial für elektrische Kontakte - eine wichtige Größe für eine optimale Randbeschichtung) 2016, p. 4.

[168] Fuhrmann et al. (Comparison between nickel and silver as coating materials of conductors made of copper or aluminum used in electric power engineering) 2014, p. 1.

[169] Rachman et al. (Analysis of Surface Roughness and Contact Pressure at Copper Connector Using Nickel and Silver Plating for EV Battery) 2013, pp. 5-6.

[170] Hatakeyama et al. (Fundamental study of surface roughness dependence of thermal and electrical contact resistance), pp. 1, 3–5.

[171] International Electrotechnical Commission (IEC 60364) 2005.

[172] International Electrotechnical Commission (IEC 60529) 2001.

because they are fixed by thin safety clips that need to be removed using a screwdriver with one hand.

The busbars themselves are usually covered by plastic caps or co-molded in plastic. Some examples taken from the battery tear-downs at PEM appear in figure 2.15.

2.5.1.4 Design rules involving electromagnetic fields

A constraint on HV connections between modules is due to the electromagnetic field (EMF) caused by high currents in the electric conductors. First, conducting components should not be ferromagnetic, such that the magnetic field is not reinforced as in an electromagnet. Second, the HV current path should not form wide coils; rather, the current flowing in one direction should be, at best, parallel and very close to the current of the same intensity flowing in the opposite direction.[173] This way, the magnetic field is canceled out. The effect of this constraint is mostly in the placement of the modules. Figures 2.10b and 2.12 exemplify this, with the Audi using mirrored modules to keep the distance between currents flowing in opposite directions small. The drawbacks of modules with mirrored terminals are the increased possibility of errors during manual assembly and the additional items in the bill of materials (BOM), whose logistics have to be managed. Furthermore, the CSCs have mirrored plugs and are not hosted in the modules themselves but on top. This means that the wiring harness is complex, making its assembly and disassembly hard to automate. Although this design approach to modularity is suited to large volume manufacturing, it adds some complexity in terms of managing replacement parts and disassembly.[174]

[173] Ivers-Tiffée et al. (Werkstoffe der Elektrotechnik) 2007, pp. 183-206.
[174] Williams (EMC for Product Designers) 2016, p. 500.

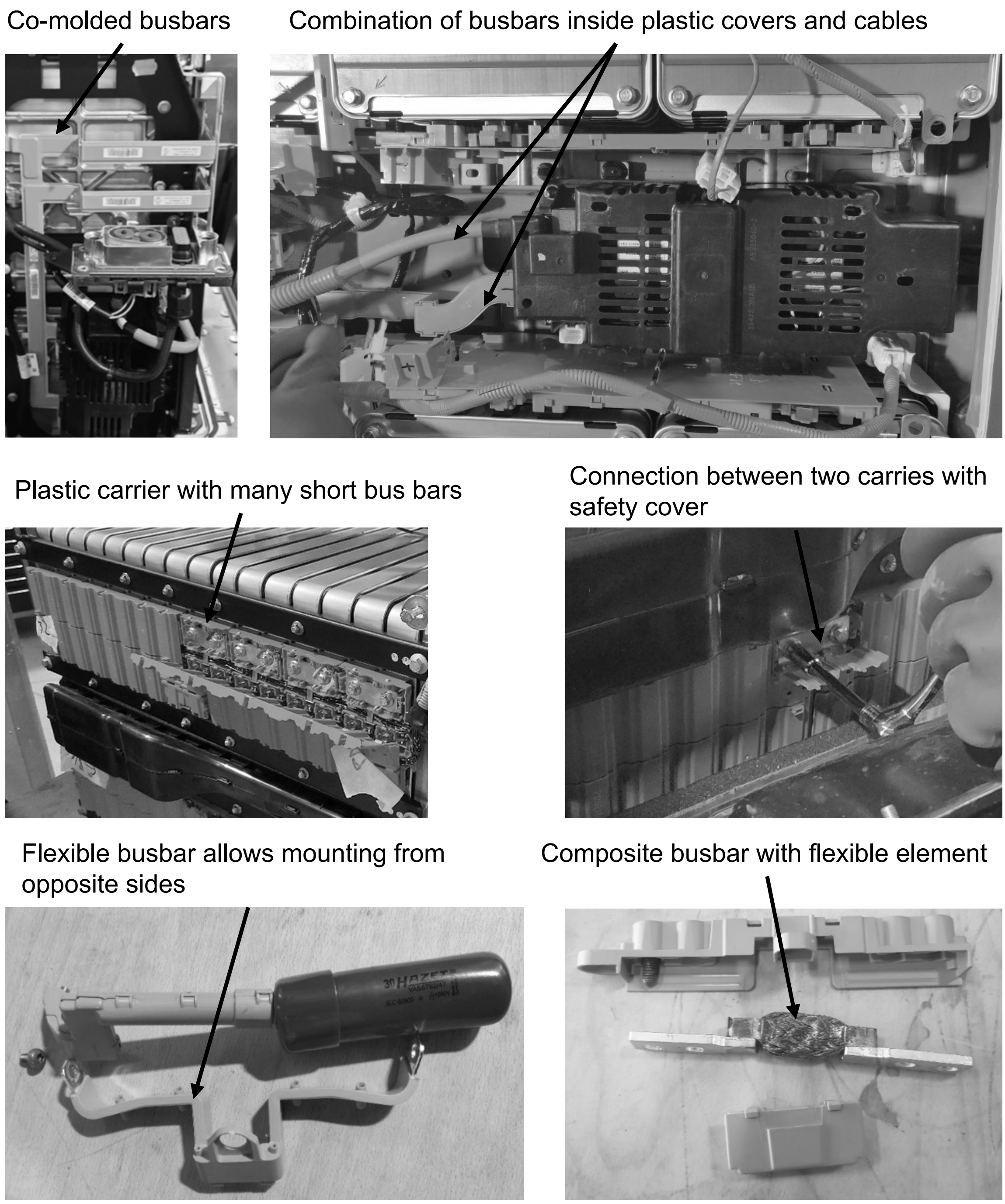


Figure 2.15: Different types of HV connections among modules

2.5.1.5 Implications of pack design for a circular economy

In summary, automotive battery packs feature a modular structure, meaning, in principle, a failed module can be replaced in the event of failure or premature aging. The same applies to other components, such as BMS and electronics, which have a longer lifespan and different reliability characteristics. With appropriate safety measures for handling of components under HV, these modules and connections can be removed.

2.5.2 Thermal management

The thermal management system of BEVs must primarily keep the battery within its safe and possibly optimal operation window, regardless of ambient conditions and power flow to and from the battery.[175] Second, it must reduce the temperature differences between cells and the thermal gradients within single cells[176] to prolong the battery's lifespan[177,178].[179]

2.5.2.1 Requirements of thermal management systems

Therefore, the thermal management system must be able to direct the heat flow both to and from the battery. In the event of short power bursts, it could save some heat in its thermal capacitance to save on its energy demand.[180] Common thermal management systems function directly or exchange heat with heat pumps.[181,182] The best type of thermal management is influenced by cell type and dimension because the heat must first be extracted from the active materials through the cell housing (surface cooling) or through the electrodes (tab cooling).[183,184,185] Kim et al. produced a comprehensive

175 Korthauer (Lithium-ion batteries) 2018, p. 156.
176 Fleckenstein et al. (Current density and state of charge inhomogeneities in Li-ion battery cells with $LiFePO_4$ as cathode material due to temperature gradients) 2011, p. 4769.
177 Vetter et al. (Ageing mechanisms in lithium-ion batteries) 2005, p. 276.
178 Waldmann et al. (Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study) 2014, p. 131-135.
179 Arora (Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies) 2018, p. 623.
180 Rao et al. (A review of power battery thermal energy management) 2011, p. 4561.
181 Karras (Optimierung der Wärmeabfuhr eines Fahrzeug-Elektromotors und Auswirkungen auf den Gesamtkühlkreislauf), pp. 26-27.
182 X. Zhang et al. (A review on thermal management of lithium-ion batteries for electric vehicles) 2022, p. 7-10.
183 R. Zhao et al. (The effects of electrode thickness on the electrochemical and thermal characteristics of lithium ion battery) 2015, pp. 224-229.
184 Y. Zhao et al. (Modeling the Effects of Thermal Gradients Induced by Tab and Surface Cooling on Lithium Ion Cell Performance) 2018, p. A3174.
185 S. Li et al. (Optimal cell tab design and cooling strategy for cylindrical lithium-ion batteries) 2021, pp. 12-14.

review of the newest cooling concepts from the cell level up to their integration in the overall vehicle thermal management system and concluded that:

- Air cooling or cabin air cooling is suitable for short-range EVs with limited power.
- A secondary cooling loop connected to the primary refrigerator cycle or heat pump used for the cabin is the state of the art.
- Direct cooling using a two-phase refrigerator offers higher performance and temperature homogeneity, while reducing the number of components.
- Heat pipes and phase change materials (PCM) work in special cases as buffers against temperature peaks.[186]

While the use of immersion cooling[187] is limited to systems subject to high power transients[188] and PCM are not yet widespread,[189] the most common cooling systems are air cooling and liquid cooling using cold plates.[190,191] A key aspect of the efficiency of a thermal management system is the required coolant temperatures, which determine the efficiency of the heat pump. The efficiency of a heat pump decreases in concert with the difference between its condensation and evaporation temperatures. The required coolant temperatures for a safe—or optimal—operation depend on the needed heat flow, the available surface for heat exchange between the coolant and the battery cells, and the global heat transfer coefficient, which considers material properties, thicknesses, contact resistances, and fluid flow properties. These are considered by a simulation model used to calibrate the cooling control strategy, which can usually react in advance of predicted temperature changes.[192]

Some design concepts are summarized in figure 2.16 and shown in section 2.5.3.

In thermal management systems with a cold plate, a key problem is heat transfer between the cells and the cold plate, which should be sufficient and homogeneous across the dedicated surface. Production tolerances, contact pressure, and the presence of air bubbles might compromise heat transfer and, therefore, the system's safety.[194,195]

186 J. Kim et al. (Review on battery thermal management system for electric vehicles) 2019, p. 208.
187 Dubey et al. (Direct Comparison of Immersion and Cold-Plate Based Cooling for Automotive Li-Ion Battery Modules) 2021, pp. 1-3.
188 G. H. Kim et al. (Battery Thermal Management System Design Modeling) 2006, p. 15.
189 Gepp et al. (Temperature gradient reduction in high-power battery systems using prismatic cells combined with Phase-Change Sheets and Graphite foils) 2016, p. 5519.
190 Arora (Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies) 2018, p. 637.
191 G. H. Kim et al. (Battery Thermal Management System Design Modeling) 2006, p, 15.
192 Afram et al. (Theory and applications of HVAC control systems – A review of model predictive control (MPC)) 2014, p. 352.
193 Korthauer (Lithium-ion batteries) 2018, pp. 157-159.
194 Korthauer (Lithium-ion batteries) 2018, pp. 158-159.
195 Zichen et al. (A comprehensive review on thermal management systems for power lithium-ion batteries) 2021, pp. 9-11.

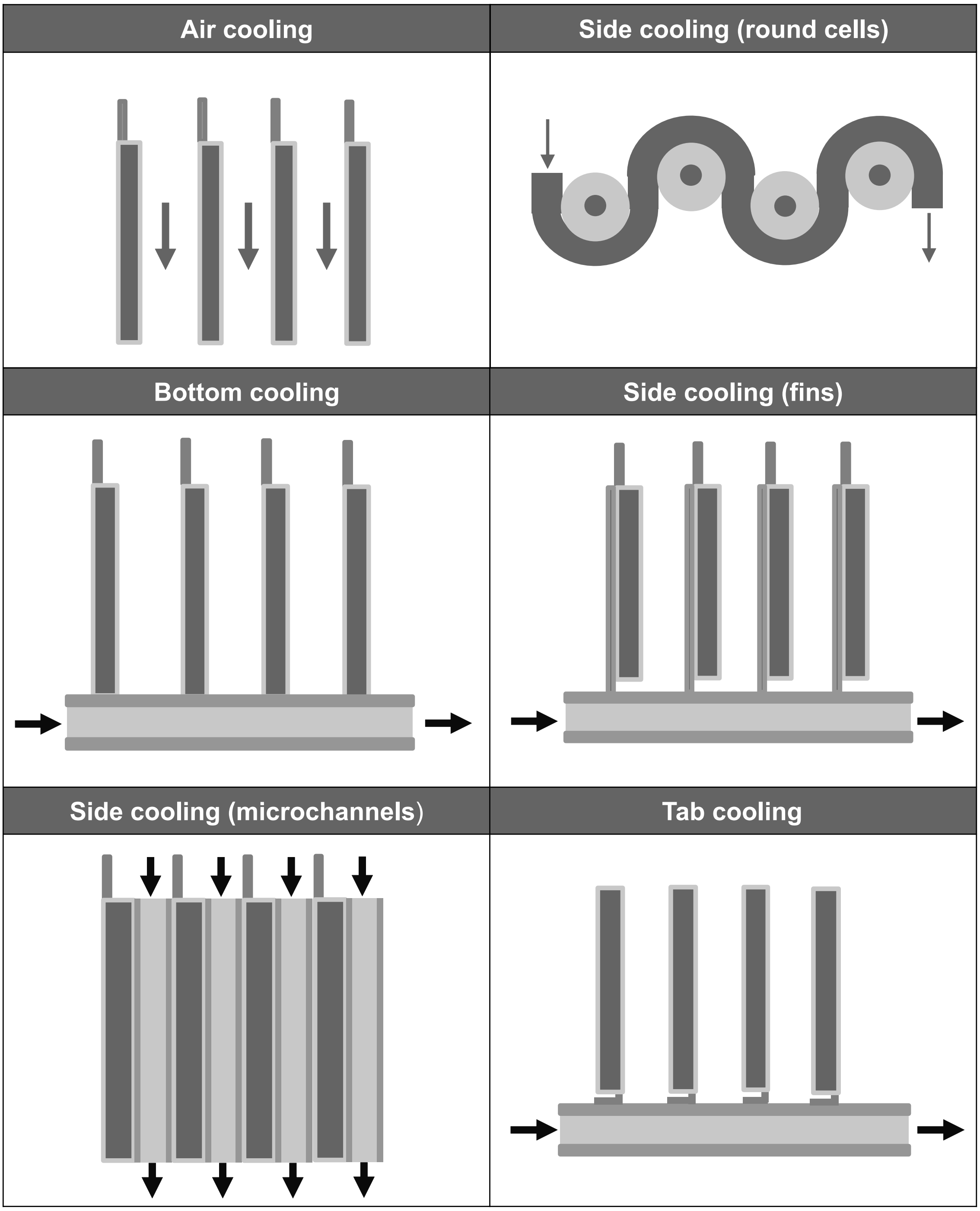


Figure 2.16: Different cell cooling concepts[193]

2.5.2.2 Gap fillers

According to the application type, several types of gap fillers exist. These ensure heat transfer between surfaces. Usually, the mechanical properties of gap fillers are given by a polymer matrix, in which thermally conductive filling particles are mixed. Gap fillers most often need to be electrically isolating, even if some other isolation is usually present in the design. This requirement limits the choice of filling materials. Typical electrically isolating filling materials are ceramics (aluminum oxide and nitride, silicon carbide, boron nitride), while electrically conductive filling materials are metal or carbon-based (graphite, nanotubes, fullerene) particles. The thermal conductivity of the matrix is between 0.1 and 0.5 $W/m^{\circ}K$, and one of the filling materials is between 30 and 300 $W/m^{\circ}K$. Hence, according to the combination and the filling ratio, overall conductivity is between 1 and 5 $W/m^{\circ}K$.

Thermally conductive paste or grease, silicon-based or silicon-free (common in electronics), wet the surfaces and stay liquid, so they need constant pressure. They are suited to small surfaces and require the design to prevent them from flowing away. Thermally conductive gels are a single-component, often silicon-based, curing compound that cures slowly after application. It does not usually solidify completely but remains plastic and lightly adhesive. For this reason, it can be removed quite easily. It is suitable for automated application because its thixotropic property enables low viscosity during application and high viscosity after. Thermally conductive glues are used when the most control over the curing process is needed, typically when a fast curing process is needed to either fill large, irregular gaps or when handling with substantial acceleration is involved. These are often epoxy-based and comprise two components that need to be mixed correctly during the application to start curing. Thermally conductive adhesive tapes made of PE or acrylate can be applied automatically on flat surfaces when the geometry allows. Thermally conductive pads are an alternative to tapes, which are softer and allow for greater geometric tolerance. They can be silicon- or polyurethane (PU)-based with filling materials. PCM can also be used to buffer temperature peaks. Because they are mostly based on wax (paraffin), they need to be contained by the design during the phase change.[196,197,198,199]

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196 Liu et al. (Recent progress of thermal interface material research - an overview) 2008, pp. 156-160.

197 Stadler et al. (Methods for Durability Testing and Lifetime Estimation of Thermal Interface Materials in Batteries) 2019, pp. 1-4.

198 Maurer (Smart Design of Electric Vehicle Batteries and Power Electronics Using Thermal Interface Materials) 2017, pp. 1, 3–5.

199 Zichen et al. (A comprehensive review on thermal management systems for power lithium-ion batteries) 2021, pp. 11.

Cell type	Pros	Cons	Interface features
Prismatic	Efficient packaging High stiffness	Large size High manufacturing cost	Locating features venting to the top
Pouch	Efficient packaging Many sizes	Low stiffness Relatively high cost	No locating features Venting at one side
Round	Stiffness and stability Lowest cost	Inefficient packaging Difficult cooling	Axial symmetry Venting at one pole

Table 2.3: Influence of cells formats on module design (based on LI ET AL.)[201]

2.5.2.3 Implications of thermal management for battery disassembly

In summary, the use of liquid cooling means that the piping and the battery pack must be emptied of coolant fluids before disassembly. Therefore, cooling systems in which each module has fittings for coolant are not optimal from this perspective. More important is the presence of gap fillers. Some kinds of gap fillers can be removed by applying force from certain directions. This makes automating disassembly slightly more difficult but not impossible. A design made for the circular economy should consider the joints between components, which need to exchange heat together for contact pressure, disassembly, and the stability of the gap fillers.

2.5.3 Module design

Because modular battery pack design is primarily driven by design for manufacturing (DfM), as explained in chapter 3, the purposes of current module design are to include a convenient self-contained item for handling and assembly, rework, and repairs; to host all the interfaces with the rest of the battery system; to preserve the cells from damaging mechanical stress; to provide heat transfer from and to the cells; and to contain the propagation of dangerous cell failures.[200]

Broadly speaking, cell format choice drastically influences module design, as table 2.3 shows.

Different manufacturing processes are fit for the specific handling characteristics of each cell type, so specific designs accommodate their manufacturing needs.

2.5.3.1 Modules with prismatic cells

The first process of module assembly is cell stacking, which must happen at maximum speed and without causing cell misalignment. Cell surfaces are cleaned and activated,

200 Korthauer (Lithium-ion batteries) 2018, pp. 90-97.
201 S. Li et al. (Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System) 2010, p. 4.

often by plasma. Then, they are glued together by fast adhesives, so that they can keep their position while the stack is quickly moved in a roll-and-eject or pick-and-place process (which is slower but viable because of the larger cell size).[202] Next, the module head plates are positioned so that they apply some pressure on the cells, counteracting internal cell pressure caused by the volume change in active materials due to charging and aging. The head plates are kept in place by the sides of the enclosures or by bolting.

To save weight and processing time, the side plates are welded to the head plates in the most common module designs, as figure 2.17 shows.

A tear-down on a module from a BMW i3 BEV was performed at PEM as part of the BatteReMan project and serves as the basis for assessing the possibility of improving the design with regard to the reuse of components (especially cells).

Many design features were observed during the module teardown to complicate disassembly and dismantling, as shown in figures 2.18, 2.20 and 2.21.

Figure 2.18 shows the relatively complex LV wiring harness for sensing cell voltages and temperatures. Each cable is clipped to a plastic frame that also serves as a fixture for the busbars. The thermocouples are pressed against the cells, allowing easy removal, and the voltage-sensing cables are attached by an epoxy resin, meaning that they can only be removed destructively. Unclipping the cables is not problematic when done manually but poses some challenges in automation, as the cables or the frame could be ripped if pulled too strongly from the wrong direction. The CSC is bolted to one side of the module, so it must be connected to the wiring harness by means of a connector.

A different approach to wiring harnesses is used in the VW MQB modules shown in figure 2.19. The CSC are located inside the module and connected by flexible circuit boards soldered to the busbars. This design presents a plastic frame with the same purpose of locating the busbars, CSC, and their connections. A connector between a wiring harness and CSC can be saved, facilitating automation in assembly and cost savings.

As also shown in figure 2.18, the busbars in the BMW i3 module are made from thin aluminum sheet metal bent into an S-shape to compensate for thermal expansion. Furthermore, they are folded over themselves, increasing both the available cross-section for electric current and the available surface area for natural convection cooling. These are positioned on top of the plastic frame by positioning features and welded to the cells in a circular pattern.

As shown in figure 2.20, the busbars can be mechanically cut because the plastic frame isolates the busbars from the cells. Therefore, debris cannot cause a short circuit provided it is removed directly during the cutting process. A vibrating holystone hand tool has been used to avoid debris being ejected at high speed and aspirated during

[202] S. Li et al. (Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System) 2010, pp. 4-5.

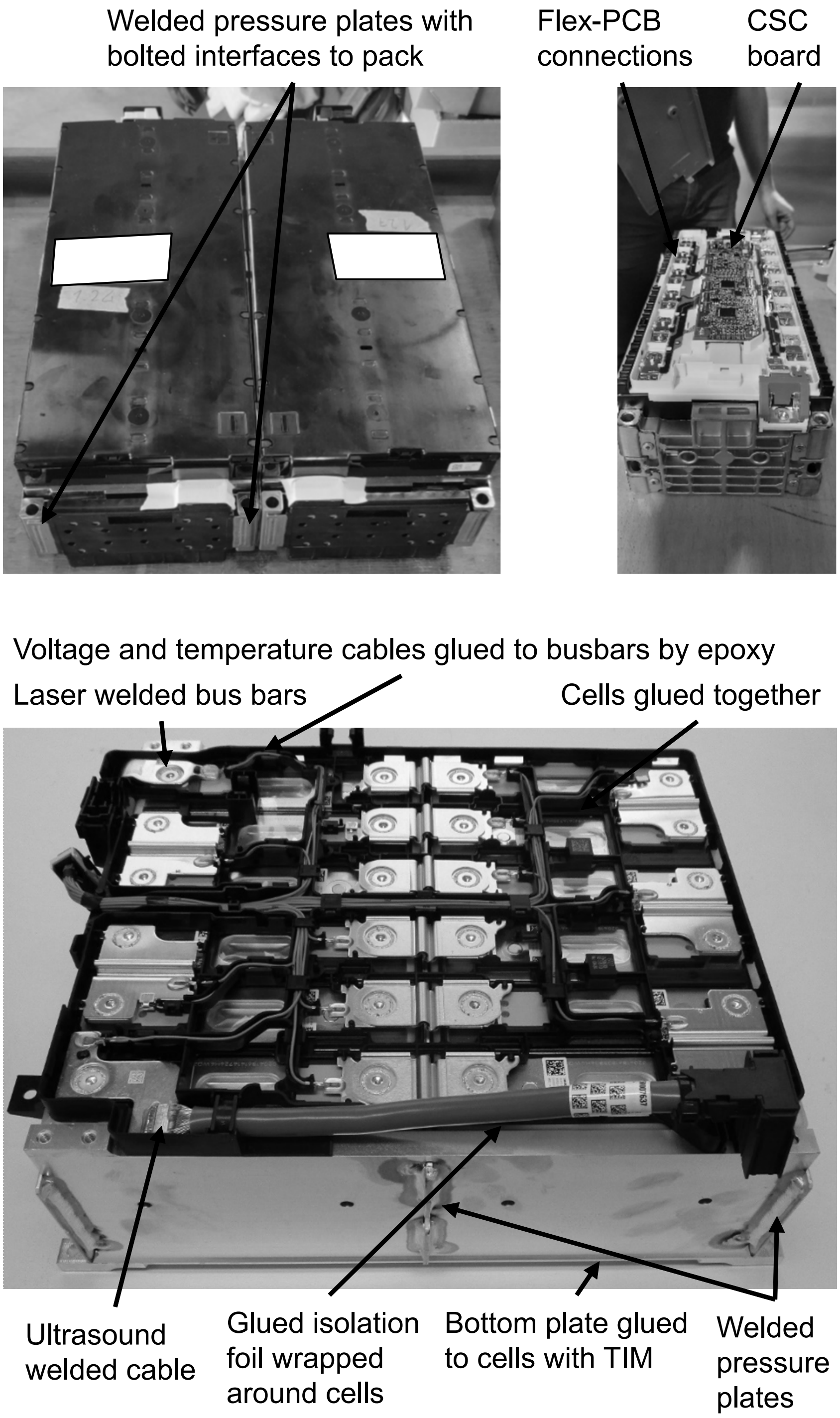


Figure 2.17: Examples of modules with prismatic cells: Audi eTron on the top left, VW MQB on the top right, BMW i3 on the bottom, from tear-down

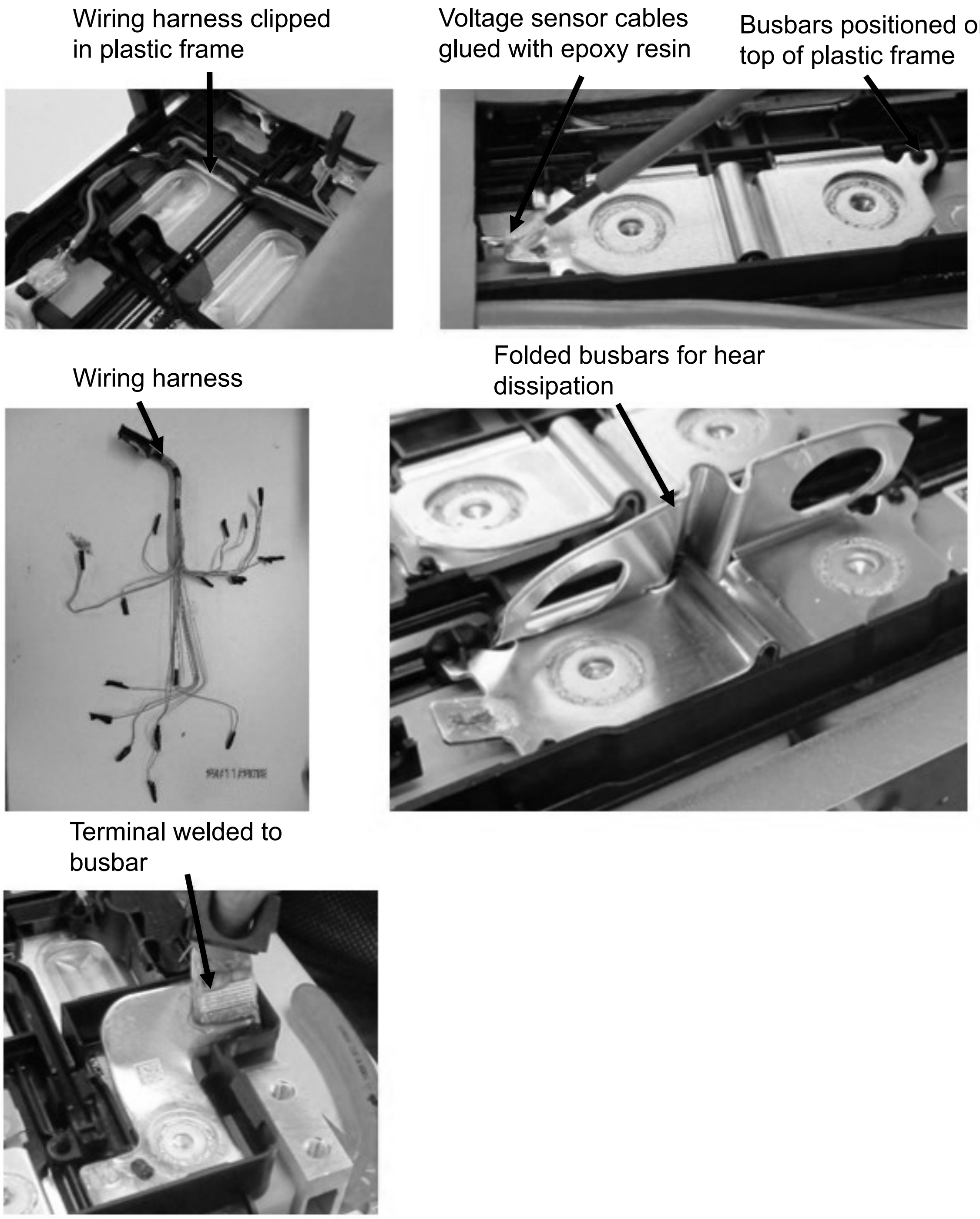


Figure 2.18: Removal of wiring harness and terminals of a module with prismatic cells during teardown

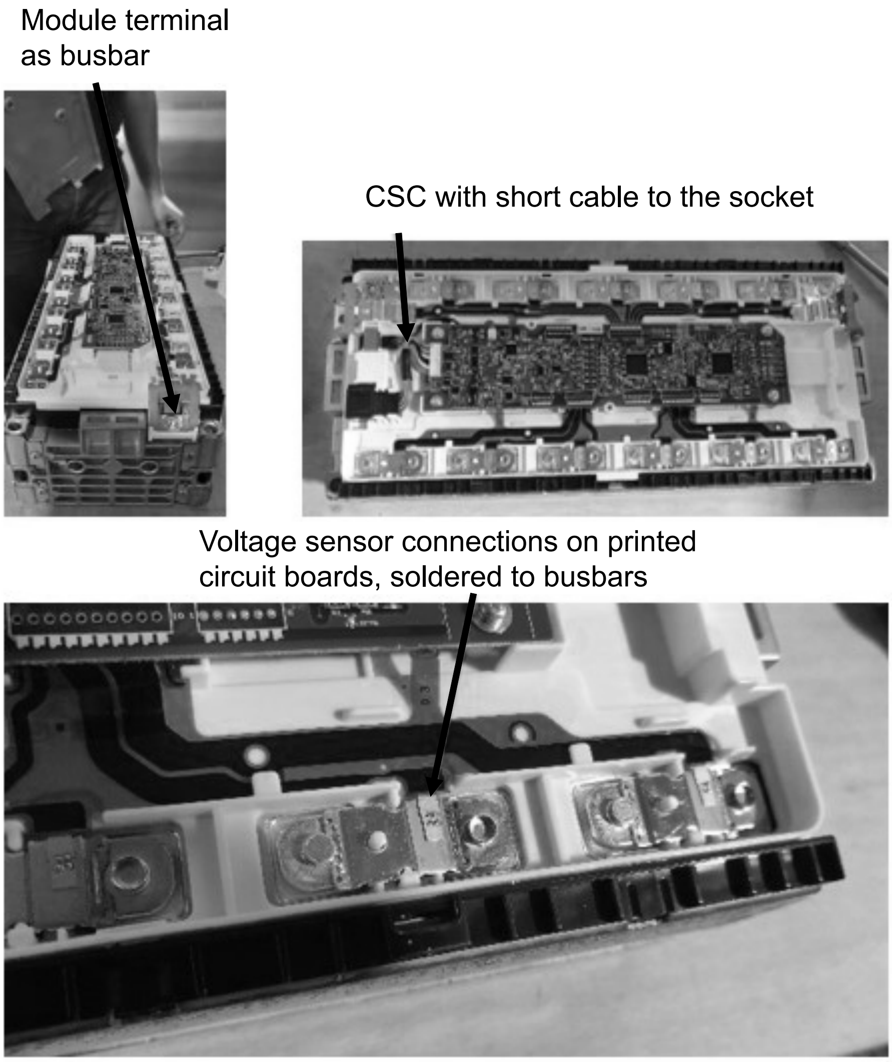


Figure 2.19: Detail of connections between CSC and busbars in the VW MQB module during teardown

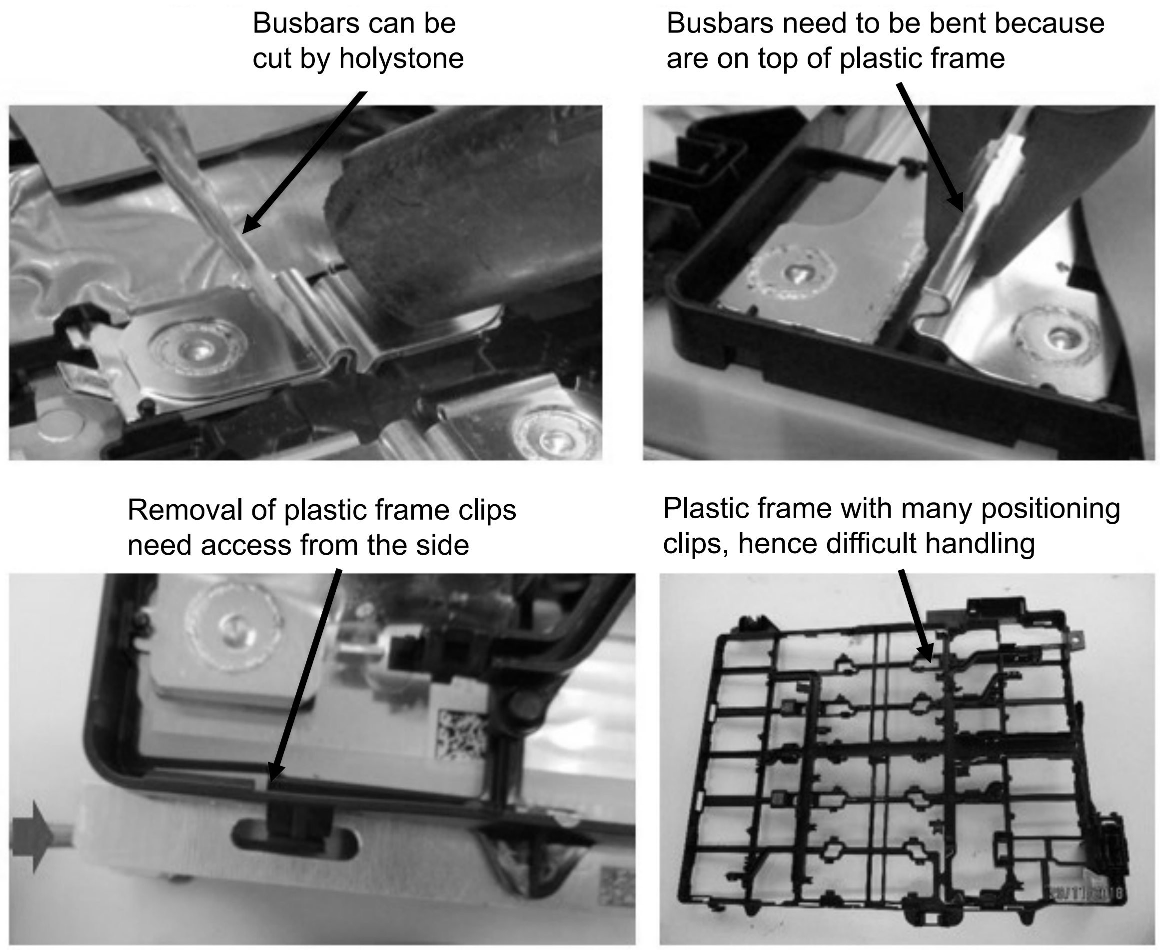


Figure 2.20: Removal of busbars and plastic frame of a module with prismatic cells during teardown

the cutting. The module terminals are cables ultrasound-welded to a busbar.

A further disassembly step involves the removal of the plastic frame, which requires tool access from one side to unclip the positioning features shown in figure 2.20. Notably, the cut busbars obstruct frame removal, meaning that they need to be manually bent. However, they should not touch the cell housing. For this purpose, an isolating foil has been placed between the cell housing and the plastic frame. However, this step would be difficult to replicable in a production environment, especially because the frame is over-constrained, requiring multiple tools and grippers to act at the same time or the frame to be bent with significant force and motion control.

As shown in figure 2.21, the housing is made of extruded profiles of an aluminum-magnesium alloy. Although this means, in the best-case scenario, it could be recycled separately from the other components, it remains quite difficult to disassemble. The side plates can be cut mechanically. However, the head plates are glued to a plastic insulation sheet that is glued to the cells. The head plates could be removed by applying a strong force that would tear the plastic sheet apart. The bottom of the modules is sheet metal made of the same aluminum alloy as the side and head plates, and it is kept in place by a thermally conductive gap-filler plate. The sheet metal can be peeled off destructively because the gap filler paste is not glued on too strongly. From a thermal perspective, the module bottom needs to be placed on the cold plate, which is on the bottom of the pack, and there needs to be more gap filler between the two. The presence of the gap filler on two sides of the aluminum bottom plate is an obstacle to thermal conduction and produces a considerable temperature difference between the cells. This is justified by the need to keep the bottom of each cell isolated, meaning that the system can tolerate two electrical insulation faults because cell housing cannot be connected by errors during pack assembly and handling, which would likely provoke an infringement on electrical safety requirements.[203]

For the same reason, the cells are glued strongly to one another, as shown in figure 2.22, meaning that they can be stacked quickly in a roll-and-eject process. The glue can be injected, as in patent US20190131678A1[204]. The process likely requires the glue to act rapidly and to be fluid to maintain a high stacking speed, and the glue strength is probably a side effect of this and other requirements, even if it exceeds the actual mechanical requirement during vehicle operation.

Avoiding the glue would require the development of manufacturing equipment that prevents cells from moving during the assembly process. This would allow issues that are usually not a priority to be addressed by the design. Examples might include detachable cell contacting, connecting CSC to cells, and thermal interfacing.

Obviously, this design poses many challenges for disassembly up to the cell level. In particular, the widespread use of glue has represented an insurmountable obstacle

[203] Standard (FMVSS 305) 2022.

[204] Soo-Youl et al. (Method For Manufacturing Battery Module) 2021, p. 1.

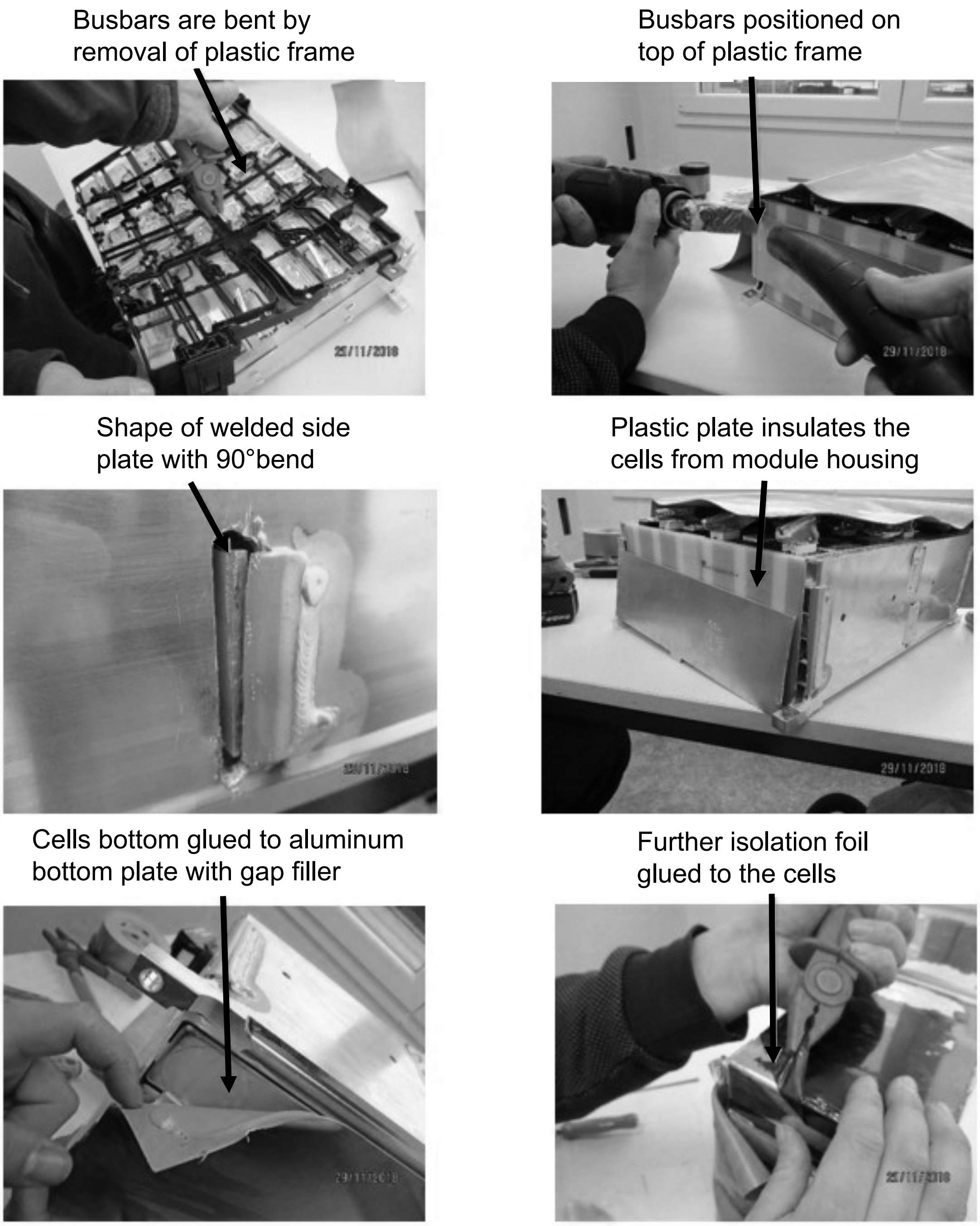
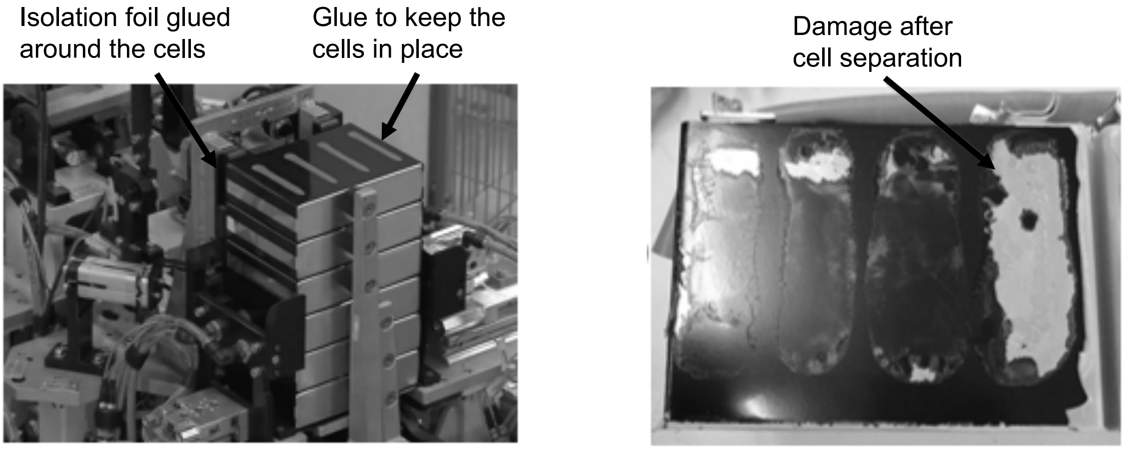


Figure 2.21: Removal of module housing and insulation with prismatic cells during teardown



(a) Stacking process of prismatic cells *Source: BMW A.G.*

(b) Damaged isolation foil and cell surface after teardown

Figure 2.22: Process of stacking prismatic cells with isolation foil and glue and results of cell separation during teardown

in the numerous trials attempted in this work. This is because neither a mechanical tool nor a chemical solvent could penetrate the small spaces between cells, and applying mechanical forces would damage the cells and cause unacceptably hazardous electrolyte leakage. Other design features that make disassembly to the cell level disadvantageous are the presence of over-constrained parts, especially ones whose removal requires contemporary tool access from different sides. Furthermore, removing parts that serve as insulation exposes the operator to the risk of a short circuit.

2.5.3.2 Modules with pouch cells

Pouch cells are most often stacked using a roll-and-eject process.[205] Their position is hard to locate because of the lack of positioning features in the pouch bag and the large dimensional tolerances. This means that the module design must accommodate such imprecision and cell volume change, which is not constrained by the pouch bag.

Some designs see the cells positioned inside a tray such that their relative positions and stacking tolerances are controlled by the tray.[206] An important requirement in modules for pouch cells is to avoid local mechanical stresses to the cells. A certain compressive pressure helps to maintain contact between cell elements and avoid delamination and deformation. Volumetric expansion due to charging and aging increases that pressure to a level that accelerates aging because of mechanical stress. According to

[205] S. Li et al. (Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System) 2010, pp. 4-5.

[206] Kritzer et al. (Dichtungs- und Elastomerkomponenten für Lithium-Batteriesysteme) 2013, pp. 127-128.

CANNARELLA ET AL., the optimal initial compression of pouch cells for long cell life should be between 0.05 and 0.5 MPa, which then evolves into a wide range, up to 10 times the initial pressure.[207] The module design must prevent high-stress concentrations and allow for cells' volumetric expansion, which is usually achieved by gap pads. Similar to prismatic cells and in accordance with standard electrical safety requirements, the pouch cells must be isolated from each other to avoid an internal isolation error causing a system-level isolation error.[208] This is especially important at the edges of cells, where aluminum foil is exposed by the cut. For this reason, the sides of the cells are usually bent. The tray presented by KRITZER has the additional function of assuring isolation and guiding venting gases in the event that the pouch bag is opened due to overpressure.

Modules from the disassembled Nissan Leaf batteries appear in figure 2.14 as they are mounted in the pack. Because these modules contain only four cells (eight in later versions), the housing is atypical, comprising a thin steel sheet-metal rectangular can, where the head plates have no rigidity, but the pressure on the cells is ensured by stacking the modules between two aluminum head plates, which are part of the pack and not the modules. The stack tolerance is achieved by tightening the bolts against the block of the cell-locating frames, the housing, and the distance and locating parts. Due to the housing flexibility, the cells, and the gap pads for a parallel tolerance stack, the cells are allowed to expand and contract against the gap pad, and they are subject to the same force.

A disassembled module from the Nissan Leaf in figure 2.23a shows the cell stack removed from the housing. The cell locating frames hold the ends of the pouch cells together, isolating them, preventing opening in the event of overpressure, and allowing the venting gas to flow at the opposite side of the cell contacts. On the sides, the cell foil is bent over for isolation and pressed for safety against the opening. The cells are connected in parallel in cell pairs by ultrasound welding by pressing the sonoctrodes against the cell-locating frames. The cell pairs are connected to the two terminals and to a central terminal, which senses the voltage in the same way.

A more common example of a module with pouch cells is the Audi eTron. Because the modules are sealed, cutting them open would have risked cutting the pouch cells, releasing dangerous electrolytes, and likely causing a short circuit.

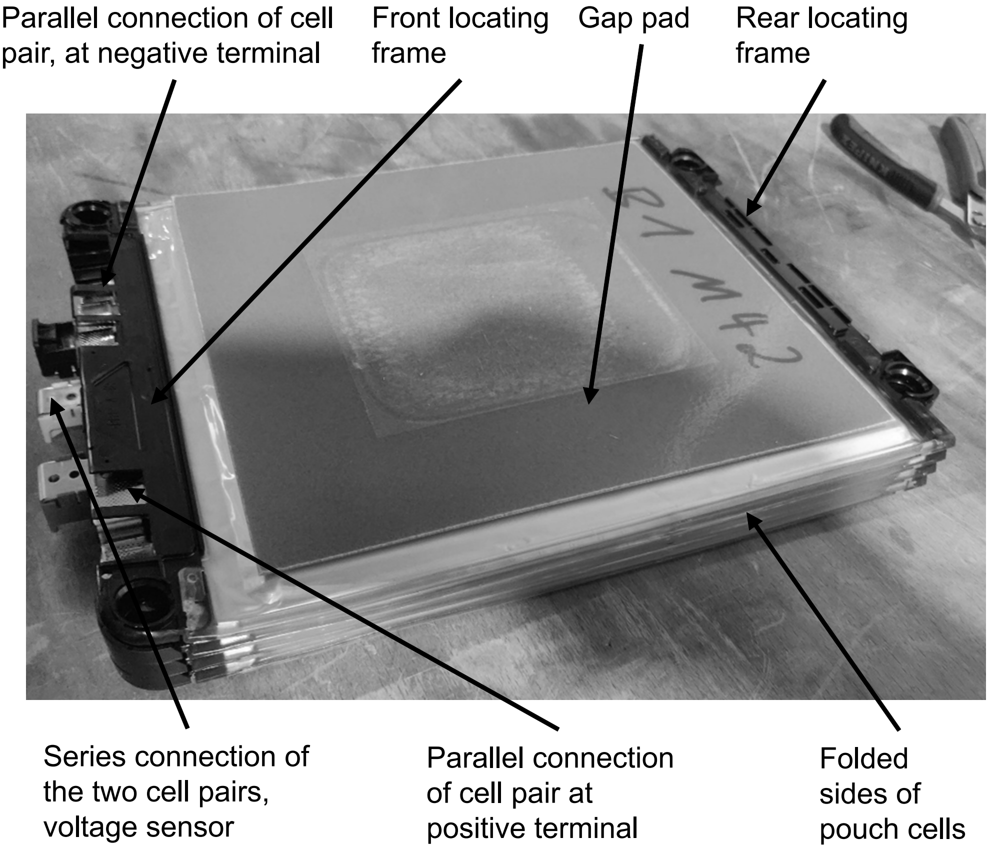
For this reason, the module has not been opened to obtain figure 2.23b, which is publicly available from the press release presentation of the Audi eTron 55 module, with 120Ah pouch cells made by LG Chem, in which strings of three cells are connected in parallel.

The cells are stacked with a gap pad in between them that absorbs the volume expan-

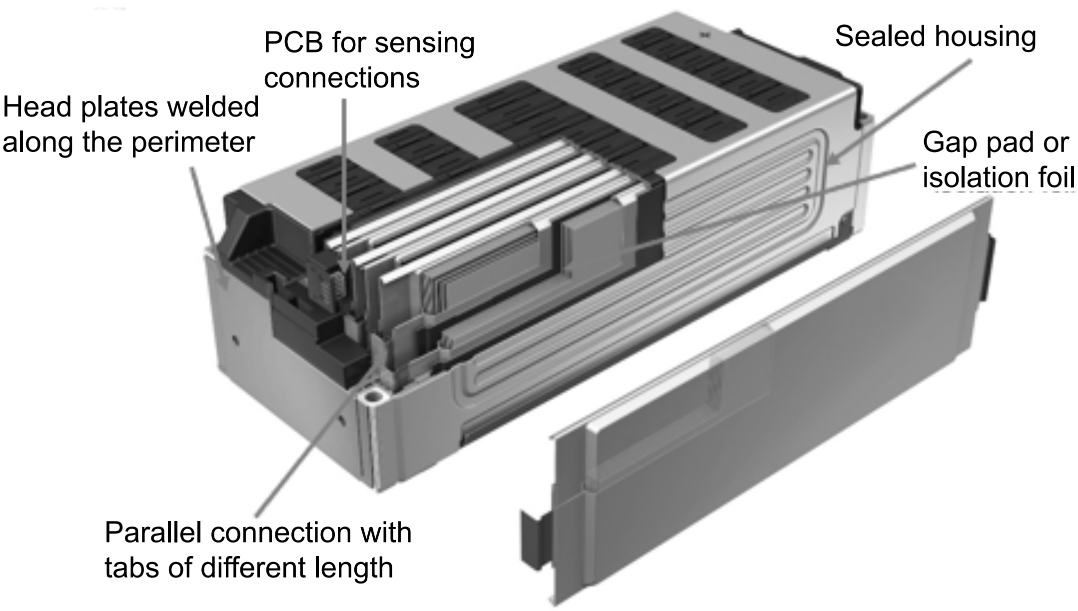
[207] Cannarella et al. (Stress evolution and capacity fade in constrained lithium-ion pouch cells) 2014, pp. 746-750.

[208] Standard (FMVSS 305) 2022.

[209] Audi (Batterie im Pouchzellen-Modul-Prinzip) 2015, p. 1.



(a) Disassembled Nissan Leaf modules, from teardown



(b) Concept picture of Audi eTron 55 modules[209]

Figure 2.23: Module designs with pouch cells

sion. The cells and gap pads are likely glued to each other to allow the insertion inside the aluminum housing that is isolated by plastic sheets. The head plates are inserted inside the housing and welded along the perimeter. The cell tabs are bent to connect three cells in parallel and four in series. A printed circuit board hosts the interface to the LV connector, to the external CSC, and to the cell tabs.

The figure does not show any feature of the thermal coupling to the outside. Cooling fins between the cells transfer the heat to the bottom of the module by heat transfer adhesive.

This and similar designs are difficult to disassemble up to the cell level. However, with sufficient information about the design, it could be possible to cut the housing open and extract the cell stack. Given the limited resistance of the gap pads (usually made of PU), the cells could be detached from one another, but at the risk of damaging the pouch bag, meaning it would be possible for recycling but not for cell reuse.

Many design challenges inhibit non-destructive disassembly up to the cell level. Examples include the necessity of compressing the cells, making extraction of the stack difficult without scratching and damaging those cells; the realization of a thermal interface on the soft pouch bag surface, precluding air gaps; the absence of features for cell handling during disassembly; detachable cells coming into contact with each other; and the detachable connection of CSC to cells.

Thus, non-destructive disassembly requires other solutions.

2.5.3.3 Modules with round cells

The first module assembly process involves cell insertion in a cell holder. Round cells are inserted into the holders with mechanical interference.[210]

Examples of common design features using this concept are demonstrated by the battery of a light delivery truck that was disassembled during the EFRE BatteReMan project and analyzed, as shown in figures 2.24 and 2.25.

The CSCs are bolted on a perforated plastic top plate inside the module, which is fixed by the busbar bolts. To remove the cells from the module housing, bolts need to be removed from all sides. These bolts fix the cell holders to create a stiff structure. The housing is isolated by plastic sheets that are also bolted onto the cell holders. The cells are stacked on two levels, with each level a 24 V string separated by a perforated plastic plate and rubber gap pads. Each string comprises a series connection of six groups of cells that are connected in parallel. The busbars connect the two strings in series, such that one of the two terminals features a 90° angle and is fixed in two directions. Furthermore, because the cells are fixed to the housing by plastic and rubber parts, the busbars are subject to vibration. To avoid bolts loosening, which would cause a potentially dangerous temperature increase in the bolted joint, the screws are glued.

[210] S. Li et al. (Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System) 2010, p. 5.

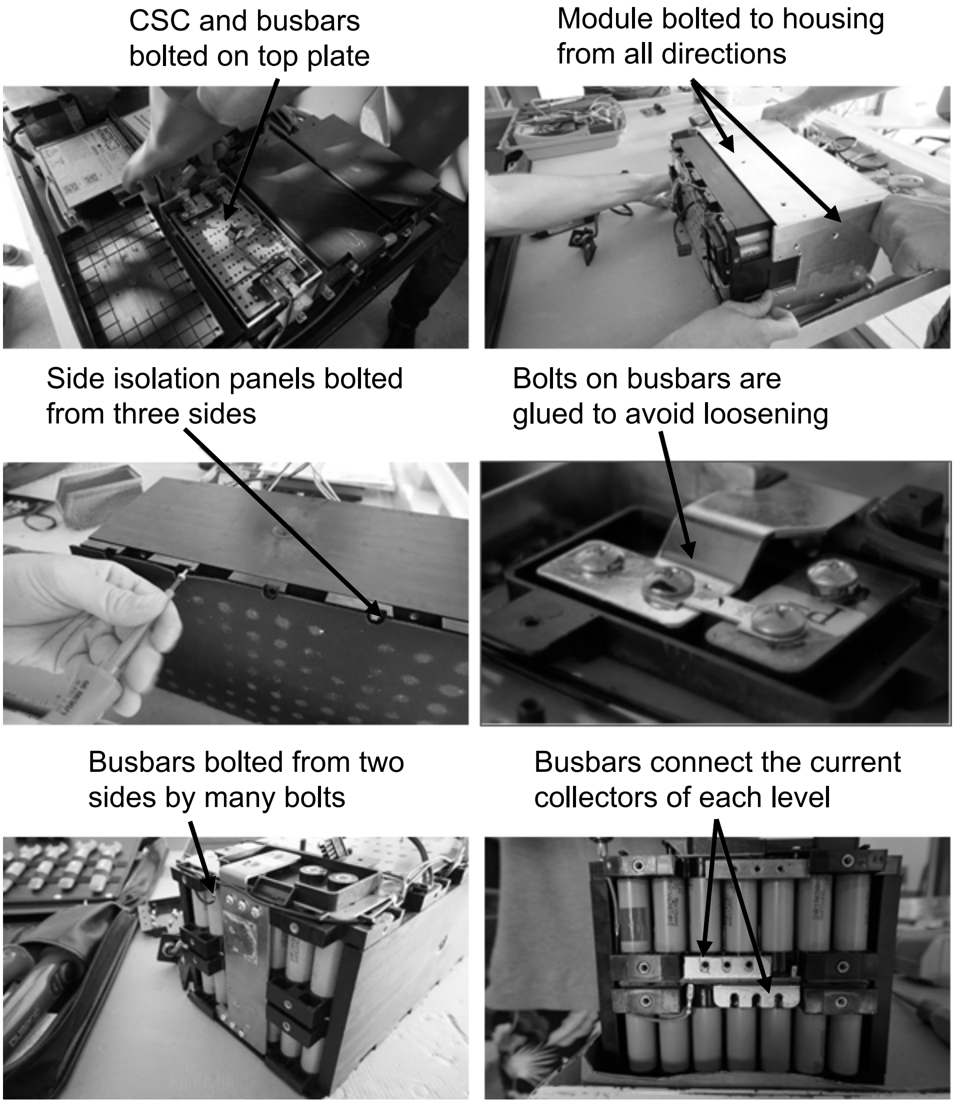


Figure 2.24: Teardown of a battery module used in the project BatteReMan: housing and terminals

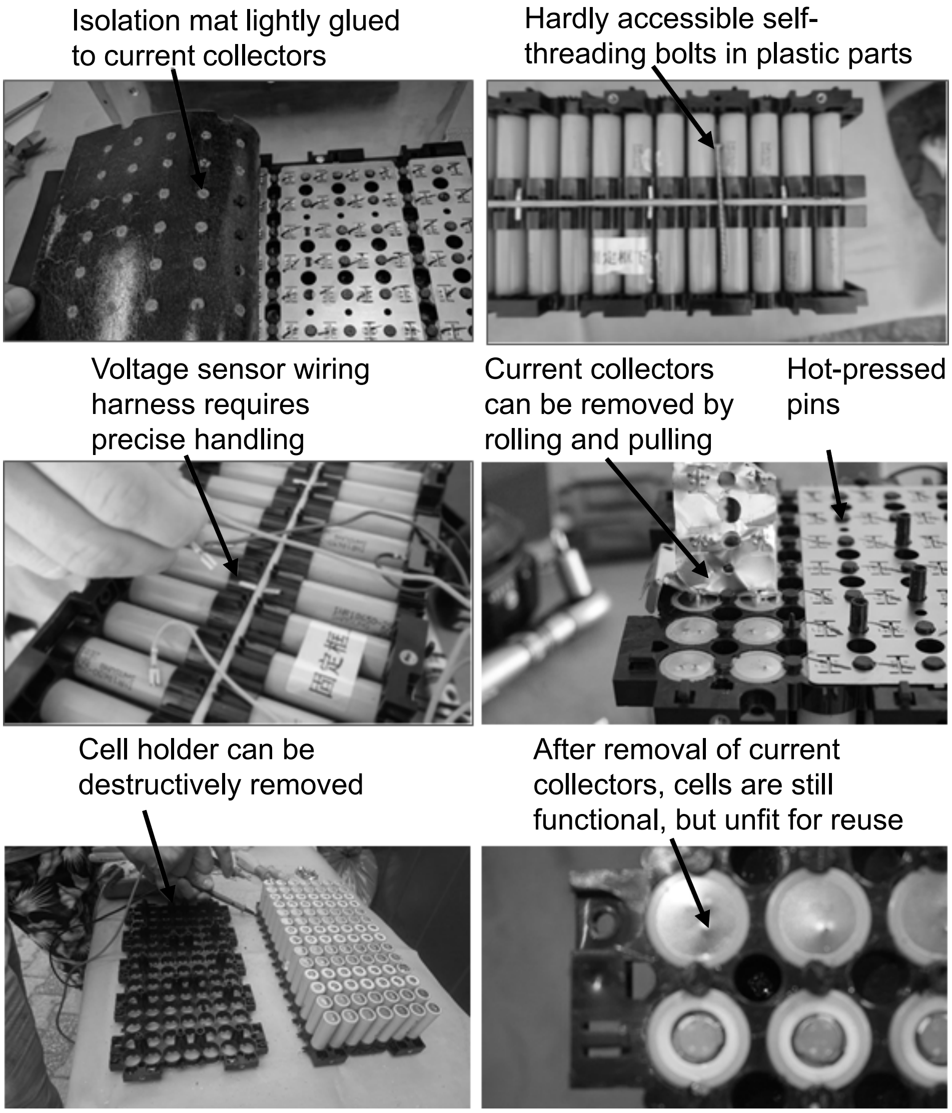


Figure 2.25: Teardown of a battery module used in the project BatteReMan: cell holders and wiring harness

The current collectors are isolated by a lightly glued rubber gap pad, and the ones on the side are bent to connect with the busbars. The cell holders are bolted together by self-threading bolts that are not easily accessible because the bolt heads are deep inside the modules. The cell holder keeps the current collectors in place with hot-pressed pins that can be destructively removed. Then, the current collectors can be removed by pulling and rotating them, while keeping the cells pressed down. In this way, functional single cells can be extracted. However, their surfaces are damaged in the welding spots, precluding reuse.

This means that, in principle, the cells can be recovered for recycling but not for reuse. However, the operation is time-consuming and requires precise handling and many-side tool access. Although the disassembly sequence is lengthy, most parts can also be destructively recovered. Notably, joints that are convenient during assembly are problematic during disassembly due to the difficulty locating and accessing them and the danger of damaging the cells.

This module design is not the most up-to-date: Some design issues have been solved by integrating most functions into the plastic cell holders. However, the features that prevent the economic recovery of reusable cells can be derived from it:

- Parts fixed in cascade to other parts prolong the disassembly sequence; instead, a common reference part (frame) to which all parts are connected allows a more flexible disassembly sequence and fewer part placements.
- The need for tool access from many directions requires many handling steps during disassembly; meanwhile, tool access from a single direction secures parts placement and the tolerance chain while also reducing the possibility of vibrations.
- A two-level module reduces the accessibility of the wiring harness and increases the length of the disassembly sequence.
- Although plastic cell holders present no difficulty in terms of extracting cells, they could be used to fix other parts with interference fit, instead of hot pressing them.
- The cell-welding parameters are such that the cells are damaged when the current collector is removed. This is probably implemented to ensure good electrical contact and the mechanical stability of the joints.

An alternative to a solid cell holder is a flame retardant foam or gel, as in the Tesla Model 3 presented in figure 2.26 by Bower.[212]

In theory, this solution would be optimal for disassembly if it were possible to debond and dissolve the gel by chemical or other means to recover the cells without damaging their housing.

[211] Bower (New Tesla Model 3 Battery Details, Images & Video Released) 2018, p. 1.
[212] Bower (New Tesla Model 3 Battery Details, Images & Video Released) 2018, p. 1.

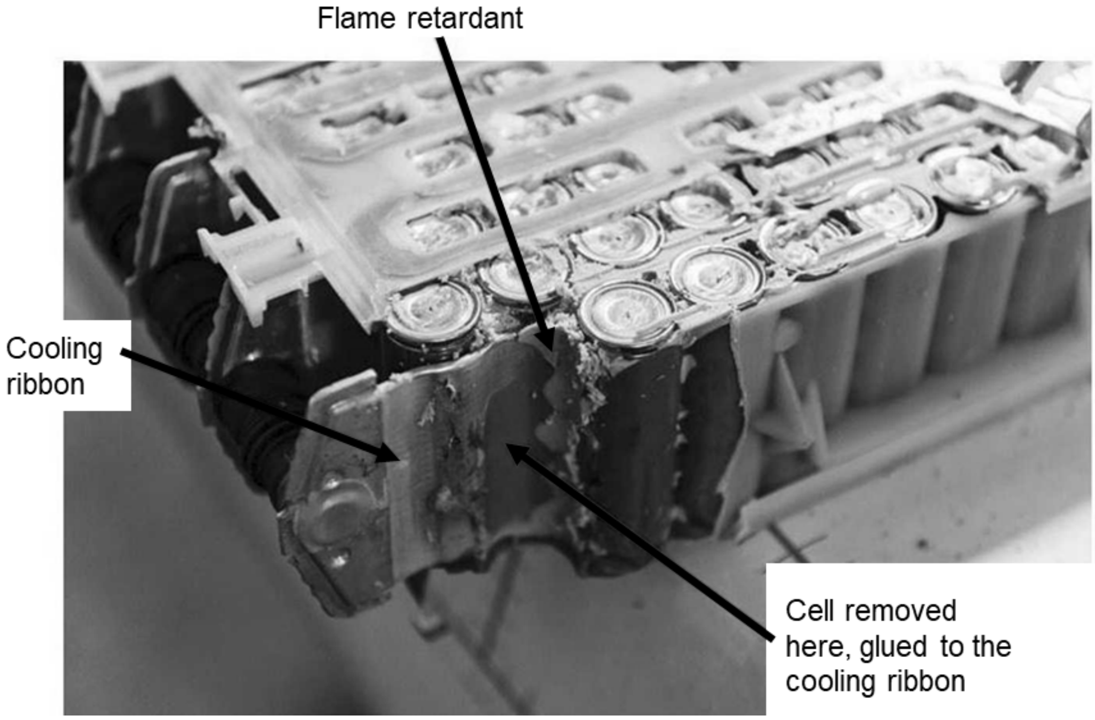


Figure 2.26: Detail of Tesla Model 3 battery module[211]

2.5.3.4 Implications of module design for battery disassembly

Current module designs are a major obstacle to the safe and non-destructive recovery of cells and other homogeneous components because they utilize several non-detachable joining techniques for functional, safety, or economic reasons connected to cell-stacking processes. The need to isolate the housing of different cells produces the need to isolate materials that are glued to the cells to ensure their position. The cells are often glued together to allow fast processing times in automatic production lines. The need to transfer heat from the cells results in the widespread use of liquid TIMs. The module housings are often welded to provide safety against thermal propagation, compensate for stacking tolerances, and facilitate fast processing times. The cells are welded together to ensure low internal resistance and low processing times. The next section analyzes the joining techniques used in the module and pack production process to identify potential alternative designs that would allow cell recovery.

2.6 Assembly and disassembly

To assess the potential for disassembly, it is important to understand the assembly process chains of modules and packs.

2.6.1 Module assembly

The cells arrive at the assembly line at a SoC between 30% and 50% and are scanned for serial number and classification to ensure that battery packs are built with homogeneous cells. Round cells are inserted into the cell holders, with more steps required for pouch and prismatic cells. These are cleaned and their surfaces are activated for the subsequent gluing process. Isolation foils are applied as needed to ensure two-fault tolerance and isolation resistance, and then they are stacked. Next, the stack is compressed between the head plates and the module housing is assembled.

At this point, the cells make contact, as explained in section 2.6.2, and the LV wiring harness or circuit board is positioned and connected. Finally, the CSC is mounted and connected and the module housing is closed. According to Berckmans, module assembly accounts for 5% of the total cost of battery packs.[213]

2.6.2 Joining technology of between-cells contact

Various processes are currently used to electrically connect cell poles.[214] Reliable contact between cells and modules is essential for the safe and proper functioning of a battery system. That contact must fulfill many requirements.[215] Schmidt divides the requirements for electrical contact into three areas: lightweight construction, production, and function. In terms of weight, Schmidt says that it is desirable to design the contact elements to be as weight-optimized as possible to limit the total weight of the battery system to the extent possible. The joining technology sets the limits for the feasibility of contact. According to Schmidt, the requirements for contact with regard to production are safety during the assembly process, the quality of contact, and production time. The quality of cell contact refers to the constant electric resistance of the various joints (the time required to test all contact resistances and rework modules would be prohibitive). During assembly, cells and modules must not be damaged, with particular vigilance demanded against short circuits and high heat flow, which could propagate into the cells and exceed the cell temperature safety window. Schmidt primarily mentions low-contact resistance as the primary functional requirement, because the main function of electrical contact is to transmit electrical energy with as little loss as possible. Because high-power losses at the joint might cause overheating, this requirement is linked to safety. There is also a requirement to keep contact resistance as constant as possible over the service life of the battery to avoid failures and the uneven aging of the cells.[216] Beyond those listed by Schmidt, further requirements regarding

[213] Berckmans et al. (Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030) 2017, pp. 12-13.

[214] Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, p. 1.

[215] Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, p. 2.

[216] Schmidt (Laserstrahlschweißen elektrischer Kontakte von Lithium-Ionen-Batterien in Elektro- und Hybridfahrzeugen) 2015, pp. 12-13.

the mechanical strength of contacts can be derived from the work of DAS ET AL. These contacts would have to be designed without sensitivity to deformations and vibrations to avoid damaging the contact mechanism, which is also a concern for induced residual stresses and vibration energy.[217]

ZWICKER[218] and SCHULER[219] analyzed the interdisciplinary challenges of joint technologies:

- Mechanical: dynamic loading because of inertia, especially periodic vibrations, amplified by the modules' periodic structures, which causes many vibration modes to resonate at close frequencies. Residual stress from the joining process and from cell volume change are superimposed on the dynamic loads.
- Thermo-mechanical: thermal expansion of different joined materials causes additional stress.
- Electro-thermal: heat generation because of the energy dissipated by the joint's electrical resistance can cause faster battery aging and safety hazards.
- Electro-mechanical: materials fatigue increases electrical resistance.
- Metallurgical: atmospheric and galvanic corrosion (oxidation at the interface between two materials), as well as fretting corrosion at the interface between two vibrating materials.

2.6.2.1 Welding

The possible working principles of the electrical joints used in batteries are:[220,221,222]

- Resistance and laser welding, which melt metals at the joint interface into different phases (alloys).[223,224,225,226,227]

217 Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, pp. 2, 9.
218 Zwicker et al. (Automotive battery pack manufacturing – a review of battery to tab joining) 2020, p. 3-12.
219 Schuler et al. (Praxiswissen Schweißtechnik) 2019.
220 Brand et al. (Welding techniques for battery cells and resulting electrical contact resistances) 2015, pp. 8-11.
221 Martinsen et al. (Joining of dissimilar materials) 2015, pp. 1-7, 11.
222 Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, p. 3.
223 Schedewy et al. (Prospects of welding foils with solid state laser for lithium-ion batteries) 2011, p. 817-818.
224 Reisgen et al. (Influence of the degree of dilution with laser beam vacuum-welded Cu-Al mixed joints on the electrical properties) 2018, pp. 23-24.
225 Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, pp. 3-5.
226 S. S. Lee et al. (Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review) 2010, p. 2.
227 Fahrenwaldt et al. (Praxiswissen Schweißtechnik) 2014, pp. 7-96.

Joining method	Pros	Cons
Resistance welding	Low cost Efficiently automated No protective atmosphere Standard quality control	Limited joint area No very conductive materials Electrode sticking Possible cell damage
Laser welding	No contact process Little thermal input Very high precision High speed	Limited joint area Needs good joint fit Protective atmosphere Investment cost
Ultrasound welding	No melting process Fits conductive materials Fits different materials No atmosphere	Only overlap joints Limited thickness Needs surface quality Sonoctrode sticking
Mechanical joining	No heat input Easy disassembly	Long process time Added parts and mass

Table 2.4: Cell-joining technologies; based on LEE ET AL.[236]

- Ultrasound welding, which causes material plasticization at the joint interface by pressure and vibrations, such that they adhere to each other in a solid state.[228,229,230,231]
- Wire bonding, which involves ultrasonically welding wires onto a prepared surface.
- Soldering, whereby a molten material that adheres to both parts is poured and solidifies in the joint.[232,233]
- Mechanical joints, which are realized by pressing the joint surfaces together using bolts or clamps. The real contact area is considerably smaller than the joint area due to surface irregularities.[234,235]

228 Shin et al. (Parametric Study for Low-Resistance Joint of REBCO Coated Conductor Tapes Using Ultrasonic Welding) 2016, p. 4.
229 Schedewy et al. (Prospects of welding foils with solid state laser for lithium-ion batteries) 2011, pp. 817-818.
230 S. S. Lee et al. (Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review) 2010, p. 3.
231 Fahrenwaldt et al. (Praxiswissen Schweißtechnik) 2014, pp. 99-136.
232 Jagt (Reliability of electrically conductive adhesive joints for surface mount applications: a summary of the state of the art) 1998, p. 215.
233 Brand et al. (Electrical resistances of soldered battery cell connections) 2017, pp. 45-47.
234 Brand et al. (Detachable electrical connection of battery cells by press contacts) 2016, p. 76.
235 S. S. Lee et al. (Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review) 2010, p. 4.
236 S. S. Lee et al. (Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review) 2010, pp. 2-8.

Lee et al. summarized the pros and cons of typical cell-joining technologies. Their findings appear in table 2.4.

2.6.2.2 Soldering

Soldering is a thermal process in which a material bond can be produced between two metallic joining partners by using a molten brazing alloy. The melting temperature of the solder is always below the melting temperature of the materials to be joined. Heating the solder to the melting temperature can be achieved by various methods. Since July 1, 2016, the use of lead-free solders has been mandatory to protect human and animal health and the environment.[237,238,239] In the manufacture of electrical contacts, soft soldering is generally used to protect temperature-sensitive components and achieve better contact resistance. By priming the surface, the oxidation layer of the materials to be joined is removed by a chemical process and further formation of this layer is prevented during the soldering process because an oxidation layer would prevent contact between the molten solder and the metal. Given that residues from the primer liquid can lead to corrosion, it is important to remove them after the soldering process or use non-corrosive primers. When a solder is applied to a metallic, prepared workpiece, bonding occurs due to adhesion. If the temperature is sufficient, diffusion processes also occur, further increasing the adhesion of the solder to the metal.[240] Wetting a metal piece with solder is described by the angle between the solder drop and the surface, which should be between 0°and 30°.[241] Soldering copper to aluminum presents a complication because aluminum has a more resistant oxidation layer and a significantly lower melting temperature than copper. This requires that a solder with a lower melting temperature than aluminum be selected. Meanwhile, the primer must be able to remove the resistant oxidation layer of the aluminum. The use of primer and solder for aluminum materials usually results in poorer wettability of the copper workpiece. Research results have shown that the wettability of copper can be significantly increased with a zinc-nickel coating of 16 μm thickness. The dihedral angle could be reduced by a factor of at least 6 when using Zn-Al solder.[242] In addition, shear tests have demonstrated that shear strength could be increased from 24.6 MPa to 73-76 MPa. However, the extent to which this coating affects the electrical resistance of the joint still needs to be evaluated. Accordingly, soldering is not commonly employed in HV batteries.

[237] European Parliament (Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)) 2003, p. 5.
[238] European Parliament (Directive 2012/19/EU on waste electrical and electronic equipment (WEEE)) 2012, p. L 174/100, L174/103.
[239] Förster et al. (Einführung in die Fertigungstechnik) 2018, p. 116.
[240] Brand et al. (Electrical resistances of soldered battery cell connections) 2017, p. 46.
[241] Fahrenwaldt et al. (Praxiswissen Schweißtechnik) 2014, pp. 141-142.
[242] Mirski et al. (Soldering of aluminium with copper and steel using intermediate layer Zn–Ni) 2015, pp. 903-904.

2.6.2.3 Mechanical joining

Electrical contact by mechanical joining processes is achieved by pressing the joined parts together. This means that it is also possible to join materials of different types.[243] Except for noble metals, metallic surfaces are usually covered by layers such as oxides, sulfides, or organic coatings. In addition, they are rough, so if two such surfaces are pressed together with sufficient force, the highest peaks on the contact surface will deform elastically and, with increasing force, plastically. If sufficient force is applied, the extraneous layers can be ruptured, establishing direct metallic contact between the mating surfaces.[244] A mechanical joint is characterized by the apparent contact area, that is, the area on which contact can occur between the contact pieces. This is the surface area "occupied by the joint." In contrast, the load-bearing contact area is the sum of the effective contact areas on a microscopic scale, and it is much smaller than the apparent contact area. The contact resistance between two joining partners is largely the result of constriction resistance and impurity resistance. Constriction resistance is caused by a constriction of the current lines from a bigger to a smaller area, with impurity layers on the surface of the joining partners resulting in an impurity layer resistance.[245] Based on these principles, it is evident that contact resistance depends mainly on the contact pressure of the two joining partners, the electrical conductivity, and the surface properties of these elements. Research results demonstrate that the contact resistance of joining partners made of identical materials decreases with increasing contact pressure.[246] The increase in contact pressure results from the larger contact surfaces and leads to a decrease in contact resistance. The influence of the surface finish on the contact resistance depends on the material. A material such as aluminum has a hard, poorly conducting oxidation layer, meaning that roughening the aluminum surface can lead to lower contact resistance when the two parts are pressed together.[247] Reduced contact resistance results from more pronounced micro-peaks on the surface of the aluminum that can better penetrate its hard oxidation layer. Experiments have shown that various samples of brass, copper, and nickel-plated steel each sort in descending order of their material-specific electrical conductivity. In contrast, aluminum has a lower electrical conductivity than brass and exhibits significantly higher contact resistance than brass at the same contact pressure. This is due to its very hard oxidation layer, which must first be broken.[248] Tests have shown that the contact resistance between two aluminum joining partners could be reduced by increasing surface roughness. Aluminum's hard oxidation layer can promote problems when joining with a copper workpiece because the oxidation layer of copper has a significantly lower hardness than the oxidation

[243] Martinsen et al. (Joining of dissimilar materials) 2015, pp. 1-5.
[244] Vinaricky (Elektrische Kontakte, Werkstoffe und Anwendungen) 2016, p. 4.
[245] Vinaricky (Elektrische Kontakte, Werkstoffe und Anwendungen) 2016, pp. 5-7.
[246] Brand et al. (Detachable electrical connection of battery cells by press contacts) 2016, pp. 75-76.
[247] Vinaricky (Elektrische Kontakte, Werkstoffe und Anwendungen) 2016, pp. 7-12.
[248] Brand et al. (Detachable electrical connection of battery cells by press contacts) 2016, p. 74.

layer of aluminum. The extent to which the contact resistance of an aluminum-copper interference fit is affected by the surface finish of the aluminum workpiece remains to be evaluated.[249] The following sections present various methods for implementing press-fit joints.

2.6.2.4 Bolted connection

Bolted connections belong to the group of mechanical joints and are detachable fasteners. They allow non-destructive disassembly, and they are often used where a non-detachable connection is absolutely necessary. The connection between the components to be joined is mainly based on the surface pressure, which is generated by screws. Independent loosening of the screws is mainly prevented by the friction in the thread.[250,251] Notably, in bolted connections, surface pressure can decrease due to their settling behavior or the plasticization of the contact area. This can increase contact resistance. Thus, when designing a bolted connection, a surface pressure that is as constant as possible must be guaranteed over its service life. If the screw loosens, the higher electrical resistance can cause a dangerous temperature increase.[252] No expensive tools or machines are required for joining, and there is no heat input into the components to be joined. However, the additional weight of the required components, such as bolts and nuts, has a disadvantage. Furthermore, high demands are placed on the quality and, thus, the assembly process of the bolted joint.[253] Constant, reproducible contact resistance must be reliably achieved during both manufacturing and the screw connection's lifespan to prevent differential loading and aging of cells or modules.[254]

2.6.2.5 Clinching

Clinching refers to permanently joining overlapping sheets by cold forming using a punch and die. Cold forming produces a force-fit and form-fit connection. No further joining elements, additives, or auxiliary materials are required for joining. As with bolted joints, there is no heat input into the materials to be joined. However, several factors can increase contact resistance over the course of the joint's service life: the loosening of the joint due to vibration, the settling of the materials, and moisture penetration.[255]

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[249] Brand et al. (Detachable electrical connection of battery cells by press contacts) 2016, p. 74-75.
[250] Martinsen et al. (Joining of dissimilar materials) 2015, p. 2.
[251] Vinaricky (Elektrische Kontakte, Werkstoffe und Anwendungen) 2016, pp. 556-559.
[252] Gatherer et al. (A Multi-Variable Parametric Study on the Performance of Bolted Busbar Contacts) 2015, p. 1, 5.
[253] Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, pp. 2, 6.
[254] Xin et al. (Characteristics of Overheated Electrical Joints due to Loose Connection) 2011, pp. 1, 5–6.
[255] Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, pp. 3, 6.

2.6.2.6 Implications of module design and joining technologies for battery disassembly

Because all welding processes realize a material connection, they are optimal from a functional and safety point of view. Unfortunately, these joints can be disassembled only destructively, and the module design does not always allow for a safe way to break the welded joints without damaging the cells with debris, high temperatures, or mechanical force.[256]

Mechanical joints, such as clamps, are not used because of their additional parts and susceptibility to vibrations. Nevertheless, BRAND ET AL. researched the feasibility of clamped contacts on cells and concluded that lower electric resistance (compared to welding) is possible with a marginally higher contact area than ultrasound welding. However, no results are yet available about the service life in real conditions.[257] Bolted joints are used between modules, but they are no longer used between cells of the same modules because of cost, weight, and reliability issues. SINGER ET AL. proposed a design with self-threading bolts capable of a single disassembly that featured double the electrical resistance of a laser-welded joint. This means that its use is viable only for connecting strings of many cells that will be disassembled in a single unit.[258]

2.6.3 Module disassembly

GERLITZ ET AL. examined the possibility of automatically disassembling modules up to the cell level for recycling or cell reuse using a branched morphological box. After classifying the joints and the separation operations, they concluded that some operations must be destructive or partially destructive. Two layers of fixation have been identified:

- Cell-to-cell, or primary fixation
- Group-of-cells to housing

They concluded that at least one of the two, and usually the first, includes non-detachable joints (e.g., glue) for pouch and prismatic cells.[259]

SCHÄFER ET AL. analyzed the possibility of redesigning a battery module with prismatic cells capable of remanufacturing with only detachable joints. Each joint was examined, with the following results:

- The need for adhesive flexible elements between the cells is acknowledged.

[256] Das et al. (Joining Technologies for Automotive Battery Systems Manufacturing) 2018, pp. 7-12.
[257] Brand et al. (Detachable electrical connection of battery cells by press contacts) 2016, p. 76.
[258] Singer et al. (Demontagegerechtes Batteriemodul) 2018, pp. 102, 103.
[259] Gerlitz et al. (Analysis of the Variety of Lithium-Ion Battery Modules and the Challenges for an Agile Automated Disassembly System) 2021, pp. 176-179.

- The substitution of laser welding with conductive glue was excluded because of the long curing time.
- Wire bonding was excluded because thin wires cannot transmit the required current.
- Self-threading bolts demonstrate considerably greater electrical resistance than laser-welded joints.
- The module can be tightened by straps instead of welded side plates but at a higher cost and process complexity.
- The laser-welded joints can be milled, but the cells need to be protected from debris and accidental drilling.
- A single cell can be replaced while a special gripper keeps its place open by compressing the other cells.

In summary, although the possibility of designing prismatic cell modules to enable remanufacture has been proven, it implies an extra cost or performance reduction compared to the state-of-the-art.[260] This effort does not seem justified from an economic perspective (i.e., to hold onto the possibility of an expensive remanufacture operation at an uncertain time in the future).

Although gluing and welding operations decrease processing time for module assembly, they make disassembly extremely hard and less economical, meaning that, in practice, modules are not disassembled before recycling. Furthermore, applying force to detach strong glues and cutting welding joints can damage the cells, making module disassembly dangerous. As explained in section 2.7.1.2, the modules are mostly shredded as a whole, which negatively impacts the safety and durability of the shredding operation.

2.6.4 Battery pack assembly

Battery pack assembly consists mostly of handling and bolting operations. Pack housings are generally made of homogeneous metals, such as steel sheet metal or (more commonly) aluminum alloys. Cold plates and piping are sometimes integrated into the housing and sometimes mounted afterward, and their sealing is tested before the assembly of the electrical component starts. The assembly of modules, junction boxes, and electronics is widely robotized and followed by the HV connections, which must happen under two-fault tolerant conditions. These safety conditions are enabled by covering exposed HV surfaces with service covers, by integrating the covers into the

[260] Schäfer et al. (Challenges and Solutions of Automated Disassembly and Condition-Based Remanufacturing of Lithium-Ion Battery Modules for a Circular Economy) 2020, p. 619.

battery pack itself, and by having the surfaces sunk in isolating components. Tolerances in the pack assembly occasionally need some positioning help, such as fixtures or camera systems. The LV wiring harness is then mounted, mostly manually, before the housing is closed. Liquid sealant is often applied automatically to the housing flange to ensure proper sealing.[261] The final quality control step tests the housing sealing and (often) the presence of anomalous heat sources, which might signal short-circuit potential or anomalous electric resistance.[262]

2.6.5 Battery pack disassembly

Generally, manual pack-to-module disassembly is possible because it is foreseen for repair in the event of one module malfunctioning. However, to economically recycle or remanufacture the batteries, disassembly must be automated and not necessarily performed by the battery manufacturer. Blankemeyer et al. analyzed some packs regarding the possibility of automatic disassembly and classified the components according to their handling:

- Flat components, such as cold plates and covers
- Prismatic components, such as battery modules and junction boxes
- Non-rigid components, such as wiring harnesses
- Cylindrical components
- Fasteners, such as bolts and nuts

Because some components, such as modules, can only be gripped in only a ways, they need special grippers. The typical connections to be disassembled are:

- Screws and nuts
- Plugs
- Clips
- Adhesion
- Clamp

Fortunately, not all types of connections are present in the same pack, and standardization greatly helps to plan a disassembly line. The difficulty of disassembly increases drastically if it has to happen non-destructively, as remanufacture and repair demands.

[261] Korthauer (Lithium-ion batteries) 2018, p. 223.
[262] D'Souza et al. (Automated assembly of Li-ion vehicle batteries: A feasibility study) 2020, p. 135.

Considerably challenging connections between non-rigid components and other components—in the form of plugs—need special sensibility and coordination, with the relevant process steps according to DIN 8591[263] as follows:

- Empty the cooling system
- Disassemble shape connections
- Disassemble friction connections
- Desolder
- Disassemble adhesive connections

As a sequence of loosening and handling steps, during the entire disassembly process, the battery needs to be tested for damage and potentially dangerous states. In remanufacturing, the operation must happen under HV until the modules are disconnected, with various dangers always present: short circuits, fire, toxic gas release, and electric shock.[264]

The experience gained during the DemoSens project added two additional dimensions to the classification: weight and size. This has implications for the requirements for disassembling robots. Parts weighing under 10–12 kg and that are narrower than 0.5 m can be handled by robots for human-robot collaboration (HRC). Meanwhile, bigger and heavier components must be handled by bigger robots in a protected environment. The following represent some additional findings made by the author within the project regarding the accessibility and handling of specific parts for disassembly. The screws used in electrical HV contacts are made of diamagnetic steel, making it impossible to collect them magnetically (i.e., following the usual procedure). Furthermore, they need to be gripped after loosening, which is a potentially dangerous operation because loosening a conductive component can cause a short circuit. Because the areas to be gripped are often hidden when the battery pack is in the assembled state, 3D models are needed in advance to plan the disassembly operation. These can be obtained by either CAD data (if provided by the manufacturer) or by scans (i.e., cameras equipped with an infrared distance sensor). Component fixtures used for their manufacturing (i.e., casting) and handling often require special tools that are available in the product-specific automated assembly line and must be replicated in the disassembly line. This requires a certain degree of flexibility in tooling (i.e., rapid tooling). Tooling for non-destructive disassembly is far more complex than for destructive disassembly. After a destructive disassembly step, some residuals remain on the pack, potentially impeding a further step (i.e., a cable is torn and jammed between two components). This means that it

[263] Deutsches Institut für Normung (DIN 8591) 2003, pp. 3-6.
[264] Blankemeyer et al. (Investigation of the potential for an automated disassembly process of BEV batteries) 2021, pp. 562, 563.

is appropriate to assess the status of the pack before initiating certain steps. In big covers sealed by liquid sealing, some openings might be needed to insert special tools that grip and lift one part of the flange so that the rest can be peeled off from that entry point.

The work of HERRMANN ET AL. recognizes the complexity and heterogeneity of disassembly processes and the uncertainties of battery EoL in terms of corrosion, damage, lifespan at recovery, and economic variables at the time of recovery. It builds scenarios and establishes a flexible morphological box of disassembly lines to realize sensible goals in each scenario, concluding that the key aspect of managing uncertainties is reducing them by design. In this way, the disassembly line can be modular and, therefore, scalable.[265] WEGENER ET AL. achieved highly flexible battery disassembly using a HRC system, with the robot recognizing the screws and unscrewing them, allowing the human operator to focus on the more complex tasks.[266,267]

GERBERS ET AL. recognized the need to scale automatic disassembly and identified small lot sizes and design variety as the main obstacles that have prevented fully automated disassembly from becoming industrially feasible as yet. Full automation will only be possible if design standardization is widely implemented. In the meantime, HRC will increase its relevance as more complex tasks, such as the separation of components, become automated while guaranteeing the flexibility and safety needed in an HV environment.[268] As locating and handling capabilities improve, more flexibility will be achieved by leveraging knowledge management. Specific tasks are planned and executed as instances of adaptive algorithms, which improve as they gain experience. Computer vision and task planning have been demonstrated for EV batteries by CHOUX ET AL.[269,270] and are already in use in remanufacturing gearboxes and electronic equipment.[271]

FLEISCHER ET AL. examined the product-specific requirements for the disassembly of automotive batteries in both recycling and remanufacturing and proposed a disassembly line design based on tool selection. Based on a list of the necessary operations, a set

[265] C. Herrmann et al. (Scenario-Based Development of Disassembly Systems for Automotive Lithium Ion Battery Systems) 2014, p. 393.

[266] Wegener et al. (Disassembly of Electric Vehicle Batteries Using the Example of the Audi Q5 Hybrid System) 2014, pp. 159-160.

[267] Wegener et al. (Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries) 2015, pp. 718-721.

[268] Gerbers et al. (Safe, Flexible and Productive Human-Robot-Collaboration for Disassembly of Lithium-Ion Batteries) 2018, p. 100, 103–111, 123–124.

[269] Gerbers et al. (Safe, Flexible and Productive Human-Robot-Collaboration for Disassembly of Lithium-Ion Batteries) 2018, pp. 121-122.

[270] Choux et al. (Task Planner for Robotic Disassembly of Electric Vehicle Battery Pack) 2021, pp. 3-5, 16–18.

[271] Jäkel et al. (Tagungsband AALE 2020) 2020.

of tools was identified according to VDI 2860[272], DIN 8580[273], and VDI 2343[274], around which the workstation was designed.[275]

Li et al. studied the impact of increasing the concentration of strategic materials before recycling by robotic disassembly and found it especially promising for the material contained in electronics. They analyzed the sensitivity of recyclate quantity and quality with regard to the depth of the disassembly by an iterative method and found the best results achieved at full depth of disassembly, which is anti-economical unless addressed by the design.[276]

2.7 End of life strategies for automotive batteries

The limit for the useful life of automotive batteries is conventionally set to 80% SoH, and no explicit limit on the power fade is set. However, the batteries are functional far beyond this limit, although at reduced performance.[277] When a battery can no longer fulfill its purpose, it must be decided whether it should be repaired at a service center, disassembled but many of its components reused, used for another application, or recycled. Many EoL strategies are then possible that are more resource- and cost-efficient. The more information available on the used batteries, the easier it is to obtain the maximum residual value of each battery.[278]

2.7.1 Battery recycling

In cases where the value of a functioning battery, or some functioning components, is not possible, the batteries need to be recycled. This section provides an overview of the recycling legislation, including the currently used and most promising future recycling processes, enabling later chapters to identify how battery design could make recycling more efficient and profitable. Because none of the examined cell-manufacturing processes are reversible, repairing failed cells is not possible. Recovering electrode sheets for recycling has been attempted only at a lab scale because it poses serious handling challenges.[279]

[272] Verein Deutscher Ingenieure (VDI 2860) 1990.
[273] Deutsches Institut für Normung (DIN 8580) 1974, p. 2.
[274] Verein Deutscher Ingenieure (VDI 2343) 2001.
[275] Fleischer et al. (Concepts and Requirements for Flexible Disassembly Systems for Drive Train Components of Electric Vehicles) 2021, pp. 579-582.
[276] J. Li et al. (Robotic disassembly for increased recovery of strategically important materials from electrical vehicles) 2018, pp. 3-9.
[277] Saxena et al. (Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models) 2015, p. 2.
[278] Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, pp. 23-25.
[279] Marshall et al. (Disassembly of Li Ion Cells—Characterization and Safety Considerations of a Recycling Scheme) 2020, pp. 17-18.

2.7.1.1 European legislation

Batteries have been identified as a special waste product in an effort to counteract the potential environmental pollution caused by the widespread casual disposal of battery-powered appliances, with the reuse of recycled raw materials among the stated objectives. However, the battery recycling industry has been propelled by the "polluter pays" principle, ensuring that recycling prices become embedded in the product prices. Thus, despite recycling itself not being profitable, a recycling market took off.[280]

Directive 2000/53/EC establishes the objective of achieving a circular economy for automotive batteries and components and states specific goals for developing used parts and recycled materials. Furthermore, it demands that the requirements for correct disassembly, reuse, and recycling be considered in the design phase.

Meanwhile, the European Union acknowledged the strategic value of lithium-ion battery recycling with Battery Directive 2006/66/EC, which prescribes minimum collection rates and recycling efficiency.[281] Under Directive 2006/66/EC, the recycling of lithium-ion batteries is primarily economically driven by the prices of nickel and cobalt, which are expected to increase alongside the widespread adoption of electric mobility.[282] However, Directive 2006/66/EC does not consider three important aspects:

- The different values and environmental footprints of different materials (recycling efficiency is defined as a fraction of the total mass, where all materials are counted together);
- Whether the recycled materials are of a sufficient quality to be reused in batteries of similar characteristics (closed-loop recycling) or whether they have to be used in less-demanding applications (down-cycling);
- Whether used batteries can be reused before being recycled, prolonging their lifespan.

These topics are under discussion by the European Commission and will be enforced by the new Regulation 2023/1542[283], repealing Directive 2006/66/EC. The new regulation aims to address the following issues to facilitate the adoption of electric mobility in the European Union:

- Harmonization of legislative conditions to increase battery production;

[280] European Commission (Council directive on batteries and accumulators containing certain dangerous substances) 1991, p. L78/39.

[281] European Parliament (Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC) 2006, pp. 7, 20.

[282] Rothermel et al. (Background) 2018, pp. 21-22.

[283] European Parliament (Regulation (EU) 2023/1542 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC) 2023, p. L191/3.

- Recycling loops for different materials (to improve the security and stabilize the price of raw materials);
- Transparency across the battery life cycle.

High recycling efficiencies for specific strategic materials (lithium and nickel) will be mandated and tracked across the value chain by electronic databases. Used batteries will also not be immediately categorized as waste according to Directive 2008/98/EC.[284] Instead, a second-life application will be considered the default option. Whether a buyer for the used batteries is available and how these used batteries need to be diagnosed remain unresolved in the context of proposal 2020/0353/COD[285] and Regulation 2023/1542, and is delegated to further legislation.[286] With the aim of addressing the problems of lithium recycling and fostering innovation, the European Commission is working on a new directive to increase collection-rate goals further and introduce material-specific objectives for recycling efficiencies.[287,288]

2.7.1.2 State-of-the-art of lithium-ion battery recycling

Batteries have a short life span and are expensive. Theoretically, this makes them very good products for a thriving closed-loop recycling industry. Although this is true for lead-acid batteries, it is not yet the case for lithium-ion batteries.[289] Although the challenge around recycling small consumer batteries is their collection and sorting, automotive batteries are assembled in large modules and packs. As such, the amount of work needed to prepare them for recycling is considerably greater than for portable batteries and requires more advanced skills.[290]

Because most of the valuable materials recovered from battery recycling are metal, the first historically established recycling processes were pyrometallurgical: evaporation of the electrolyte at 300°C, pyrolisis and incineration of plastics and volatile el-

[284] European Parliament (Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives) 2008, pp. 3-4.

[285] European Commission (Proposal for a regulation of the European Parliament and of the Councli concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020) 2020, pp. C220/129, C220/132.

[286] European Parliament (Regulation (EU) 2023/1542 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC) 2023, p. L191/18.

[287] Euröpähische Kommission (Vorschlag für eine Verordnung des Europäischen Parlament und des Rates über Batterien und Altbatterien, zur Aufhebung der Richtlinie 2006/66/EG und zur Änderung der Verordnung (EU) 2019/1020 - Dokument 1) 2020, p. 10.

[288] Euröpähische Kommission (Vorschlag für eine Verordnung des Europäischen Parlament und des Rates über Batterien und Altbatterien, zur Aufhebung der Richtlinie 2006/66/EG und zur Änderung der Verordnung (EU) 2019/1020 - Dokument 2) 2020, pp. 19-20.

[289] Pavel et al. (Materials impact on the EU's competitiveness of the renewable energy, storage and e-mobility sectors) 2017, pp. 41-42.

[290] Melin (State-of-the-art in reuse and recycling of lithium-ion batteries) 2019, pp. 33-34.

ements at 700°C (with the release of toxic gases such as dioxin), and, finally, the reduction of metal oxides and smelting of metals into an alloy and a slag phase. This approach requires little preparation of the batteries and is very robust and scalable to high throughput. Although this procedure successfully achieves very high recycling efficiency in lead-acid batteries—60% of the mass is recoverable lead—the process is much more complicated for lithium-ion batteries because of the diversity of the materials used. Moreover, this method can only recover heavy, noble metals such as nickel, cobalt, copper, manganese, and iron, with light metals such as lithium and aluminum recovered as slag, preventing them from being used in closed loops. Process viability strongly depends on the ever-decreasing quantity and volatile price of cobalt in the batteries. To achieve high recycling efficiencies and recover strategic materials for a circular economy, the pyrometallurgical processes and thermal treatments must be considered part of a more complex process chain that also involves pretreatment and hydrometallurgy.[291]

As the Lithorec research projects show, it is technologically possible to recover and recycle most (especially high-value) lithium-ion battery materials in a closed loop, optimizing the consumption of energy, time, and resources. Nevertheless, some trade-offs must be met between the quality of recycled materials and economic profitability because the cost and complexity of some process steps increase more than the economic return when scaling from the pilot-plant scale up to the mass-production-plant scale. Hence, not all materials can be recovered at a lower price than the primary materials, with high investments needed and revenues dependent on the highly uncertain quantity of batteries to be recycled. Moreover, different battery chemical compositions feature different quantities of valuable materials, cobalt being the most expensive and that which is decreasing in quantity due to technological efforts to replace it. The pre-processing of batteries (classification, discharge, and disassembly) represents a high fraction of the costs, and disassembly automation is also very important for determining the ratio between investment and operating costs. Handling and discharging represent the highest aggregate cost, followed by disassembly, even if periphery materials can produce considerable revenues. The highest revenues are delivered by the mechanical separation of the highest-value metals (copper, aluminum, and electrode coating materials), with lower revenues associated with recycling lower-value (but strategic) materials, such as lithium and graphite, which require complex processes and equipment and are the most susceptible to impurities. A focus on high-quality recycled materials increases the process complexity and pushes the return on investment further into the future. However, the process is expected to be profitable only with relatively high throughput and risk mitigation measures, such as long-term recycling contracts with battery producers.[292]

[291] Huang et al. (Recycling of lithium-ion batteries: Recent advances and perspectives) 2018, p. 277.
[292] Kwade et al. (Recycling of Lithium-Ion Batteries) 2018, pp. 253-255.

Regarding the integration of recycling processes into a circular value chain, both pyrometallurgical and hydrometallurgical processes face the problem of impurities being present in the recycled materials. This prevents the latter from being used as precursors to active battery materials with similar performance to those materials obtained from raw ore, with copper impurities a particular problem, as these tend to follow the same route as nickel in terms of the decreased capacity of cells made from recycled materials.[293]

The current research into the established processes mostly aims to achieve the stated objectives of upcoming legislation proposals while providing sufficiently pure recycled precursor materials for use in the manufacture of new batteries.

In response to the foreseen mandated material-specific recycling efficiencies, processes have been optimized to work as steps in more-complex process chains that also involve a combination of mechanical, pyrometallurgical, and hydrometallurgical steps.[294,295]

For instance, pyrometallurgical process chains have been completed by a hydrometallurgical treatment of slag to recover lithium.[296]

Lower-temperature vacuum-thermal treatments derived from pyrometallurgy have been developed for the safe deactivation of batteries before hydrometallurgical treatments to recover lithium and graphite[297]

The Institute of Process Metallurgy and Metal Recycling (IME) of the RWTH-Aachen University is studying a method of recovering about half of the lithium at a quality sufficient for closed-loop recycling with little energy expenditure. In this process chain, only the black mass of active electrode materials is treated by water and supercritical carbon dioxide, which is energetically and environmentally advantageous in comparison to the slug treatment out of a pyrometallurgical process.[298]

Research into hydrometallurgical process chains has focused on costs and scalability

[293] Peng et al. (Role of impurity copper in Li-ion battery recycling to LiCoO2 cathode materials) 2020, p. 1.

[294] Friedrich et al. (New Science Based Concepts for Increased Efficiency in Battery Recycling) 2021, p. 1.

[295] Sommerfeld et al. (A Combined Pyro- and Hydrometallurgical Approach to Recycle Pyrolyzed Lithium-Ion Battery Black Mass Part 1: Production of Lithium Concentrates in an Electric Arc Furnace) 2020, p. 1.

[296] Klimko et al. (A Combined Pyro- and Hydrometallurgical Approach to Recycle Pyrolyzed Lithium-Ion Battery Black Mass Part 2: Lithium Recovery from Li Enriched Slag—Thermodynamic Study, Kinetic Study, and Dry Digestion) 2020, p. 1.

[297] Wang et al. (Development of a Highly Efficient Hydrometallurgical Recycling Process for Automotive Li–Ion Batteries) 2015, pp. 170-171.

[298] Schwich et al. (Early-Stage Recovery of Lithium from Tailored Thermal Conditioned Black Mass Part I: Mobilizing Lithium via Supercritical CO2-Carbonation) 2021, p. 1.

by combining cheap mechanical and chemical processes.[299,300]

One of these approaches is the Electro-Hydraulic-Fracturing procedure developed at the Fraunhofer Institute for Silicate Research (ISC), where cells are disassembled and active materials are separated from electrode sheets by induced cavitation. This scalable method can produce precursor materials capable of closed-loop recycling.[301] Other approaches use centrifugal force for mechanical separation and ultrasounds to accelerate chemical reaction kinetics.[302,303] The bio-leaching process, which has previously been used to recycle electronics, only requires shredding as preprocessing and has produced promising results for batteries of different chemistries in studies by Baniasadi from the Coventry University.[304] In the field of mechanical preprocessing, the TU Bergakademie Freiberg has focused on separating the electrode sheets at a very low cost in a process that should be profitable even for LFP-based cells, a context in which other recycling routes are not profitable because they lack expensive cobalt, nickel, and manganese.[305]

The quality of recycled materials depends on not only purity but also the structure of the resynthesized active materials. Within the Lithorec projects, Rothermel investigated both graphite extraction and its synthesis by means of supercritical carbon dioxide extraction.[306]

In theory, the economic value of active battery materials could be even higher than resynthesized materials if they could be retrieved as ready-to-use compounds for manufacturing new batteries. This direct recycling approach involves targeting the binder and treating the active materials by removing impurities and conditioning their structure so that they can be applied as a new coating. This process could be the most environmentally friendly because it requires very little energy input and small quantities of toxic chemicals. However, direct recycling is not yet applied industrially because good battery performance makes substantial demands of material purity and structure. Direct recycling will gain the most advantage from specific designs that facilitate the

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299 Melin (State-of-the-art in reuse and recycling of lithium-ion batteries) 2019, pp. 28-30.

300 Diekmann et al. (Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes) 2017, p. A6190.

301 Öhl et al. (Efficient Process for Li-Ion Battery Recycling via Electrohydraulic Fragmentation) 2019, pp. 76-77.

302 Sinn et al. (Investigation of Centrifugal Fractionation with Time-Dependent Process Parameters as a New Approach Contributing to the Direct Recycling of Lithium-Ion Battery Components) 2020, p. 1.

303 Ning et al. (Recycling of cathode material from spent lithium ion batteries using an ultrasound-assisted DL-malic acid leaching system) 2020, p. 60.

304 Baniasadi et al. (Advances in bioleaching as a sustainable method for metal recovery from e-waste) 2019, p. 80.

305 Wuschke et al. (Zur mechanischen Aufbereitung von Li-Ionen-Batterien) 2016, p. 276.

306 Rothermel et al. (Graphite Recycling from Spent Lithium-Ion Batteries) 2016, p. 10.

disassembly of batteries and cells.[307,308]

Furthermore, cell disassembly would allow the direct recycling of active materials without destroying their structure, as[309] proved possible for lithium-cobalt oxide (LCO) cathodes, obtaining only slightly worse performances compared to new materials.

Regarding upcoming battery technologies, various preliminary studies investigated the possibilities of recycling all-solid-state and lithium-sulfur batteries. To recycle solid-state batteries, a similar approach to direct recycling has been proposed, with the strong bond between solid electrolytes and active materials used to extract them from cell housing. Then, the binder is dissolved in a thermal treatment and the separator is mechanically removed to regenerate the materials. A similar approach could even be used in cells with liquid electrolytes, provided the cells are designed for easy disassembly.[310]

Although lithium-sulfur batteries are completely different chemically, they could be recycled in similar process chains, with the chemical steps adapted accordingly. Despite the absence of expensive materials, about 90% of the lithium could be recovered. However, the process costs would need to be extremely low to make recycling profitable.[311]

2.7.2 Repair and Remanufacturing

When a battery fails and is no longer fit for use, it can be repaired. Alternatively, it can be partially disassembled, its faulty parts replaced to restore it to its previous condition, or it can be completely disassembled and cleaned, have its components inspected, and then be reassembled, restored to an ”as new” condition that can be guaranteed in the manner of a new product. Remanufacturing can be performed for its original purpose—or for a new purpose—if the original specifications cannot be met.[312] If the costs of a remanufacture operation are not justified by the recovery in performance and durability, the best option is to repurpose the battery with minimal intervention.[313,314]

After performing LCA of all EoL strategies, Ahmadi et al. found remanufacturing to be the most environmentally sound approach because of the maximum life extension and minimal energy input demanded by remanufacture operations. However, they observed three main obstacles to this strategy's widespread deployment:

307 Larouche et al. (Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond) 2020, p. 34.
308 Xu et al. (Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing) 2020, pp. 9-10.
309 Lahtinen et al. (The reuse of LiCoO2 electrodes collected from spent Li-ion batteries after the electrochemical re-lithiation of the electrode) 2021, p. 2.
310 Schwich et al. (Recycling Strategies for Ceramic All-Solid-State Batteries—Part I: Study on Possible Treatments in Contrast to Li-Ion Battery Recycling) 2020, p. 15.
311 Schwich et al. (Recycling Potential of Lithium–Sulfur Batteries—A First Concept Using Thermal and Hydrometallurgical Methods) 2020, p. 1.
312 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, pp. 29-32.
313 Ramoni et al. (End-of-life (EOL) issues and options for electric vehicle batteries) 2013, p. 890.
314 Ahmadi et al. (Environmental feasibility of re-use of electric vehicle batteries) 2014, pp. 71-73.

- EV batteries are not designed to be easily, safely, and cost-effectively disassembled.
- BMS are not arranged to manage the residual lifespan of each cell and module to provide information about reliability and optimal load profile for a second use via on-board diagnostics (OBD).
- Safety concerns must be addressed regarding the prevention of dangerous faulty states and warranties.[315]

2.7.3 Repurposing

Used batteries could be adapted with minimal disassembly to fit the interfaces of a new setting, such as a home photovoltaic system or a battery array to stabilize the electric grid. A key factor for success in this new setting is the availability of information about battery performance and aging, which can enable it to fit the most suitable application and ensure satisfactory performance and a long residual life. In general, the requirements of second-life stationary applications are less demanding than EV applications. However, the most effective use of residual value involves fitting high-power batteries into high-power applications and high-capacity batteries into high DoD applications. The diagnosis must happen without testing the single cells individually.[316,317]

Foster estimated the economic viability of both remanufacturing and repurposing and found both viable. As such, the decisive issue is the diagnostic of used batteries and the costs of the remanufacturing operations compared to the cost of new batteries. Both strategies are far more economically viable than recycling with the current price range of materials.[318]

Casals et al. found that matching battery degradation characteristics with the charge and discharge cycle critically determines economic viability.[319] De Rousseau et al. listed several application fields for repurposing as well as the requirement ranges for the applications.[320]

During the BatteReMan project, three batteries from eight-to-ten-year-old Nissan Leaf vehicles were disassembled and their module tested singularly. The results appear in figure 2.27. These mostly cyclically aged batteries seem fit for repurposing.

[315] Ahmadi et al. (A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems) 2017, pp. 1, 11.
[316] Beverungen et al. (Ensembles of context and form for repurposing electric vehicle batteries: an exploratory study) 2017, p. 205.
[317] Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, pp. 146-170.
[318] Foster et al. (Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries) 2014, pp. 705-712.
[319] Casals et al. (Second life of electric vehicle batteries) 2017, p. 12.
[320] DeRousseau et al. (Repurposing Used Electric Car Batteries: A Review of Options) 2017, pp. 4-7.

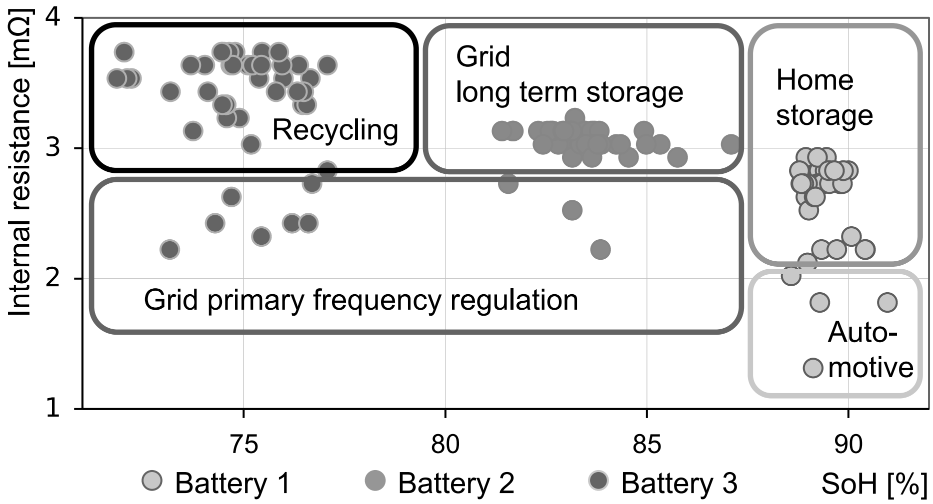

Figure 2.27: SoH and internal resistance of modules from used batteries fit for repurposing

Potential application fields for repurposed batteries include automotive spare parts, buffers for charging infrastructure, home storage for renewable energy and island solutions, frequency stabilization, day storage, long-term storage at the grid level, and heavy off-the-grid equipment in, for example, maritime and mining contexts.[321]

Available standards certify the safety of repurposed batteries[322] and indicate the minimum requirements for specific applications.[323]

2.8 Testing and diagnostics

As explained in section 2.7, the selection of the best EoL strategy depends on the reliable testing of used batteries.

Because the value of used batteries depends on the EoL decision, testing should happen as soon as possible in a circular process chain, preferably during the first use, as part of predictive maintenance, or as soon as used batteries are collected and before they are disassembled.[324]

Usually, a battery model comprising an aging module runs in the BMS and estimates the SoC according to proprietary algorithms.[325] The use of historical data from the BMS is the most accurate diagnostic method: Because it considers the response of a battery model to the real charge cycles and environmental conditions, it continuously corrects the model with the response from the battery and considers the whole history of every

321 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, pp. 212-232.
322 Underwriters Laboratories (UL 1974).
323 Underwriters Laboratories (UL 1973).
324 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, p. 14.
325 Korthauer (Lithium-ion batteries) 2018, p. 167.

cell. However, these data are often available only to the OEMs, which uses it for other purposes, such as cell balancing,[326] meaning that this data is usually not saved unless repurposing is planned.[327] Alternatively, the internal resistance of the used cells can be measured, albeit with less precision.[328]

European regulation 2018/858 does not mention repurposing or remanufacturing, instead reading, "Manufacturers shall provide to independent operators unrestricted, standardized, and non-discriminatory access to vehicle OBD information, diagnostic and other equipment, tools including the complete references, and available downloads, of the applicable software and vehicle repair and maintenance information. Information shall be presented in an easily accessible manner in the form of machine-readable and electronically processable datasets. Independent operators shall have access to the remote diagnosis services used by manufacturers and authorized dealers and repairers."[329] Most on-board diagnostics on the CAN bus according to ISO 15765 (OBD2) scanners can read single cells' voltages in most vehicle batteries[330], and the OBD2 port is usually encoded in the ISO 15765-4 / SAE J2480 controller area network (CAN) protocols[331]. Nevertheless, single-cell voltages are not encoded in a standard format.

At the PEM, RWTH-Aachen University, a simple method based on OBD data and pulse tests has been tried on Nissan Leaf batteries: The battery terminals were connected to a battery tester, and the battery was subjected to three 10-second-long pulses (one at low, one at middle, and one at high SoC) to measure the DCR at three different time constants, each representative of different aging mechanisms.[332]

The transfer rate of the OBD2 port is sufficient to pick three voltage data points per cell and hence identify the parameters of a simple ECM of each cell and specifically identify obvious cell faults, as figure 2.28 shows. Although this method does not provide accurate lifespan prediction, it is a proof of concept that makes EoL decisions for used batteries possible for third parties, as figure 2.27 shows.

Substantially more advanced methods exist to diagnose single cells during opera-

326 Pichon et al. (Balancing control based on states of charge and states of health estimates at cell level) 2015, p. 204.

327 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, p. 132.

328 Becker et al. (Umwidmung und Weiterverwendung von Traktionsbatterien) 2019, p. 133-136.

329 European Parliament and Council (Regulation (EU) 2018/858 of the European Parliament and of the Council on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/ 2007 and (EC) No 595/ 2009 and repealing Directive 2007/ 46/ EC) 2018.

330 McClave (Which OBD2 Protocol Is Supported By My Vehicle?), p. 1.

331 International Organisation for Standardization (ISO 15765) 2016, p. 1.

332 Waag et al. (Experimental investigation of the lithium-ion battery impedance characteristic at various conditions and aging states and its influence on the application) 2013, pp. 3-5.

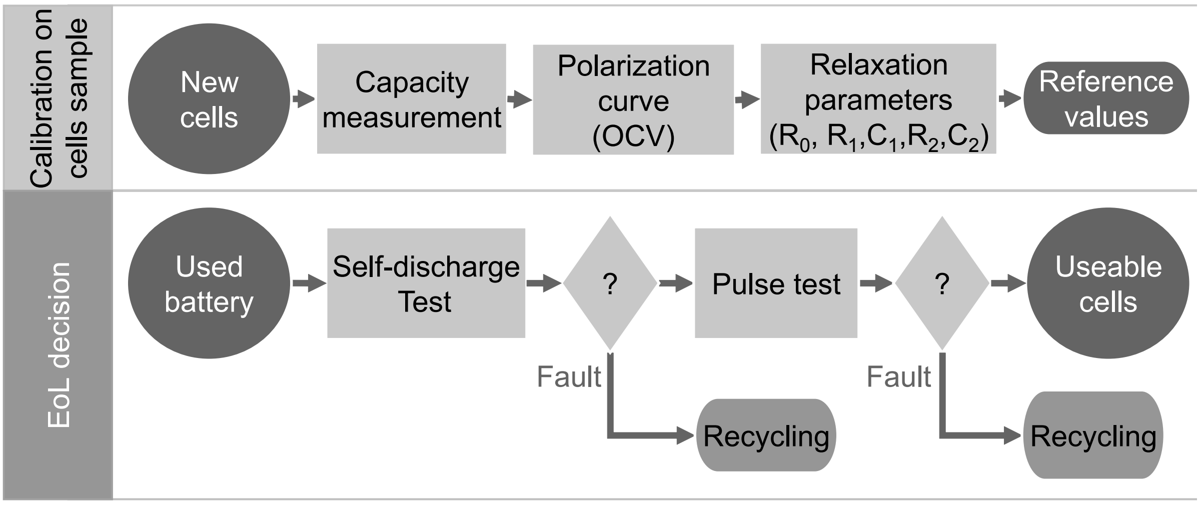

Figure 2.28: Quick method for EoL cell sorting, enabled by logging data from OBD2 port

tion[333] and these can be integrated in BMS into future generations.[334,335]

2.9 Interim summary: challenges for the implementation of a circular economy for automotive lithium-ion batteries

Currently used recycling processes are either reliable and can be scaled up or can recycle most strategic materials in a closed loop. However, some new technologies in the pilot stage can possibly increase the quality of the recycled materials, lower costs to facilitate the adaption to newer cell chemistries with less or no cobalt and improve the environmental footprint of batteries. The newest and most promising recycling methods rely on accurately separating the active materials from the cells' housing and periphery, making it important to disassemble the batteries at least up to the cell level before they are further disassembled or shredded. Notably, Nan has achieved a test/pilot line capable of disassembling 5,000 cells per hour,[336] meaning a special cell design is not strictly necessary with current batteries but should be addressed in the next generations

[333] Zappen et al. (In-Operando Impedance Spectroscopy and Ultrasonic Measurements during High-Temperature Abuse Experiments on Lithium-Ion Batteries) 2020, p. 1.

[334] Kuipers et al. (An Algorithm for an Online Electrochemical Impedance Spectroscopy and Battery Parameter Estimation: Development, Verification and Validation) 2020, p. 1.

[335] Sauer et al. (Future Battery Management - Next generation diagonstic algorithms and advanced measurement technologie) 2019, pp. 17-21.

[336] Nan et al. (Recovery of metal values from spent lithium-ion batteries with chemical deposition and solvent extraction) 2005, pp. 283-284.

of batteries.

To summarize this chapter's results, to establish a truly circular economy around automotive batteries, it is extremely important that the next generation of battery packs be designed to enable disassembly at least up to the cell level to ensure that the most promising recycling technologies can be adopted six to 10 years after the massive adoption of automotive batteries[337].

It is also critical to extend the lifespan of the batteries currently on the market such that most of their strategic materials can be recycled using improved future technologies.

The strategies to prolong battery lifespan are repurposing and remanufacturing, which both rely heavily on the battery diagnostics that will soon evolve enough to detect faster-than-average single-cell aging, both on-board and via quick tests.

Another enabling technology for remanufacturing is disassembly automation, which allows many industrial products to be disassembled non-destructively or semi-destructively. Due to features inherent to cell contact and the assembly process, automotive batteries are currently not made to be disassembled up to the cell level, requiring a new generation of battery designs that can extract the maximum residual value from every single cell at a minimum cost and without losing reliability.

After discussion with experts in the fields of automotive batteries, remanufacturing, joining technologies, and automation, some key areas of improvement for battery design have been identified that would enable the previously stated goals of this work.

Some intrinsic characteristics of automotive batteries pose a challenge to existing designs. The many battery cells are inevitably subject to different conditions, which lead to divergent lifespans and, thus, a shorter lifespan for the battery pack.

The widespread use of adhesives and welded joints is not yet combined with appropriate joint layout, material choice, and process design, factors that would enable non-destructive and safe disassembly.

Because the handling and fixtures used for assembly cannot be used for disassembly, disassembly, and service operators are subject to more risks than assembly operators because the disassembly requirements are considered later in the development process.[338]

Accessibility is especially problematic: Access to live parts must be prevented during disassembly while access for handling must be warranted from multiple directions to apply the forces necessary to detach adhesive joints.

Figure 2.29 summarizes the requirements of a design method that addresses these key challenges.

[337] Natkunarajah et al. (Scenarios for the Return of Lithium-ion Batteries out of Electric Cars for Recycling) 2015, pp. 743-745.

[338] Mohsseni (Gestaltung von lebenszyklusrobusten Produktarchitekturen am Beispiel des Lithium-Ionen-Batteriesystems), p. 61.

Challenges from the industry	Requirements of a design method
Extend battery life until better recycling technologies are available	Include a framework for reuse, repurposing and remanufacturing
Allow non-destructive recovery of cells	Consider both joining and detachment technologies during design
Improve recycling efficiency and reduce cost	Consider both manufacturing and recycling methods of components
Enable automation in both assembly and disassembly	Integrate multiple design approaches in a single workflow
Recover maximum value out of single cells	Focus the analysis on the life-cycle of single cells

Figure 2.29: Requirements of a design method that addresses the challenges posed by the industry

3 State of the art in lifecycle engineering

Building on the review of the specific properties of automotive lithium-ion batteries in chapter 2, this chapter considers theoretical approaches to product design and development for the circular economy, including the extent to which these are applicable to the case of automotive battery systems. The particular properties of automotive battery systems will be analyzed at an abstract level to understand the extent to which the analyzed theoretical models apply. Moreover, the scope of theoretical approaches will be assessed with the objective of designing products that fulfill the goals of the circular economy envisaged.

3.1 Requirements of a suitable design method

Because the challenges listed in 2.9 can be addressed within the disciplines of product development and life-cycle engineering, the problem of developing suitable automotive batteries for a circular economy is abstracted into the problem of finding a suitable method for developing products with similar characteristics.

Although these theory-based requirements are not sufficient for either evaluating existing methods or developing new methods, they must be further decomposed.

Such a method must be applicable to the field of automotive battery systems. It must model their distinctive properties. This renders their reuse, repurposing, remanufacturing, and recycling a particular challenge, demanding a response to design objectives that facilitates informed decisions that balance conflicting objectives and is, ultimately, practicable.

These requirements, derived from the challenges listed in 2.9, are further detailed in figure 3.1.

3.1.1 Applicability to the context

Because these requirements ensure that the method is applicable to automotive batteries, they aim to capture the particularities of their design and life cycles. First, the product's value is mostly not concentrated in a single component but distributed among many components. Furthermore, these valuable components do not only function until they fail but degrade at variable rates and in variable ways. However, each of the valuable components can be reused if it is not too degraded and if it is matched with a suitable second-life application. Meanwhile, although not all joints in the product can

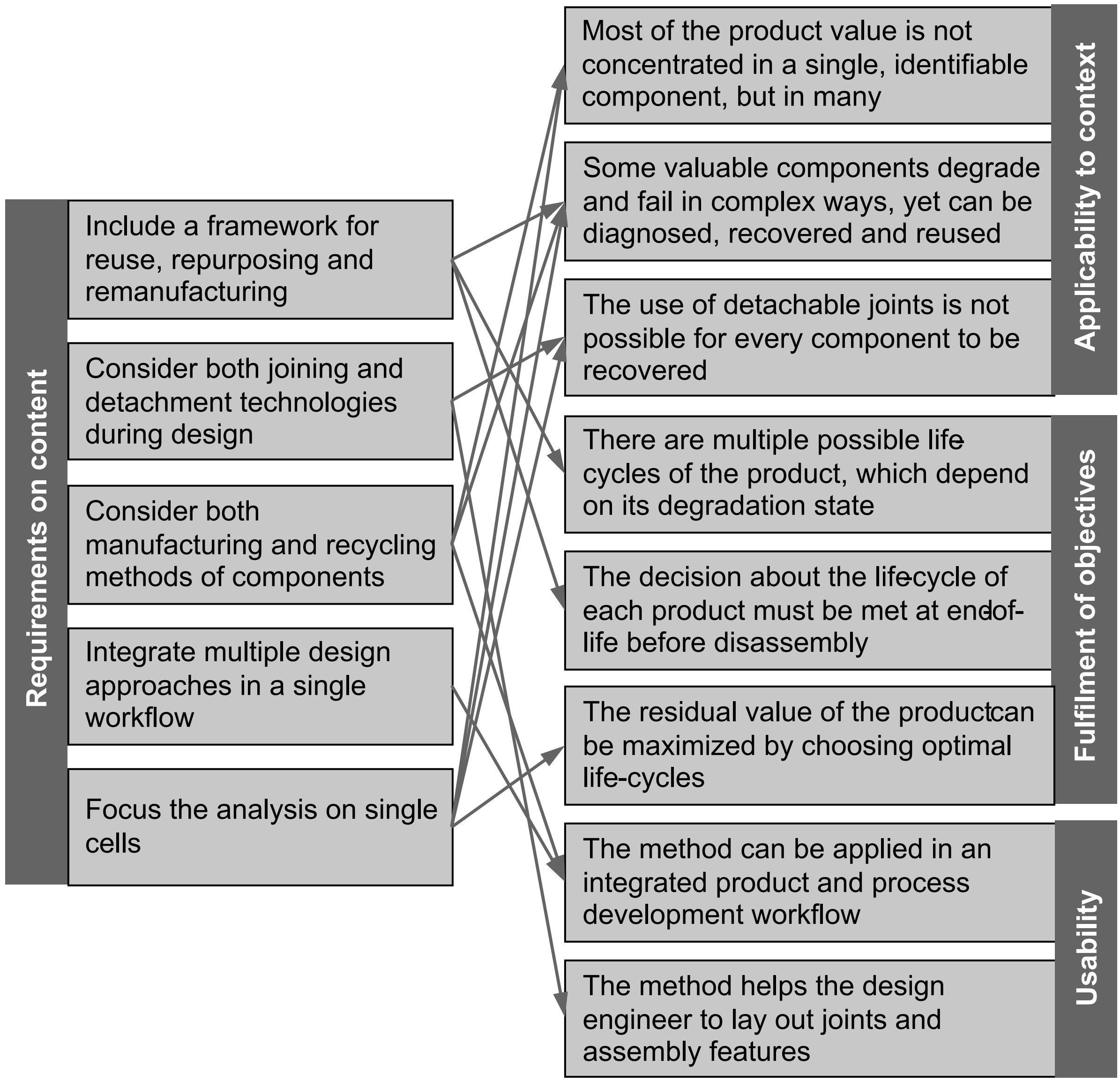

Figure 3.1: Requirements of a suitable design method

be non-destructively detachable, some joints must use non-detachable technologies, and the design method must provide a way to detach them destructively and join them again a limited number of times.

3.1.2 Fulfillment of objectives

These requirements ensure that the correct application of the design method fulfills the objectives of a circular economy. In the most general case, the product can follow multiple life cycles according to its state of degradation at the end of its first life. Furthermore, a decision about what life cycle should follow should, at best, be met at EoL before disassembling the product. It might not be economical to disassemble and reassemble the product for some second-life applications. The method should enable the life cycle that maximizes the total residual value of the products used and should preclude neither optimal second-life configurations nor optimal first-life configurations.

3.1.3 Usability

These requirements ensure that the engineers responsible for the concept design consider all relevant aspects when drafting and evaluating concepts in a concurrent engineering environment, possibly with a limited number of iterations and the option of applying the method recursively from the top assembly to smaller sub-assemblies. Meanwhile, the necessity of non-detachable joints is a problem that must be addressed by the designers, who must make the necessary provisions to destructively separate and rejoin them a finite number of times. If these requirements are met, the extra product development effort will be limited and adoption will be widespread.

3.2 Review of existing approaches to product development

3.2.1 Design for manufacturing and design for cost

After it became evident in the airspace industry that most design choices have huge and often hidden impacts on the total cost over the life cycle of a product, research efforts were dedicated to defining a product development methodology that considers these design choices. Conscious design choices can avoid expensive manufacturing processes, time-consuming assembly steps, and the high logistics costs associated with an elevated number of components. The interdependence of design and manufacturing required multidisciplinary teams to weigh decisions together and establish a method to quantify performance. The design proposals were subject to a structured design review by an interdisciplinary team of manufacturing experts and assembly, service, and logistics operators who would analyze each manufacturing and assembly step and propose design improvements in the first drafts. The variants were assessed on the basis of the metrics of the required manufacturing effort, such as the number of parts, required assembly operator time, and production costs. This approach is called design for manufacturing and assembly (DfMA), with design for manufacturing (DfM) focused on single parts, materials, and manufacturing processes, with branches in each production technology (design for casting, design for sheet metal), and design for assembly (DfA) focused on assembly processes and the needs of assembly operators, such as fool-proofing certain orientation features and reducing the number of parts.[339] To avoid many design iterations, the expertise of designers must include a deep understanding of the manufacturing technologies used in their branch and the capacity to anticipate the potential problems and practical concerns of the operators that are going to assemble and service the product. For this reason, a set of guidelines (best practices) has been developed by researchers such as Bralla et al. to help the designers formulate and monitor the most common manufacturing requirements.[340] Some DfM tools are integrated into specific modules of computer aided design (CAD) software as features optimized for manufacturing and as tools for simplified model checking. The possibility of seeing the results of design choices upfront allows the designers to justify positioning resources where they have the most effect, simplifying parts with a prohibitively expensive manufacturing process, or integrating more parts into one to simplify assembly. The CAD design workflows are usually taught at advanced CAD courses and constitute the knowledge of the expert designers who moved from a ”keep it simple” approach—where each feature performed a function—to the integration of features and parts in more complex product structures.[341] This system-functional approach is only possible by tracking the requirements of the individual functions and parts and mapping them together.[342]

Wouters et al. investigated whether a product should incorporate features with functions not yet required by the market, solving that problem using risk-analysis tools. This is only applicable when the design problem concerns add-on features, such as new modules or software in an upgraded version. In cases where a process innovation in the future (for example, a new recycling technology) affects a product’s subsequent life cycle EoL, this method is not very helpful because it cannot quantify the risks and opportunities and nor can it provide guidance to the designers beyond adding or removing features.[343]

339 Ashley (Cutting costs and time with DFMA) 1995, pp. 74-76.
340 Bralla (Handbook of manufacturing processes) 2007, p. xxxii.
341 Ashley (Cutting costs and time with DFMA) 1995, pp. 75-76.
342 Feldhusen et al. (Der Produktentstehungsprozess (PEP)) 2013, pp. 13-14.
343 Wouters et al. (Assessing the product architecture decision about product features - a real options approach) 2011, p. 406.

This approach allows for the definition of the requirement specifications and interfaces of each component, enabling the carry-over of existing parts or suppliers' parts, hence profiting from economies of scale.[344] The integrated product and process development (IPPD) goes a step further in integrating DfM, design for quality, and design for cost (DfC) for complex products within large organizations with the additional overarching purpose of reducing development time.[345] In complex systems with many interconnected components from different sources and engineering domains, where deep knowledge is not available within the organization, as in the case of mechatronic systems, the necessary design iterations for traditional DfM would be too numerous to achieve a competitive time to market (TTM). Thus, a standardized product development process has been codified in the VDI 2206 that stresses the importance of cross-domain communication by means of requirements and interface specifications and methods to validate the design iteratively from an early stage. Because this method is scalable to the subsystem level, it allows many development teams to develop subsystems independently and to iteratively validate them before the whole product is ready. This methodology foresees the testing of product functions with specific tests according to the V-shaped model.[346] To accelerate development time and manage product variants, design methods, such as modular product architecture (MPA), have been developed to condense the product and process requirements of modules and then develop and validate those products and processes according to the V-shaped model. This allows product variants to be derived by replacing interchangeable modules with compatible interfaces.[347] GAUTAM emphasizes the use of computer models for the successful reuse of components to reduce TTM.[348] The MPA considers some requirements for interchangeable modules and places restrictions on their product family to ensure interchangeable modules share the same life cycle.

KAMPKER ET AL. have identified the types of requirements that must be considered when designing a family of modules (see table 3.1), arguing that, for some products, the complexity handled in a IPPD process can be reduced by realizing such product architectures, with key technologies developed and contained in a unit around which the rest of the product is designed, reducing complexity and, therefore, TTM, allowing faster innovation cycles. KAMPKER derived his principle from the observation that the architecture of BEVs evolved toward the ”skateboard” platform design, which sees the whole product designed around the battery system, the most expensive and technology-

344 Feldhusen et al. (Die Hauptarbeitsschritte des Gestaltungsprozesses) 2013, pp. 189-193.
345 Secretary of Defense (Integrated Product and Process Development Handbook) 1998, pp. 1-5.
346 Gausemeier et al. (VDI 2206- A New Guideline for the Design of Mechatronic Systems) 2002, pp. 786-790.
347 Kampker et al. (Integrated Product and Process Development: Modular Production Architectures based on Process Requirements) 2014, pp. 111-113.
348 Gautam et al. (Design reuse framework: a perspective for lean development) 2007, p. 485.
349 Kampker et al. (Integrated Product and Process Development: Modular Production Architectures based on Process Requirements) 2014, pp. 111-112.

Topic	Type of requirements
Handling	Defined regions or features for handling equipment and definition of handling forces
Alignment	Alignment processes and forces during handling
Fixation	Fixtures between machinery equipment and workpiece are defined
Service and rework	Accessibility and dismantling issues
Logistics	Packaging concept, such as containers for transport and storage
Ergonomics	Accessibility of tools and maximum forces
Production concept	Restrictions derived from process sequence and compatibility
Tools and Machinery	Available machinery, materials, maximum product dimensions
Process Data	Data that accompany the product over the life cycle, such as tolerance classes
Quality	Inspection of product and production process at specific stages
Safety	Safety restrictions, such as HV safety

Table 3.1: Requirements for consideration in the development of a product family according to KAMPKER ET AL.[349]

intensive component. This architecture allows battery suppliers to innovate in shorter cycles and adopt agile processes to follow changing requirements while using standardized interfaces and tooling constantly.[350]

In his quality function deployment (QFD) method, ERIXON derives the product architecture from the relationships between product requirements and technical dependencies.[351]

GÖPFERT and SIMPSON ET AL. developed multi-step methods for deriving product architectures from requirements by generating possible alternatives that are compatible with the required functions and component interfaces and are then selected according to known criteria at the time of design.[352,353]

SIDDIQUE AND ADUPALA developed a method for optimizing the product architecture for product families with regard to parts commonality and manufacturing and assembly costs by calculating an index and optimizing it.[354]

Because these methods account for large lists of requirements and tracking inter-

350 Förstmann (Modellbasierter Ansatz zur automatisierten Gestaltung von Montagevorrichtungen) 2019, p. 169.
351 Erixon (Modular function deployment) 1998, pp. 63-65.
352 Göpfert (Modulare Produktentwicklung) 1998, pp. 267-270.
353 Simpson et al. (A Product Platform Concept Exploration Method for Product Family Design) 1999, pp. 294-300.
354 Siddique et al. (Product Family Architecture Reasoning) 2008, p. 1.

dependencies, some researchers have used alternative approaches to reduce complexity in practical applications. According to KAMPKER, the definition of a product's architecture—and, thus, of the scope of each module—is a strategic decision that depends on the perceived customer value of each subsystem and the knowledge available to the various supply chain participants.[355]

An effective strategic choice based on heuristics reduces complexity and allows agile DfM because each module can be validated and improved upon early in the development process.[356]

These methods do not focus on the lifespan, instead presupposing that a certain product architecture (i.e., modularity) will solve future uncertainties about the product's development.

SCHIFFER and SUH AND DE WECK addressed the problem of developing platforms to make products adaptable to future uncertainties. However, this happens outside the framework of a circular economy, and only the life cycle of the design is prolonged, not that of the actual products, which are replaced by new products whose design is derived from the same platforms.

These methods presuppose that uncertainties affect certain components, which can be lumped together and substituted.[357,358]

BLACKENFELT researched product modularity from the IPPD perspective and addressed the requirements of product platforms. His method is based on combining the module indication matrix (MIM)[359] and design structure matrix design structure matrix (DSM)[360], considering the strategic and functional aspects at the same time, and then performing a heuristic evaluation. Although this method could be used to address life cycle problems, such as recycling, it is not usable in its current form if these problems cannot be solved by modularization.

ESKILANDER ET AL. addressed the problem of DfA by providing an actual design workflow and evaluation by quick heuristics. This method is more agile than those that require quantitative evaluations of many variants and depend on data that are often unavailable.[361]

DfM, especially IPPD including MPA, address some general topics that are relevant to the circular economy, including handling, packaging, logistics, process data, accessibility for service, and the production process chain. However, it is too generic insofar as it does not set targets for what is desirable in a circular economy and does set re-

355 Kampker et al. (Using E-mobility as an Enabler for a Fast and Lean Product Development to Optimize the Return of Engineering with the Example of Lithium-ion Battery) 2016, pp. 169-171.
356 Kampker et al. (Using E-mobility as an Enabler for a Fast and Lean Product Development to Optimize the Return of Engineering with the Example of Lithium-ion Battery) 2016, p. 170.
357 Schiffer (Szenariorobuste Produktarchitekturgestaltung) 2013, p. 215.
358 Suh et al. (Flexible product platforms: framework and case study) 2007, pp. 68-70.
359 Erixon (Modular function deployment) 1998, p. 65.
360 Pimmler et al. (Integration Analysis of Product Decompositions) 1994, pp. 3-9.
361 Eskilander (Design for automatic assembly) 2001, pp. 69-105.

quirements that assume that the product life cycle will not change.

Of the requirements identified by KAMPKER, some aspects are insufficiently specified to guarantee successful implementation of the products in a circular economy. Table 3.2 lists these.

Although the general DfM method is currently widely used for battery development at the pack level, some more-specific guidelines for battery modules have been mapped by LI ET AL.[363] for cost-effective module design:

- Modular design is recommended for automatic and flexible assembly to simplify operation in early manufacturing stages while allowing for product variants at later stages.
- Design should be simple and the number of components should be small.
- Standardized and common parts should be used to facilitate design activities to minimize the amount of inventory in the system and to standardize handling and assembly operations.
- Mistake-proof product design should be used to render the assembly process unambiguous. Notches, asymmetrical holes, and stops can be used to ensure the process is mistake-proof. However, these features may add to the assembly cost.
- Design features should facilitate orientation and handling, with guidelines including the following: 1) Parts must be designed to consistently orient themselves when fed into a process; 2) Parts design should incorporate symmetry around axes of insertion; 3) The guide surface might be needed to facilitate insertion; 4) Parts that are sticky, slippery, easily damaged, or with sharp edges should be reduced; 5) The amount of flexible, thin, or very small parts should be reduced because they are more difficult to pick up.
- Interconnections using, for example, cables or wire harnesses should be reduced. A rigid plug-in board is recommended instead.
- Efficient joining methods demand an integral attachment to the assembly (e.g., snap-fit, adhesive bonding, or welding). Threaded fasteners (screws, bolts, nuts and washers) are time-consuming to assemble and not cost-effective to automate. Meanwhile, the joining technology should meet disassembly and service requirements.

[362] Kampker et al. (Integrated Product and Process Development: Modular Production Architectures based on Process Requirements) 2014, pp. 111-112.

[363] S. Li et al. (Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System) 2010, p. 3.

Topics	Requirements
Handling	A repair workshop or a dismantling line before recycling generally features more basic handling equipment than a production line
Alignment	Alignment processes must be reversible to allow non-destructive disassembly for component reuse
Fixation	Fixtures between machinery equipment and workpiece are defined
Service	Only service of certain parts prone to failure and wear is planned: It is possible that other components could not be disassembled
Logistics, handling, and packaging	The handling of the product in a hazardous, faulty state must also be considered for product return; decentralized disassembly at a workshop and the transport of separate subassemblies might be necessary
Ergonomics	Accessibility of tools might vary between assembly and disassembly
Production concept	A disassembly process chain is not necessarily the reverse of an assembly process chain
Tools and machinery	Machinery used for dismantling must also be considered
Process data	Some proprietary data might be needed for appropriate recycling and diagnosis
Quality	Inspection methods and target values must be set as input in a remanufacturing line
Safety	A safety concept must include how to handle uncertainty in dealing with a used, potentially dangerous product

Table 3.2: Specific aspects of a circular economy to be considered in the development of a product family, with reference to KAMPKER ET AL.[362]

- Simple patterns of assembly movement should be used, and the assembly axes should be minimized.

In light of Kampker's conclusions regarding EV architecture, we can observe an analogy between the EV battery—the component with the most proprietary technology and expensive materials within the EV—and the battery cells within the battery system. Accordingly, the supply chain structure and expertise of the integrated product teams (IPTs) is arranged around either cells or modules, the units around which the battery system is designed. As section 2.5 makes apparent, the perimeter of the modules was either expanded to incorporate outsourced products and processes or reduced to obtain flexibility and use in-house expertise in fields such as CSCs. Mohsseni's method of defining suitable product architectures expands on these concepts to allow for a life cycle that includes post-first-life repurposing.[364]

3.2.2 Design for environment

This approach to product development started in the 1980s and gained traction in the early 1990s, when products started being advertised as "green."[365]

A definition of Design for environment (DfE) is "the consideration of the effects on environment, health, safety over the full product and process life cycle, in the design phase,"[366] and the most effective way to improve the environmental impact of products is during the design phase (i.e., when the most options are available).[367,368,369,370,371]

The key concept of design for environment (DfE) is that the product developers consider requirements beyond product function, manufacturing process, serviceability, and, ultimately, cost. According to the priorities, specificity, and context of products, DfE works similarly to DfM and DfC, comprising certain additional related sub-disciplines, such as design for health and safety, regulatory compliance, minimization of hazardous materials, disposal, recovery, recycling, and disassembly.[372]

DfE considers further aspects, such as the environmental impact of material waste streams associated with the product's usage and the disposal of products. Such environmental impacts are computed by performing an LCA of the product and weighting

364 Mohsseni (Gestaltung von lebenszyklusrobusten Produktarchitekturen am Beispiel des Lithium-Ionen-Batteriesystems), pp. 102-107.
365 Baumann et al. (Mapping the green product development field: engineering, policy and business perspectives) 2002, pp. 413-415.
366 Fiksel (Design for environment) 1996, p. 3.
367 Handfield et al. (Integrating environmental concerns into the design process: the gap between theory and practice) 2001, p. 193.
368 Allen et al. (Environmentally Benign Manufacturing: Trends in Europe, Japan, and the USA) 2001.
369 Fiksel (Design for environment) 1996, p. 66.
370 Ashley (Designing for the environment) 1993.
371 Kutz (Environmentally conscious mechanical design) 2007, p. 2.
372 Allen et al. (Environmentally Benign Manufacturing: Trends in Europe, Japan, and the USA) 2001.

Topics	Guidelines
Product structure	Modular design Few components Few variants
Materials	Several different materials Recyclable materials No hazardous materials
Joints	Several joints Accessible joints Removable joints No adhesives
Components	Standard components Lightweight Easy to handle Robust Not hazardous Not painted nor coated
Disassembly	Automated No special procedures Standard tools

Table 3.3: Design for disassembly (DfD) guidelines according to Bogue et al.

the results of different alternatives to select the more suitable concepts. The degree to which different parameters are optimized depends on the objectives and priorities of the product developers and the organization they work for. For example, DfE can be used to simply comply with regulations or to develop novel concepts that have a net-positive effect on the environment, such as cradle-to-cradle (cradle to cradle (C2C))[373].[374,375] The life-cycle sustainability assessment (LCSA) includes the environmental LCA, the social social life-cycle assessment (S-LCA) and the economic dimensions of life-cycle costing (LCC)[376].

To reduce complexity, Bogue et al. identified the DfD design shown in table 3.3.

Furthermore, Bogue et al. has identified how DfD is not simply the reverse of DfA. The two can be in conflict. For example, the joints that allow the fastest and cheapest assembly might be impossible to disassemble. For this reason, he rated the separability of various joints, as table 3.4 demonstrates.[377]

373 McDonough et al. (Cradle to cradle) 2002, p. 1.
374 Fiksel (Design for environment) 1996, p. 130.
375 Kutz (Environmentally conscious mechanical design) 2007, p. 4.
376 Finkbeiner et al. (Towards Life Cycle Sustainability Assessment) 2010, p. 3309.
377 Bogue (Design for disassembly: a critical twenty–first century discipline) 2007, pp. 288-289.

Rating	Requirement
1	Disassembled easily manually in <1 min
2	Disassembled with effort manually in <3 min
3	Disassembled with effort and a partially destructive, fully proven process
4	Disassembled with effort and a partially destructive, tentative process
5	Cannot be disassembled with a known process

Table 3.4: Joint separability ratings according to Bogue et al.

Mascle and Zhao considered design for life-cycle (DfL) within a DfE framework and provided not only metrics but also guidelines. They addressed the reliability properties of different components and applied a fuzzy decision support to the problems of predictive maintenance, DfA, and manufacturing tolerances for a CAD tool. The value to be optimized is a broad definition of entropy across all life cycle phases. Cost estimation of handling operations is also provided via a knowledge database. It estimates new-part values based on similar parts.[378]

Krikke et al. proposed a method where the product structure, the consequent production processes, and possible life cycles are modeled, boundary conditions on the market at different times are imposed, and a genetic algorithm optimizes the product structure to achieve target values of costs and LCA. The key findings indicate that there are two viable sets of solutions. On the one hand, there is an efficient solution that maximizes high-value-added life cycles (e.g., remanufacturing) but is very sensitive to the recovery rate and the quality of returned products. On the other hand, there is a robust solution that compromises between all life cycles, including rework, repair, and recycling.[379]

LCSA methods are dependent on precise input data, such as material flows, product use cases, and lifetime, to compute the indicators of the impacts of product life cycles on the environmental, social, and economic dimensions.[380] Such data might not be available during the early development phases of products with life cycles that are subject to disruptions, as is the case for battery chemistry and recycling. Methods such as that of Krikke et al. can, at best, suggest possible future scenarios and advise on robust solutions. Meanwhile, DfE relies on evaluating many design iterations. However, because the product architecture is substantially determined by the structure of the available knowledge across the supply chain, and not all information is available to

[378] Mascle et al. (Integrating environmental consciousness in product/process development based on life-cycle thinking) 2008, pp. 8-11.

[379] Krikke et al. (Concurrent product and closed-loop supply chain design with an application to refrigerators) 2003, pp. 3700-3707.

[380] International Organisation for Standardization (ISO 14040) 2006.

all participants, some product architectures might not even be considered in the design process due to organizational constraints. For this reason, it is not possible to exclude the possibility that product variants that might score near-optimally are excluded before the LCA evaluation begins.

DfE offers tools to designers that must be used critically to obtain the best results in terms of specific goals and priorities. These must be systematically established with the organization's stakeholders, and their use must be considered in the early development stage and integrated into the best practices for product development.[381]

Lindahl studied the use of DfE methods in many industries and emphasized that DfE methods are only successful if they are clear and easy to use from the designer's perspective and if they do not delay product development. Furthermore, they must be clearly and easily integrated into requirements management such that all requirements are clearly tracked and prioritized. If these criteria are not met, the DfE tools are only used to assess and document an existing concept design because development time is the scarcest resource available to designers.[382]

Johansson and Sundin compared "lean product development," which is part of DfM, and "green product development," which is synonymous with DfE in the scientific literature, and concluded that although both require systems thinking, they differ in scope. Nevertheless, they can work synergistically if the organization supports both sets of goals.[383] Because of its similarity with DfM[384], whose processes must be understood and applied by the whole organization, DfE faces some obstacles to successful implementation.

This is especially the case for products that require agile development, where the knowledge of product modules is distributed among different product development teams[385].

This indicates a need for a specific development method that considers the specificity of battery systems.

One way to reduce the complexity of DfE is to assume beforehand what the product's life cycle will be and develop it for a convenient EoL.

Most design guidelines, which can be implemented without performing an LCA, are either not applicable to batteries or contradict other optimization parameters, such as DfM goals. Unfortunately, weighting those different goals presupposes knowing in advance probable EoL decisions about existing batteries.

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381 Baumann et al. (Mapping the green product development field: engineering, policy and business perspectives) 2002, pp. 418-419.

382 Lindahl (Designers' Utilization of and Requirements on Design for Environment (DfE) Methods and Tools) 2005, pp. 6-7.

383 Johansson et al. (Lean and green product development: two sides of the same coin?) 2014, p. 1.

384 Ashley (Cutting costs and time with DFMA) 1995, pp. 74-77.

385 Kampker et al. (Using E-mobility as an Enabler for a Fast and Lean Product Development to Optimize the Return of Engineering with the Example of Lithium-ion Battery) 2016, pp. 169-170.

3.2.3 Design for recycling

The aim of design for recycling (DfR) is to allow a convenient and reliable process chain to recycle the material content of products. The material pathways must be known beforehand, and the design must foresee homogeneous materials and incorporate features that can separate the materials that need to follow different pathways.[386] This approach is problematic for composite materials, with the recovery of some materials potentially not possible because of process limitations.[387]

DfR methods can be applied to the battery periphery by, for instance, using aluminum alloys of the same type in the housing and avoiding copper parts that end in the same pathway. However, battery cells, similar to composite materials, must comprise different materials tightly packaged because of their working principles, as do some battery modules because of gluing and welding. A trade-off must be found to determine how early the materials must be separated before the shredding. The same applies to electrics and electronics. Ideally, the depth of disassembly would depend on the single cells, and then these would be opened and the cathodes, anodes, separators, electrolytes, and housing would be separated mechanically, as envisioned by Lahtinen et al.[388], Larouche et al.[389], Xu et al.[390], and Nan et. Al.[391].

This is not practicable because there is no scale economy for such a level of disassembly and separation. Wegener et al. performed a case study of an Audi Q5 and identified a disassembly process chain down to the module level using a disassembly matrix and deriving a disassembly priority graph[392] The current DfR methods can only assume the currently available recycling processes in LCA calculations and, thus, underestimate the possibility that a new, improved process will more capable of material recovery if better material separation is achieved in the pretreatment. A current DfR would, in the best-case scenario, consider the level of separation of the industrially available processes and facilitate disassembly up to the module level, precluding it benefiting from new technologies, such as direct recycling, which need disassembly up to the cell level.

[386] Feldmann et al. (Innovative disassembly strategies based on flexible partial destructive tools) 1999, pp. 161-162, 164.
[387] Yang et al. (Recycling of composite materials) 2012, p. 53.
[388] Lahtinen et al. (The reuse of LiCoO2 electrodes collected from spent Li-ion batteries after the electrochemical re-lithiation of the electrode) 2021, pp. 1-2.
[389] Larouche et al. (Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond) 2020, p. 2.
[390] Xu et al. (Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing) 2020, pp. 1-4.
[391] Nan et al. (Recovery of metal values from spent lithium-ion batteries with chemical deposition and solvent extraction) 2005, pp. 283-284.
[392] Wegener et al. (Disassembly of Electric Vehicle Batteries Using the Example of the Audi Q5 Hybrid System) 2014, pp. 157-159.

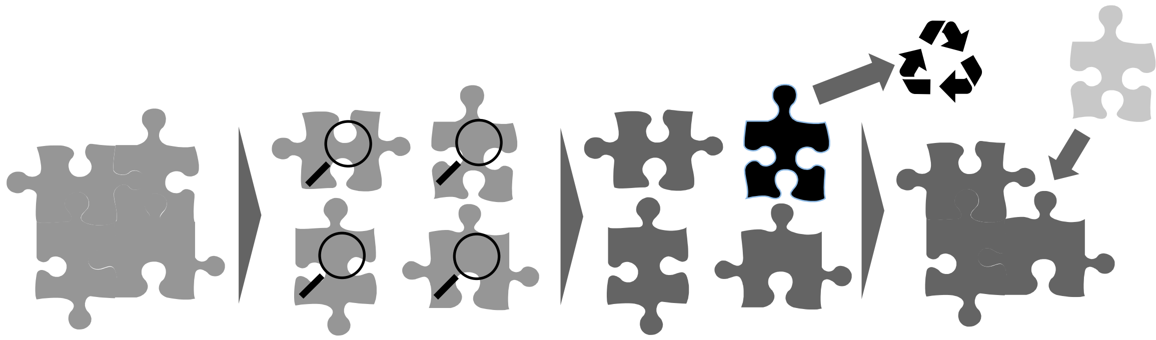

Figure 3.2: Remanufacturing process[395]

3.2.4 Design for remanufacturing

Remanufacturing involves a series of operations that restore products at EoL to a functioning state and "like-new" condition. The product is disassembled, and the components are cleaned, inspected, and, if possible, reconditioned. Components that do not fulfill the requirements for a new product and cannot be reconditioned are replaced by new components.[393] The inspection of used components is key to the quality of the remanufactured product and can be very expensive, especially with an increasing number of proofed characteristics. This requires deep knowledge of the wear and failure mechanisms to limit and simplify the number of tests while guaranteeing quality.[394]

Remanufacturing enables the use of most of the added value of a new product multiple times across several life cycles by avoiding most of the costs, emissions, energy, and material use associated with a new product.[396,397] Remanufactured products are perceived positively by environmentally conscious customers, who consider buying such products because of their sustainable image and reputation for durability.[398] Similar to recycling companies, remanufacturing companies process products from OEMs but have no control over the product design and must obtain product information via reverse engineering.[399]

After performing case studies across many industries, Tolio et al. came to the

393 Steinhilper (Produktrecycling) 1999.
394 Freiberger (Prüf- und Diagnosetechnologien zur Refabrikation von mechatronischen Systemen aus Fahrzeugen) 2007, p. 76.
395 Steinhilper (Produktrecycling) 1999.
396 Sundin et al. (In what way is remanufacturing good for the environment?) 2012, p. 556.
397 Butzer et al. (Remanufacturing Process Assessment) 2016, p. 237.
398 Abbey et al. (Remanufactured Products in Closed-Loop Supply Chains for Consumer Goods) 2015, p. 1.
399 Butzer et al. (Remanufacturing Process Assessment) 2016, p. 234.

following conclusions:

- Circular business models are already profitable for manufacturers in different sectors.
- The circular economy provides substantial social and environmental benefits.
- The application of the circular economy is synergistic with the development and manufacturing of new products.
- Remanufacturing is applied in both small and large volumes, with a trend toward larger volumes and increased automation.
- Uncertainties in product returns and market demand are the major causes of complexity in remanufacturing operations.[400]
- Product information is a key success factor in remanufacturing operations.
- Advanced technologies in automation, diagnostics, and logistics and systems are fundamental to achieving the quality and efficiency required of remanufacturing.
- The product design strongly influences remanufacturing profitability.
- Value chains need to be rearranged to implement circular business models.[401]

OEMs have the possibility of optimizing the results of remanufacturing in the design phase, but they need to increase the process integration and design complexity without necessarily adding to the cost of the product's first life.[402] In particular, by having knowledge of the failure modes and inspection methods, they can plan end-of-line tests as well as tests for returning products efficiently.

WEI ET AL. highlight the importance and strategic advantage of using an OEM to control the acquisition of used products, which are referred to as ”cores”[403]

A clarification about the concept of ”product cores” is necessary: In both industrial practice and the literature, as exemplified in the Map of Remanufacturing Product Design Landscape[404], the term ”core” refers to a used product that is acquired for remanufacture. A deeper analysis of the context in which the term is used identifies further properties that are useful for understanding the remanufacturing process. When a product

[400] Bagalagel et al. (Hybrid decision-making and optimisation framework for manufacturing-remanufacturing closed loop systems) 2021, pp. 1396-1397.
[401] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 6.
[402] Boorsma et al. (Incorporating design for remanufacturing in the early design stage: a design management perspective) 2021, pp. 39-40.
[403] Wei et al. (Core (product) Acquisition Management for remanufacturing: a review) 2015, p. 1.
[404] Prendeville et al. (Map of Remanufacturing Product Design Landscape) 2016, pp. 22, 33, 38.

is remanufactured, many components are exchanged, but not the core, which is, therefore, a privileged component in the sense that it maintains the identity of the product to be restored. The question was posed in the ancient Greek myth of ”the ship wherein Theseus and the youth of Athens returned had thirty oars, and was preserved by the Athenians down even to the time of Demetrius Phalereus, for they took away the old planks as they decayed, putting in new and stronger timber in their place, insomuch that this ship became a standing example among the philosophers, for the logical question of things that grow; one side holding that the ship remained the same, and the other contending that it was not the same”[405]. For the intents and purposes of remanufacturing according to currently existing literature, Theseus's ship would remain the same ship as long as a special ”core” component was never replaced; otherwise, its repair would be out of scope of the current remanufacturing theory. This approach makes practical sense if core degradation over the product's lifetime is negligible, and it can be restored to a ”like-new” condition. However, CHOMSKY proposed another solution to the paradox of Theseus's ship, considering the perspective of cognitive science: the concept of ”ship” is not grounded in reality, which comprises only its parts. Instead, the ”ship” is the construct of the mind, which is necessary to conceptualize the complete properties of the ship, such as those related to sailing.[406] This apparently unrelated position is interesting for remanufacturing because it allows us to understand the core not as a special component but as the feature that endows the product with traceability. Extrapolating the idea of CHOMSKY, a device which ensures traceability, such as a combination of identification labels and databases, would have the function of a virtual core and make the existing remanufacturing models applicable.

LUND listed the product properties necessary for effective remanufacturing:

- The product has a durable core.
- The product can be restored to its original specifications.
- The product can be produced in an industrial process.
- The value of the remanufactured product is close to the value of an identical new product.
- The cost of acquiring used products is low compared to the cost of remanufacturing.
- There is no technological disruption making old products obsolete.[407]

[405] Plutarch (Theseus) 75.
[406] Piattelli-Palmarini et al. (Of Minds and Language: A Dialogue with Noam Chomsky in the Basque Country) 2009, p. 382.
[407] Lund (The Remanufacturing Industry) 1996.

Sundin correlated further product properties with the steps of the manufacturing process, where these are relevant, in the form of a matrix that he called RemPro.[408]

Similar to DfR, design for remanufacturing (DfRem) presupposed a certain life cycle in which some components or modules are changed and repaired and some requirements are added to allow for the cleaning of the whole product and the restoration of its appearance.

On some occasions, the diagnostics of some components and preventive maintenance also become relevant.

design for remanufacturing (DfRem) mostly foresees the possibility of replacing damaged or worn-out components with new ones.

Ramirez et al. developed a model to optimize the cost of disassembly by weighting the value recovered at each component with the cost of disassembly up to that component.[409]

Tolio et al. defined a framework inside a circular economy, whereby de- and remanufacturing include the set of technologies and systems, tools, and knowledge-based methods needed to systematically recover, reuse, and upgrade functions and materials from industrial waste and post-consumer products to support the sustainable implementation of manufacturer–centric circular economy businesses. Thus, de-manufacturing liberates target materials and components, and remanufacturing restores or upgrades their functions.[410]

Seitz et al. noted how remanufacturing reduces all manufacturing costs except labor, suggesting that automation could have an especially relevant impact on remanufacturing.[411]

King et al. addressed the problem of remanufacturing product variants using product platforms, which are usually adopted to maximize synergies for high-value components that are standardized and aggregated in the common platform, with the differentiating components aggregated in modules and ”plugged in(to)” different product variants. King et al. proposed adding durability as an extra dimension beyond value in product platform strategies to aggregate long-lasting components of the common platform and the short-lived components in modules, which are easy to replace and upgrade.[412]

Ilgin investigated the advantages of sensors embedded in products for more cost-effective remanufacturing and identified impressive gains on the condition that the sensors can detect the optimal time to replace a part and that this part can be replaced

[408] Sundin (Product and process design for successful remanufacturing) 2004, p. 62.

[409] Ramírez et al. (Economic modelling of robotic disassembly in end-of-life product recovery for remanufacturing) 2020, p. 16.

[410] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, pp. 6-20.

[411] Seitz et al. (Challenging the implementation of corporate sustainability) 2006, pp. 830-831.

[412] King et al. (The development of a remanufacturing platform design: A strategic response to the Directive on Waste Electrical and Electronic Equipment) 2005, pp. 628-630.

with minimal disassembly operations.[413]

HILTON summarized the key goals of DfRem as:

- To create value (quality, platforms);
- To preserve value (durability, prevention, viability);
- To recover value (separability, assessability, restorability).

He also stated that deriving design heuristics and tools to achieve these goals should be achieved by focusing on not only product architecture but also on quality, durability, diagnostics, and disassembly. Still, components with the same durability need to be clustered together and easily separated from the others.[414]

The first question about remanufacturing a product concerns whether the product is fit for a post-remanufacture life cycle. Some of LUND's requirements are met, while others do not apply exactly:

- The battery cells, the highest-value component, most resemble a product core; nevertheless, they are an aggregate component, not a single component, and nor do they have the longest lifetime.
- A used battery cannot be restored to its original specifications, but to specifications that can still be useful for some purpose.
- The product can be produced in an industrial process only provided it can be disassembled non-destructively.
- Remanufactured batteries are less valuable than new ones, but they are competitive as automotive spare parts and for stationary use.
- The cost of acquiring used products is not low, but the recovery of used batteries is mandated by law.
- Despite the technological disruption, used vehicles are not compatible with newer batteries, meaning the spare-parts market cannot be disrupted by new technologies.[415]

Many aspects of DfRem are applicable to automotive battery systems, such as provisions for easy module replacement. In this case, the requirements overlap with the needs of service workshops to a significant degree. As such, they come at a small cost. One difficult aspect is diagnostics: As diagnostic methods performed by third parties on used modules are less accurate at predicting the residual life than constant online

413 Ilgin et al. (Coping with disassembly yield uncertainty in remanufacturing using sensor embedded products) 2011, p. 13.
414 Hilton et al. (Design for Remanufacturing) 2019, pp. 154-162.
415 Lund (The Remanufacturing Industry) 1996.

diagnostics over the product's lifetime, the OEMs have a clear advantage in terms of entering remanufacturing. Online diagnostics add some complexity to the BMS hardware, with most of the difficulty associated with the software. A big advantage is that it can test single cells before disassembling the battery. However, the successful detection of a few prematurely aged or damaged cells, spread across several modules, would lead to the disposal of the whole module, including many functioning cells. Furthermore, if the damaged modules or cells can only be replaced with new ones, as in the case of classical remanufacturing, the overall value added to the used battery would rarely justify the cost and would often be less convenient than repurposing without any intervention.[416] Thus, the best utilization of the residual value of cells is to pair used cells of similar characteristics in new products.

Upgrading used batteries by replacing cells seems neither feasible nor advantageous, but vehicles could receive newly upgraded batteries while the old ones are remanufactured and used as spare parts.[417]

From a design perspective, the idea of product platforms proposed by King et al. self-conflicting in the case of automotive batteries, because the cells are, on the one hand, the highest-value components and should correspond to the common platform, and, on the other hand, the components that most often determine the EoL of the battery, suggesting that they should be the easiest to replace. Moreover, the cells that fail early should be grouped in the same modules, with those that fail later included in other modules, which is not possible because the life of cells is not known before assembly.

Both the aging and the design arguments identify the necessity of a design capable of disassembly up to the cell level. Because the approach of embedding sensors on single components is already required for functional safety, the processing of these data and the implementation of testing functions could enable predictive maintenance up to the cell level.

3.2.5 Design for life-cycle

Jawahir et al. introduced the concept of "sustainable manufacturing" principles of "sustainable manufacturing" (6R) as an evolution from "lean manufacturing" reduce, as in "lean manufacturing" (1R) to "green manufacturing" that includes the "reduce-reuse-recycle" reduce, reuse, recycle (3R) principles. It understands manufacturing practices as a complex system comprising products, processes, and socio-economic systems. Although "reduce" is applicable to product design and manufacturing, "reuse" is applicable to the product itself, and "recycle" is applicable to its materials, consideration of socio-economic systems opens up the possibility of three additional "Rs":

[416] Foster et al. (Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries) 2014, pp. 706-712.

[417] Kampker et al. (Evaluation of a Remanufacturing for Lithium Ion Batteries from Electric Cars) 2016, p. 1930.

- ”Recover” is the link between the product and its subsequent life cycles.
- ”Remanufacture” involves reprocessing used products to restore their functionality.
- ”Redesign” involves learning and adapting the design to incorporate value from previous life cycles, such as by reusing components that are in good condition and upgrading certain components in next-generation products.

Because of its complexity, this approach features a high barrier to implementation, but it does have an entry point for designing next-generation products. While assessment elements are available, the approach to conceiving products is left to the visionary thinking of product innovators.[418] A further definition is needed to distinguish ”repair” from ”remanufacturing”:

- ”Repair” brings a failed product back to a functioning condition, either at EoL or in a service.[419]
- ”Remanufacturing” is a standardized industrial process performed on used products, such that remanufactured products fulfill the original function with at least the performance and technical specifications of a new product (and are covered by a warranty as such).[420]
- ”Remanufacturing with upgrade” adds new or better features to a remanufactured product to adapt to evolving customer demands by changing the least necessary amount of components.[421]

Based on many successful remanufacturing business cases, TOLIO ET AL. developed a manufacturer-centered framework for the circular economy that sees the manufacturer incorporate all value creation across multiple product life cycles because it possesses all the knowledge and product information to adapt products and processes to quickly shifting conditions. In this model, manufacturing and de- and remanufacturing are considered integrated, maximizing synergies, even if processes might happen in different plants. This means that quality inspection steps are considered during manufacturing and remanufacturing from the design phase, with the analysis of EoL products feeding back into lessons learned by the development team. Management defines the quotas to be allocated to manufacturing, remanufacturing, and recycling according to market

418 Jawahir et al. (Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing) 2016, pp. 105-108.
419 Parkinson et al. (Analysis and taxonomy of remanufacturing industry practice) 2003, p. 250.
420 Parker et al. (Remanufacturing Market Study) 2015, p. 1.
421 Chierici et al. (Remanufacturing with Upgrade PSS for New Sustainable Business Models) 2016, pp. 534-535.

conditions, generating the ”circular factory” definition[422]. The success of this framework is dependent on:

- The state of the product after the first use[423,424]
- The demand for remanufactured products at a lower price than new products[425]
- Incentives for the manufacturer to design suitable products for longer life cycles, such as ”service as a product”[426,427]

Moreover, the trend toward high product variability[428] and the complexity of product-related information [][p. 1168][429] require sustainable manufacturing systems to be highly flexible.

According to the ELLEN MACARTHUR FOUNDATION, in a circular economy, value is created in four ways:

- Circling longer: The longer products, components, and materials are used within the circular economy, the more value is created. This can happen by achieving not only a longer life cycle but also multiple life cycles.
- The inner circle (reuse): The easier it is to reuse a product for its original purpose, the larger the savings and the smaller the externalities.
- CasCADe use: Using discarded materials from one value chain as inputs for another (e.g., replacing primary materials or new components with used materials or components).
- Pure circles: keeping material flows uncontaminated to help recollection and reuse while maintaining quality.[430]

TOLIO ET AL. identified five requirements for a de- and remanufacturing system:

[422] Jovane et al. (The incoming global technological and industrial revolution towards competitive sustainable manufacturing) 2008, pp. 651-656.
[423] Watson (A Review of literature and research on public attitudes, perceptions and behaviour relating to remanufactured, repaired and reused products) 2008, pp. 3-7.
[424] Gullstrand Edbring et al. (Exploring consumer attitudes to alternative models of consumption: motivations and barriers) 2016, pp. 4-8.
[425] Widera et al. (Methodology for exploiting potentials of remanufacturing by reducing complexity for original equipment manufacturers) 2015, p. 464.
[426] Guidat et al. (Guidelines for the Definition of Innovative Industrial Product-service Systems (PSS) Business Models for Remanufacturing) 2014, p. 1.
[427] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 5.
[428] ElMaraghy et al. (Product variety management) 2013, p. 629.
[429] Subramoniam et al. (Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs) 2009.
[430] Ellen MacArthur Foundation (Towards the circular economy) 2013, pp. 33-36.

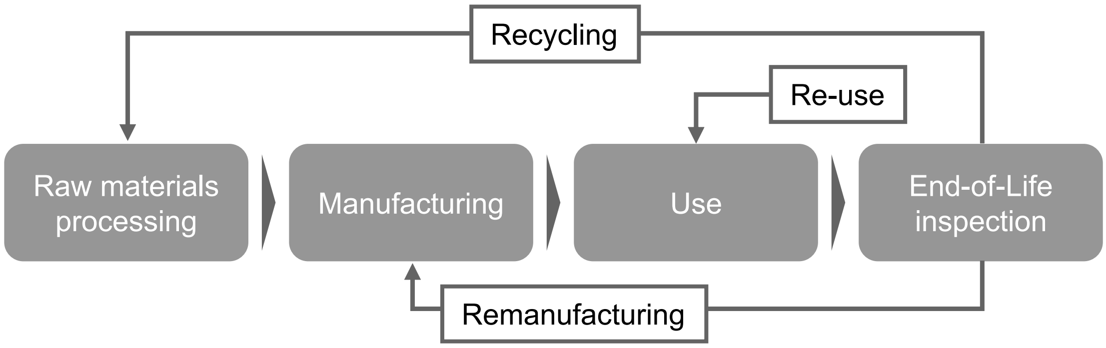

Figure 3.3: Life cycles for circular value creation according to TOLIO and the ELLEN MACARTHUR FOUNDATION

- High adaptability to product and market;
- High automation;
- Information traceability and availability;
- Safety and ergonomics;
- Data-based decision-making to manage uncertainties.[431]

ZUIDWIJK ET AL. proposed a method for designing product life cycles to meet quotas and maximize value by considering available product and process design options together. The method has been applied to consumer electronics with the following key findings:

- The minimum depth of disassembly has been set to the removal of hazardous materials.
- The remanufacturing route is pursued only if the added value outweighs the cost of testing all returning products in addition to the remanufacturing costs.
- The disassembly for recycling is only meaningful if it adds value over post shredder recovery (PST).[432]

If both recycling and remanufacturing options are available, the availability and cost of testing the return quality predominate decision-making. Under these conditions, the design for life-cycle (DfL) must facilitate testing. Under the conditions of high remanufacturing value, low testing cost, and good return quality, the best life cycle is remanufacturing, followed by recycling after the same depth of disassembly required for remanufacturing. Because disassembly shares scale economies with remanufacturing

[431] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 8.

[432] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 8.

and recycling, both the cost and process complexity of recycling improve.[433] According to TOLIO ET AL., the priorities of disassembly are the isolation of hazardous materials, the extraction of high-value components, and the extraction of components that need a dedicated process chain.[434]

This approach depends on some key enabler technologies, such as automated disassembly aided by computer vision and machine learning, automated testing and sorting, HRC, sensors embedded in products, and reconditioning technologies.[435,436,437,438]

Another enabler technology is reversible and detachable joints, which do not conflict with costs, miniaturization, or lightweight construction needs.[439] In composite materials, these are liberated by leveraging their non-homogeneities and incompatibilities with regard to mechanical, chemical, and physical properties.[440,441]

In addition to an optimized industrial and logistics environment and the utilization of enabler technologies, product design methods and guidelines have been proposed by several authors:

SAKUNDARINI ET AL. proposed a method for defining a product's architecture that considers multiple EoL strategies and future uncertainties in the product life cycle.[442]

FELDHUSEN ET AL. proposed a method where a fixed product core persists over many life cycles while the periphery is replaced or upgraded.[443]

SHOVAL ET AL. recognized optimal changes in product architecture in terms of the different phases of the life cycle, proposing a method for estimating the costs of prioritizing one life cycle over another. He also acknowledged differences in joint strength and their impact on disassembly.[444]

KIMURA ET AL. proposed a modularization method in which components are clustered according to life cycle to improve their reuse potential.[445]

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433 Zuidwijk et al. (Strategic response to EEE returns) 2008, p. 1216.
434 Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 8.
435 Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 8.
436 Krüger et al. (Cooperation of human and machines in assembly lines) 2009, pp. 632, 636, 643–645.
437 Vongbunyong et al. (Basic behaviour control of the vision–based cognitive robotic disassembly automation) 2013, p. 54.
438 Vongbunyong et al. (Application of cognitive robotics in disassembly of products) 2013, p. 34.
439 Duflou et al. (Towards self-disassembling products Design solutions for economically feasible large-scale disassembly) 2006, p. 87.
440 Reuter et al. (Opportunities and limits of recycling: A dynamic-model-based analysis) 2012, p. 339.
441 van Schaik et al. (Dynamic modelling of E-waste recycling system performance based on product design) 2010, pp. 192-194.
442 Sakundarini et al. (A methodology for optimizing modular design considering product end of life strategies) 2015, p. 2359.
443 Feldhusen et al. (A Methodical Approach to Increase the Sustainability of Physical Products and Product Models) 2008, pp. 3-4.
444 Shoval et al. (Dynamic Modular Architecture for Product Lifecycle) 2016, p. 271.
445 Kimura et al. (Product Modularization for Parts Reuse in Inverse Manufacturing) 2001, pp. 1-3.

UMEDA ET AL. expanded the idea of clustering components with the same life-cycle properties by adding some rules about accessibility and evaluating the use of available space. The trade-offs between different goals mean that this method does not apply to all products.[446]

MOHSSENI extended these methods by introducing a focus on the life cycle of a single product, with some functions and features added or reconfigured to enable repurposing under unknown future conditions.[447]

The application of a sustainable manufacturing system for automotive batteries that foresees both remanufacturing and recycling represents a most promising proposition.

The three disassembly priorities listed by TOLIO ET AL. all identify the necessity of disassembly up to the cell level to isolate hazardous materials, recover high-value components, and isolate components to a dedicated recycling process chain. Upcoming direct recycling technologies would benefit from such depth of disassembly and could fit the definition of reconditioning.

Methods such as those of SAKUNDARINI ET AL., based on product architecture, fall short of fully considering possible solutions outside defined modular structure.

3.3 Evaluation of existing design methods

This chapter has evaluated the examined design approaches in terms of their applicability to products with the characteristics of automotive lithium-ion batteries and considered how they might contribute to achieving the necessary design objectives for the successful implementation of a circular economy.

3.3.1 Applicability to context

Automotive lithium-ion batteries have distinctive properties in terms of reliability, aging, material structure, and product structure. These properties can be summarized as follows:

- Automotive battery systems do not feature a single core with the longest life cycle and the highest value of all components. The most similar component to a core is the battery cells, which represent the highest-value components. However, they are not collected in a single assembly. A design method optimized for life cycles other than material recycling must be applicable to products with a "scattered core" comprising many cells.

[446] Umeda et al. (Product modularity for life cycle design) 2008, pp. 14-15.

[447] Mohsseni (Gestaltung von lebenszyklusrobusten Produktarchitekturen am Beispiel des Lithium-Ionen-Batteriesystems), p. 108.

- The cells are the components that actually age faster and fail most often, with each cell aging differently and each cell's performance degrading in multiple ways. However, although it might fail in its original purpose, it might still be fit for a different purpose. That is, the residual value of cells decreases as they age, but they are suited for other purposes before they finally fail completely. An EoL decision method must consider the different failure states and failure modes of many cells and compare them with multiple sets of specifications for repurposing.
- Avoiding detachable joints is not always possible. For example, in cell contacts, it conflicts with safety requirements. A design method must allow reusable, non-detachable joints.

3.3.2 Fulfillment of design objectives

A design approach must not only be applicable to products with some particular characteristics, but it must also help developers achieve specific goals. In this case, it should enable a circular economy for a given product. For this to happen, the following criteria have been selected:

- It should allow multiple possible life cycles, material recycling, reuse, repurposing, and remanufacturing to enable the most circular value-creation methods.
- It should enable the extraction of as much residual value as possible from the cells.
- It should allow a quick EoL decision prior to disassembly to avoid any unnecessary disassembly.
- It should provide a workflow compatible with IPPD to ensure that automated disassembly is possible without too many iterations.
- It should provide a framework for selecting and mapping joints that fulfills the requirements across the multiple life cycles.

A summary of the evaluation of existing methodologies against the requirements derived in chapters 2 and 3 appears in the form of Harvey balls in figure 3.4

Caption:
Impossible ○
Possible ◔
Considered ◑
Helpful ◕
Guaranteed ●

		Applicability to the context			Fulfillment of design objectives				
		Product with a scattered core	Different failure states and modes	No detachable joints	Multiple possible lifecycles	Maximizes rest value	EoL decision before disassembly	Suitable workflow for IPPD	Choice and layout of joints
MPA	Wouters (2014)	◕	◕	○	○	◔	○	●	◔
DfA	Eskilander (2001)	◔	◔	◔	○	○	○	●	◕
DfE	Mascle (2008)	◕	◕	◕	◕	◔	◔	◔	◕
DfD	Bogue (2007)	○	○	○	◑	○	○	●	◕
DfRem	Hilton (2019)	◔	●	○	●	●	●	◕	◑
DfRem	Ilgin (2011)	◔	●	○	●	●	●	◔	○
DfL	Sakundarini (2015)	◔	◔	◔	●	◕	○	○	◔
DfL	Kimura (2001)	◕	◔	○	●	◕	○	●	○
DfL	Shoval (2016)	◑	●	●	●	●	○	◑	◑
DfL	Umeda (2008)	◕	◑	○	○	○	○	◔	◑
DfL	Feldhusen (2008)	○	◔	○	●	○	○	◑	◔

Figure 3.4: Evaluation of examined design approaches

3.4 Interim summary: the need for a novel design method

A design method that is applicable to products with the said properties of automotive battery systems and fulfills the design objective of maximizing their residual value over multiple life cycles must enable the following key processes:

- Low-cost testing methods for the high-value components to be replaced, possibly before disassembly, to distinguish the reuse route from routes with a limited up-front cost;
- Use of degraded but still usable high-value components in secondary products;
- Use of detachable or reversible joints without constraining low-cost weight reduction and miniaturization;
- Automatic assembly and disassembly up to the depth of disassembly of the high-value components to be reused.

The following chapter presents such a method.

4 Conception of the methodology

After identifying the shortcomings of previous design approaches for products such as battery systems in chapter 3, this chapter maps a methodology that addresses the peculiarities of this kind of product and aims to introduce a product design that fulfills the circular economy's requirements.

4.1 Theoretical framework

This section will abstract the practical problems into a theoretical problem whose solution will be a model that will be applied to solve the practical problem. The next sections will outline this model's requirements.

4.1.1 Model properties

The model must satisfy the following criteria by STACHOWIAK:

- The model must be a representation of real phenomena as perceived or constructed by any subject.
- The model must contain the relevant features of the original and exclude those that are non-relevant. What constitutes a relevant feature is determined by the modelers' knowledge.
- The model must contribute to the solution of a specific class of problems, such that there can be more than one model describing the same phenomenon, and each model might be appropriate for a class of problems but not others. The intended use of a model must guide the modeler's heuristics.[448]

4.1.2 Model types

PATZAK classifies models according to their goals:

- Descriptive models describe phenomena without any inductive or deductive conclusions, meaning they do not involve causal relationships. These can be used to answer "what" questions.

[448] Stachowiak (Allgemeine Modelltheorie) 1973, p. 130.

- Explanatory models are built on descriptive models and incorporate causal relationships. They can be used to answer ”why” questions.
- Predictive models are built on explanatory models and can predict the future behavior of phenomena. They can be used to answer ”how” questions about the phenomenon’s future.
- Decision models help actors decide among alternative courses of action on the basis of prediction models. These models need a modeled phenomenon, boundary conditions, and variables upon which actor have influence.[449]

4.1.3 Systems theory

According to PATZAK, systems theory can be used to create models of new systems. This approach is useful for investigating problems for which no solution method is apparent. This approach to modeling is called ”network thinking”[450], and it is useful for complex systems when an influence on a part of the system has an effect on many other parts. For this reason, network thinking maps the causal relationships between the parts of the model and how these relationships change the system’s behavior.[451]

HABERFELLNER identifies four guidelines for making system thinking practical:

- The model’s level of detail should proceed from the top to the bottom: It should begin with the rough structure before moving onto the fine details.
- The model should help identify many possible solutions, among which exists the real solution.
- The model should be approached over many phases.
- These steps should be recursively applicable to sub-problems within the main model.

4.1.4 Formal requirements of the methodology

Beyond the requirements of applicability and fulfillment of the purpose, as outlined in section 3.4, for PATZAK, a methodology must fulfill five formal requirements to be correct and usable:

- The model must (as clearly and exactly as possible) correspond to reality in terms of its structure and components.

449 Patzak (Systemtechnik - Planung komplexer innovativer Systeme) 1982, pp. 314-315.
450 Haberfellner et al. (Systems Engineering) 2019, pp. 4-6.
451 Probst et al. (Vernetztes Denken) 1989, pp. 3-6.

- The model must be formally sound according to the theories upon which it is based.
- The model's goal must be to answer a specific set of questions.
- The model must be easy to use, and its results must be easy to understand.
- The costs associated with using the model must be proportionate to its benefits.[452]

The first two requirements aim to design a theoretically correct and empirically accurate model and have been considered in the evaluation of existing methods in chapter 3 and decomposed into the "applicability to context" category, and the third requirement has been decomposed into the "fulfillment of objectives" category. The first three requirements must be balanced with the last two requirements, decomposed into the "usability" category, to produce a model that can be used successfully in practice. The third requirement could offer a solution to the cost-benefit trade-off by conveniently reducing the model's scope.

4.2 Outline of the proposed design methodology

After considering the necessary characteristics of a system model in section 4.1.3, a model built upon life-cycle engineering principles that fulfills the requirements derived in section 3.1 will be detailed. The assumptions made to model the product at a sufficient level of detail will be explained in section 4.2.1, the goal and scope of the model will be explained in section 4.2.2, and its structure will be explained in section 4.2.3.

4.2.1 Definitions and assumptions

In the context of the type of products that the methodology will be applied to, certain essential concepts are not present in the literature on life-cycle engineering. The next three sections explain these concepts alongside various assumptions about product characteristics.

4.2.1.1 Assumptions about the product

One of these assumptions is that the most valuable part of the product comprises not a durable "core" but many depreciating "cells." The following methodology refers to the term "cell" not in the context of batteries but as a component representing many interchangeable instances. In aggregate, these represent a high percentage of the product value, which decreases with use or over time but nevertheless retains some use value

[452] Patzak (Systemtechnik - Planung komplexer innovativer Systeme) 1982, p. 309.

singularly or in aggregate. Moreover, the failure of a few cells can cause the failure of the whole product.

Under these assumptions, the concept of modularity does not have the same implications regarding reliability because it is not possible to aggregate the components with similar reliability characteristics into modules. Thus, modules are a purely structural and functional concept that is not a solution to a DfR or DfRem problem.

The modules that contain cells will be further referred to as modules, with the others referred to as sub-assemblies. Sub-assembly is also used as a general term with no connotation for the properties of cells.

The methodology is based on several further assumptions:

- There are known technical solutions that fulfill each component function.
- There are known technologies that join, detach, and test joint quality a finite number of times.
- The assembly and disassembly operations happen at predictable times with similar equipment for similar operations.

The scope of this work is to provide a product design methodology that is effective within an environment of sustainable manufacturing as defined by Tolio[453]. As such, the considered system—to which systems theory is applied—is not made by the product itself but instead represents the manufacturing environment, including disassembly, remanufacturing, and recycling.

4.2.1.2 Assumptions about life cycle

Because the proposed methodology must function without depending on the concept of an identifiable core, it cannot assume the traceability of the product over many life cycles and must be compatible with the necessity of tracing its components, at least those for which particular life cycles are foreseen.

The fact that the components with the highest aggregate share of product value (shown in 1.2) are prone to failure and deterioration makes considerations about the life cycle of the whole product sub-optimal because no way to recover that value can be derived from such a perspective beyond very complex decision trees and probability scenarios. However, independently of EoL decisions, each cell must finally be recycled. Moreover, each cell is subject to diagnostic assessment. As such, the proposed methodology considers the perspective of a single cell's life cycle, with the following implications:

- An EoL decision considers the residual value of each cell at any given time.

[453] Tolio et al. (Design, management and control of demanufacturing and remanufacturing systems) 2017, p. 2.

- The depth of disassembly, targeted by the proposed design methodology, is the single cell.

Each product can be conceptualized in modules, some of which comprise components that fulfill the definition of cells given in section 4.2.1.1, and some of which are modules in the traditional sense. The methodology first identifies which module belongs to each category and then maps the interdependencies between components and modules.

The perspective shift from the life cycle of the whole product to the life cycle of its cells produces a freedom: Each cell can have a different life cycle and be repurposed a certain (limited) number of times in applications that have increasingly less stringent requirements and that are compatible with its degradation state. Each time the product is returned from the market, the cell-containing modules are disassembled up to the cell level, and the cells are classified and repurposed. This process is referred to as the overhaul, sort and repurpose (OSR) life cycle. When the cell diagnostic is continuous, predictive maintenance is possible, and the product can be recalled before it is unfit for its function at an optimal time, which maximizes the residual value of each cell. The other still-functioning components can be reused in the manufacturing of a new—or repurposed—product, whereby commonalities increase the economies of scale. The other conventional modules (those without cells) can be inspected and reused (e.g., in a remanufacturing life cycle) or recycled easily because they are designed according to DfRem and DfR guidelines.

4.2.2 Goals of the methodology

The proposed methodology must enable the design of products that retain a high-residual value over many life cycles despite comprising many depreciating components instead of a durable, easily identifiable product core. The resulting product must be suited to a high level of automation at both assembly and disassembly (more than a single time). Decisions about the depth of disassembly during the various life cycles and whether disassembly is destructive must be determined during the development process and must drive the product structure and the selection of joining technologies.

With respect to the issues highlighted in section 3.2.2, the methodology must focus on usability and cost-effectiveness because a lack of these will compromise industry adoption. This goal will be pursued by providing a design workflow with the development process that ensures that the relevant design problems are tackled at the appropriate time.

4.2.3 Structure of the proposed design methodology

The model input is a function that must be performed by a product that is yet to be designed. However, an idea of the necessary sub-functions is present, as is an idea of the components that might perform such sub-functions. This preliminary concept will be called ”tentative product architecture.”

The problem of product design is approached over five phases by sequentially solving the following sub-problems.

The first phase involves identifying possible life cycles for every component individually. Manufacturing and recycling technologies are analyzed, in addition to their potential for refurbishment, reconditioning, and reuse. Their failure mechanisms, expected lifetime, and reliability are estimated during this phase.

The information about the life cycles of single components is used in the second phase to identify a suitable product architecture. In this phase, decisions are made regarding the components that should be grouped together on the basis of functional interdependencies and the most convenient life cycles. In this phase, multiple possible product architectures might be identified that prioritize different components. Here, an early decision could be made on the basis of the value of components or by applying QFD methods. In cases where a decision is not clear, for example, because of uncertainty on reliability data, multiple options might be developed further and evaluated in the final phase.

Given the product architecture, the types of necessary interactions between components are known. These are analyzed in the third phase, such that a set of requirements is derived for the layout of joints among sub-assemblies and components capable of being detached and reconnected at least a finite number of times, as required by the desired life cycles identified in the first phase.

The fourth phase starts with a product architecture and organizes it in the form of a product structure, whereby the connections between components, identified in the third phase, are laid out in space, together with the provisions necessary for accessibility during assembly and disassembly. The arrangement in three-dimensional space provides some degree of freedom to reduce the depth of disassembly for the recovery of some components. The prioritization can be assessed by DSM methods. If multiple solutions exist, a decision can be made by heuristics, or all the alternatives can be evaluated in the final phase.

In the fifth and final phase, all the possible product life cycles are evaluated using LCC and LCA methods. Because each specimen of the product can follow one of the envisioned life cycles, a weighted mean is produced based on reliability data, which make some life cycles more likely than others. Based on these data, decisions can be made between alternative product structures, or the methods can be reiterated to prioritize the convenience of more likely or more impactful life cycles.

The output of the proposed design methodology comprises a possible design solution that includes:

- A product structure, which identifies sub-assemblies and components, as well as their arrangement in space;
- A set of requirements for joining and detachment technologies to guide the detailed design;
- A set of foreseen life cycles for the product and its components;
- Information concerning the assembly and disassembly sequence;
- Information to calculate a business case on the basis of measured reliability data after market introduction.

The output product structure facilitates the desired product life cycles and identifies components and sub-assemblies, which can easily be reused and recycled. Accessibility for both assembly and disassembly is facilitated by the methodology, such that each component or sub-assembly can then be developed independently in the IPPD framework. The solution contains a set of requirements regarding joint connection and detachment, including access directions and the space necessary to disconnect and reconnect the joints a finite number of times. The development of the most-critical joining technologies can also follow the IPPD framework. A set of possible life cycles is proposed for each component and for the whole product. The likelihood of each product life cycle can be derived from a reliability analysis, such that the overall LCC and LCA can be based on a weighted average.

After the product architecture has been established in phase two, the methodology can be run recursively on sub-assemblies if the connections can be localized in clearly defined interfaces. This feature is important for the usability of the methodology within a IPPD framework.

The conception of the methodology in clearly defined phases aims to avoid design iterations. However, phases two, three, and four can be iterated, especially if some external factors change, such as unexpected reliability data or new use cases for the repurposing of a component.

Figure 4.1 provides an overview of the inputs and outputs of the five phases, including the possible iteration paths in the event of unsatisfactory evaluation.

4.3 Interim summary: design process with the proposed design methodology

Based on the phases of the proposed methodology, a workflow of the design process is mapped across four modules to be followed sequentially. Each module comprises two steps.

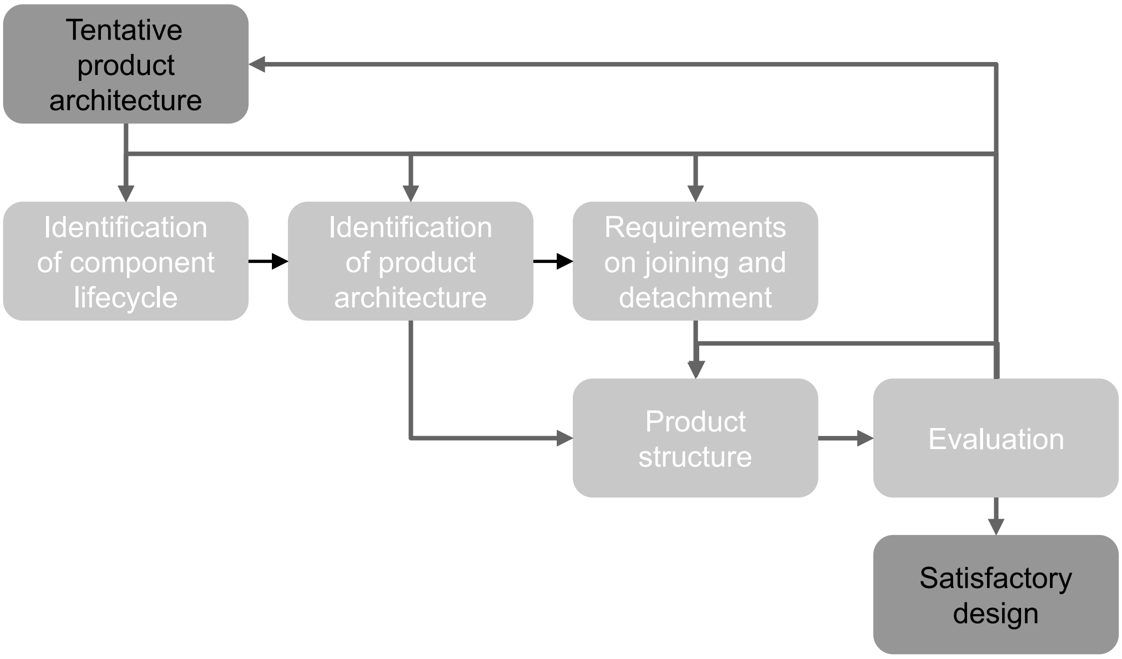


Figure 4.1: Structure of the proposed design methodology, with possible iteration paths

The first module (initialization) starts with the definition of a tentative product architecture and ends with the collection and organization of product and component information regarding structure, force, energy, information flows, and safety requirements. Given the function to be performed by the product, components are found that can perform the necessary sub-functions and their functional requirements. Using this information, possible solution spaces are explored in response to the following queries: What are the possible component types and their manufacturing and recycling technologies? How can they interact? What joint technologies are available, and which assembly and disassembly operations are possible? As such, this module encompasses the first and third phases and represents a descriptive model of the available objects that comprise the solution space. The second module (analysis) starts with an analysis of how the components must interact and then proceeds with an analysis of reliability properties and the life cycles of each component, considered individually as though they could be recovered from the product at any time without any cost. For each component, ideal life cycles are mapped, and components with a compatible life cycle are clustered, provided this does not compromise the function. When components featuring incompatible life cycles must interact, a solution for their interface must be found in the next module. This module encompasses the second phase of the model, and it is considered an explanatory model. The output is a refined product architecture with components clustered according to a DSM. The third module (synthesis) derives the product structure from the architecture and optimizes it for disassembly up to the required depth. First, the disassembly sequence is obtained. Then, the joints to be used are identified from the solution space and requirements, and accessibility for connection and detachment are ensured. This module encompasses the fourth phase, and it is a decision model because it helps to identify a viable alternative among many. Its output is a product structure capable of disassembly to the required depth. The fourth module (assessment) evaluates the product's performance, time, and cost and the derivatives obtained by repurposing its modules and cells. This module not only describes the performance of the design but also explains its weak spots and suggests where the design can be improved, making it an explanatory model. This module also encompasses the fifth phase, and its output is an LCC and LCA of the product with regard to its life cycle scenarios.

The proposed methodology is to be used from the preliminary phases of product development to the product's evaluation in a pre-series environment. The evaluation module provides feedback for the iteration of the methodology into next-generation products. However, the methodology is oriented toward providing viable options for circular life cycles from the first execution to overcome the drawbacks of inherently iterative DfE methods.

Figure 4.2 is an overview of the methodology, with each module represented by its first step at the top and its second step at the bottom.

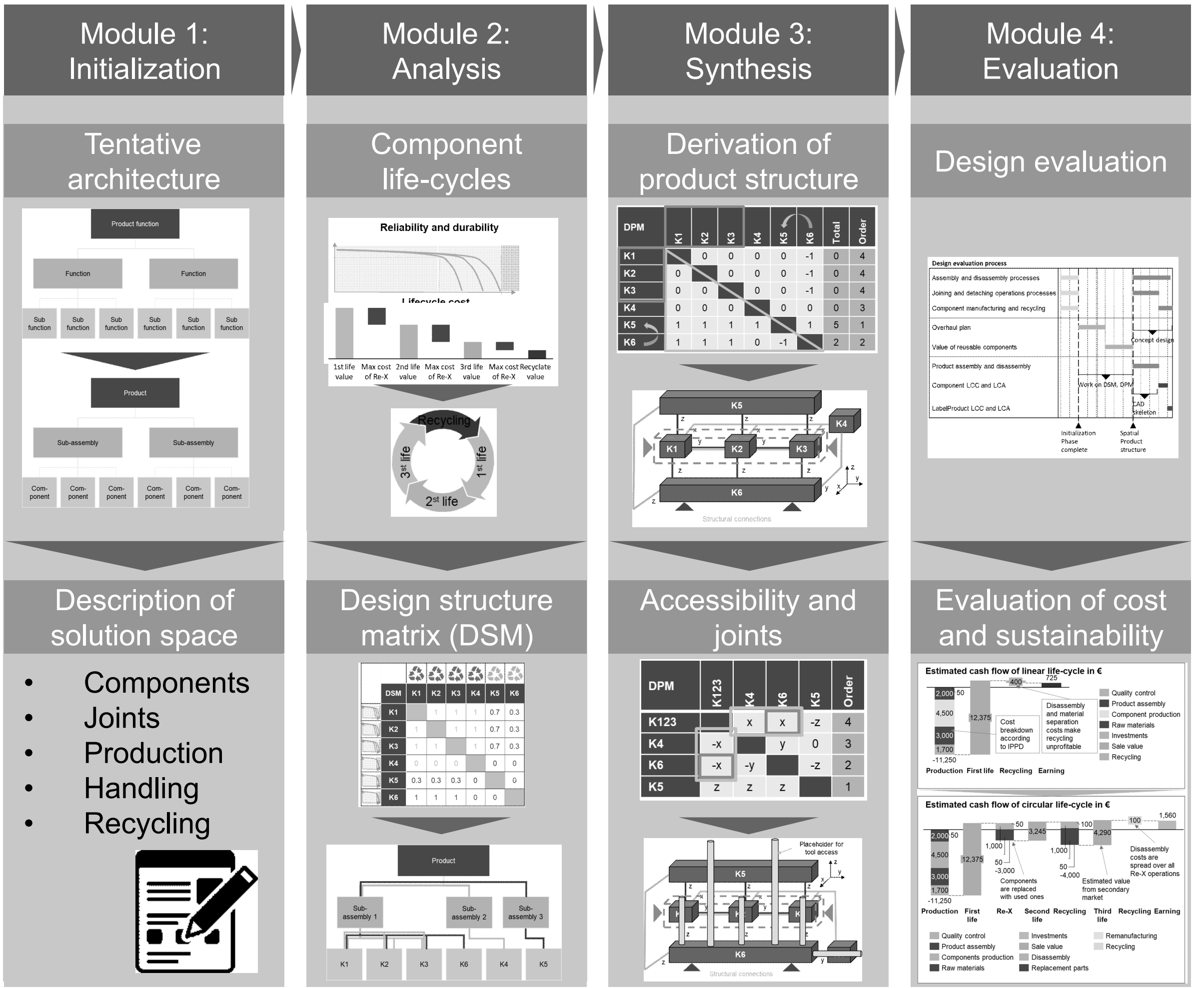


Figure 4.2: Overview of the proposed design methodology

5 Detailing of the methodology

Having outlined the phases of the methodology in chapter 4, this chapter explains each step of the methodology so that it can be applied in a design workflow. Each module comprises two steps to be followed sequentially.

5.1 Initialization module

The initialization module aims to identify the product components and their relevant properties, which will be needed in the later modules, and to characterize the ways that the components interact. It collects and structures information for convenient use during the product development process.

5.1.1 Tentative product architecture

First, the product function must be identified and derived from customer requirements and decomposed into a function structure.[454]

Different from DfM methods, the product structure must not be immediately derived from the function structure—as proposed by FELDHUSEN[456] and shown in figure 5.1a—because it would prematurely constrain the solution space to certain components, which would dictate the way they are assembled. Instead, the present methodology limits itself to identifying viable components for each function, leaving the field open for alternatives. In selecting each component's scope, there is space for arbitrary choice informed by the distribution of knowledge across contributors to the development process and the need to deliver tested components according to specifications.[457]

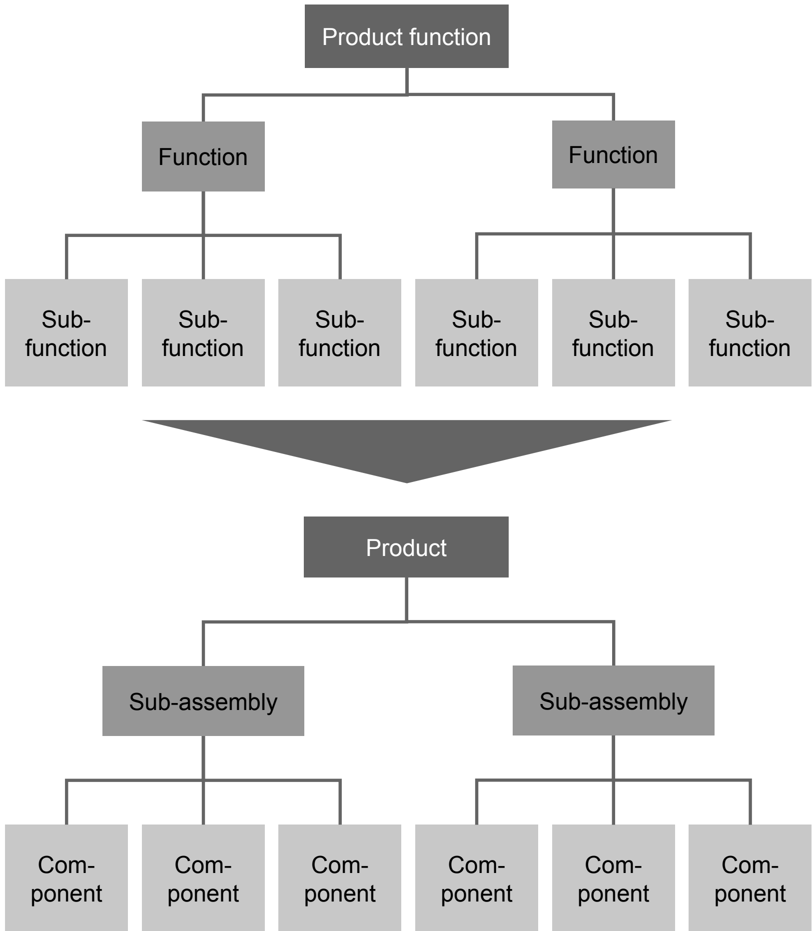
Overall product requirements are decomposed into requirements for components, and suitable components are listed. Furthermore, the requirements for possible components for the whole system are listed, such that components can be grouped together in sub-assemblies that satisfy each function's requirement. This extra degree of freedom allows for choice between different architectures if the results of the following modules are not satisfactory. In particular, this might be the case for the choice between

[454] Göpfert (Modulare Produktentwicklung) 1998, pp. 74-75.

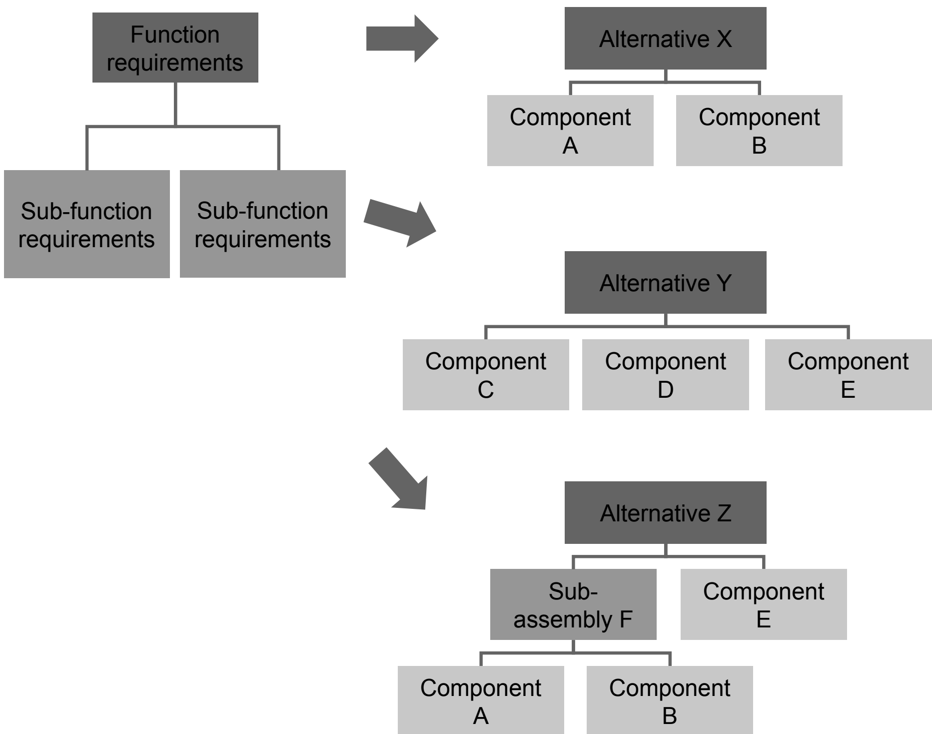
[455] Göpfert (Modulare Produktentwicklung) 1998, p. 75.

[456] Feldhusen et al. (Die Hauptarbeitsschritte des Gestaltungsprozesses) 2013, pp. 470-471.

[457] Kampker et al. (Using E-mobility as an Enabler for a Fast and Lean Product Development to Optimize the Return of Engineering with the Example of Lithium-ion Battery) 2016, p. 169.



(a) Product architecture according to GÖPFERT[455]



(b) Example of multiple architectures, which might satisfy the same requirements

Figure 5.1: Product architecture

components that require an external interface or have difficult assembly requirements.

In addition to these DfM criteria, the present methodology suggests determining whether it is possible to further decompose the component scope and to cluster components into sub-assemblies in the analysis module (when the product structure is derived). The present methodology can be applied recursively to such sub-assemblies, allowing for some freedom in the selection of the life cycle. The following criteria are relevant for determining whether a component should be further decomposed:

- Recycling: If an available recycling process for this component is not available, but it can be disassembled into recyclable parts, the component must be decomposed further.
- Safety: If a component is hazardous in its stand-alone state and during manufacturing operations, it should be handled in a manufacturing environment with controlled risk. The provisions to make the components safe during industrial operations must be considered and tracked. Items such as service covers and caps will be considered as part of the components at this abstract level and will be handled in detail at the design phase.
- Environment: If a component is dangerous if released in the environment or it is subject to special regulations about its disposal, it should consist of no more than the hazardous part and the necessary provisions to make its handling possible (e.g., containers and covers).

In principle, a component that can fulfill a function should be known in terms of its rough properties (e.g., size, shape, and materials). Alternative solutions for possible components can also be considered when more technical solutions are available.

Systems theory defines a component in the abstract model by its inputs and outputs, as well as the operations it performs.[458]

Having identified components from the tentative product architecture, the proposed methodology proceeds to characterize them abstractly—as needed for later stages—by gathering information about the components in the table shown in figure A.18:

- Reliability: time to failure, failure mode.
- Interface: forces, electromagnetic energy, heat transfer, information.
- Safety and environment: hazards, recycling process.

The reliability characteristics of the identified components are here summarized and compared. They are classified according to their failure modes as:

[458] Neumann (Objektorientierte Softwareentwicklung mit der Unified Modeling Language (UML)) 1998, p. 2.

- Components that function with constant performance until they fail (spontaneous failure mode);
- Components that wear or age until they fail and are no longer functional (damage accumulation);
- Components that wear or age until they fail but continue to function at a level of performance below the original specifications (performance degradation);
- Components that degrade and can be regenerated up to the original specifications by additive technologies, treatment, or refilling (consumption or wear).

One further type of component information that needs to be gathered is whether there is a market demand for used components and what level of performance and reliability is required for such markets.

5.1.2 Description of solution space

After having described the components in the previous section, this section describes their operations within the scope of the system. Within the scope of the model, the components can be connected to one another, the components can be manipulated in the manufacturing environment, new components can be manufactured, and old components can be either regenerated or recycled.

5.1.2.1 Scope of possible component connections

Possible joints are summarized with the methods used to inspect their quality and detach them. It is important that all these aspects are considered together alongside the consequent requirements for product design and manufacturing equipment, such as accessibility. These are listed, and their possible solutions compared. Because the components are defined as too small to be recycled, it is important that at least one appropriate joint detaching method is paired with each joint technology to ensure the component's recyclability. Joint detachment can be reversible, irreversible, or quasi-reversible, that is, reversible only a certain number of times, with or without extra provisions. For every joint and detachment technology, requirements about component fixtures and tool access need to be listed in a table, as figure A.19 shows.

5.1.2.2 Scope of possible assembly and handling operations

The scope of handling, assembly, and disassembly operations and their requirements must be identified. In particular, the need for fixtures featured for object recognition, movement patterns, and accessibility must be identified. The available options should be listed in a table as shown in figure A.20 and represented geometrically by libraries of placeholders in a CAD environment.

5.1.2.3 Scope of manufacturing technologies

The economies of scale in mass production differ from those present in remanufacturing operations. Before product life cycles are known and when there are uncertainties about the quantities of products undergoing different life cycles, some clarity is necessary to retain or consider the added flexibility facilitated by producing some components at a smaller scale at a later time compared to using the same production facilities. The production technologies available for each component must be listed in a table—as shown in figure A.21—that includes suitable quantities for each component. Furthermore, component design components must be listed and compared to understand design implications and guide design decisions toward flexibility. Design requirements, such as mold parting planes, injection ports, size limitations, thickness limitations, drafts, round radii, and surface quality, must be considered and represented in a library of CAD reference parts. The possibility of regenerating components using additive manufacturing must also be included.

5.1.2.4 Scope of recycling technologies

The scope of recycling technologies available for each component must also be listed in a table—as shown in figure A.22— including requirements for the acceptable quality of the recyclate. If multiple recycling technologies are available, their requirements should be further weighted against the quality and, thus, the value of recovered materials. Their requirements should be compared to foresee a future, better technology surpassing an older one if both requirements are similar.

5.1.3 Summary of the initialization module

The module starts with the identification of the function to be performed by the product, its breakdown into sub-functions, and the definition of requirements for such sub-functions. Then, possible components are identified that can perform each sub-function and satisfy its requirements. Meanwhile, the system's requirements of the components (environment, assembly, force, energy, and information transfer) are analyzed to organize them in a tentative product architecture or in alternative architectures. The collection of information about each component's life cycle and reliability requirements, such as manufacturing and recycling technologies, lifetime, and expected failure mode, leads to the mapping of the life cycles of the individual components. If they are unsatisfactory, some components can be broken down into sub-assemblies of simpler components. From the assembly requirements of the components, the available joining technologies and the requirements for assembly and disassembly are analyzed. Requirements are established for joints that can only be detached a finite number of times. This produces one or more tentative product architectures, from which the most promising can be selected for optimization in the following modules.

5.2 Analysis module

In this module, the components are classified according to their reliability and EoL characteristics to identify their optimal life cycles and derive a tentative product structure that aims to fulfill the product function by enabling the preferred life cycle for each component.

5.2.1 Definition of component life cycles

The prevalent failure mode of each component substantially influences not only its reliability but also its optimal life cycle. In particular, two dimensions are considered by the model: first, the predictability of the component's lifespan; second, performance degradation during that lifespan.

The predictability of the component EoL lifetime allows for a design in which such components have a limited useful life and are replaced at planned intervals. According to standard DfRem practice, these components with a similar lifespan should be collected to simplify the overhaul operation. If the overhaul operation extends the product lifetime considerably, it can demand greater effort. Meanwhile, components that fail unpredictably need to be easily and quickly accessible and replaceable.

The performance degradation of components over their lifespan means that these components meet their EoL when they no longer fulfill the requirements of their original application but continue to function. In this case, these components can be replaced well before their EoL and repurposed in a less-demanding application. In some cases, performance degradation can be reversed by regenerating the component. The possibilities of repurposing and regenerating components should be known by the initialization module.

	Spontaneous failure	**Damage accumulation**
Catastrophic failure	Reuse with fail-safe	Reuse for residual lifetime
Performance degradation	Repurpose	Regenerate or repurpose

Table 5.1: Component classification according to expected failure modes.

According to the two criteria presented in table 5.1, components are classified into four categories:

- Spontaneously failing components, which do not degrade, can be tested and reused indefinitely;
- Components subject to damage accumulation, which degrade and fail, can be reused only if their residual lifespan is sufficient to allow reuse, and may need to be monitored to predict their residual lifespan and avoid failure;
- Components subject to performance degradation but which remain functional can be repurposed and could be monitored;
- Components subject to wear and which can be regenerated should be regenerated and reused as long as possible.

According to this classification, possible life cycles for each component need to be selected on the basis of component level LCC, estimated costs for overhaul, and LCA. At this stage, there is no guarantee that these hypothetical life cycles will be profitable or convenient, because the costs to recover the components and their value when they are repurposed are not yet known. Furthermore, if they are newly developed components, their lifetime is only an estimation. Given the market values of new and used components and recycled materials, it is possible to estimate the maximum budget for the operations needed to reuse the component in the calculation of a business case, as figure 5.2 shows. A similar criterion can be used to assess LCA measures, such as GWP. This classification criterion is referred to as the reliability criterion.

On the basis of these evaluations, a target life cycle should be selected for each component that includes the expected lifespan before replacement, the possibility of reuse or repurposing, and the selected technology for recycling, as figure 5.2 shows. Components that can be recycled or reused together are identified according to this criterion, which will be referred to as the EoL criterion.

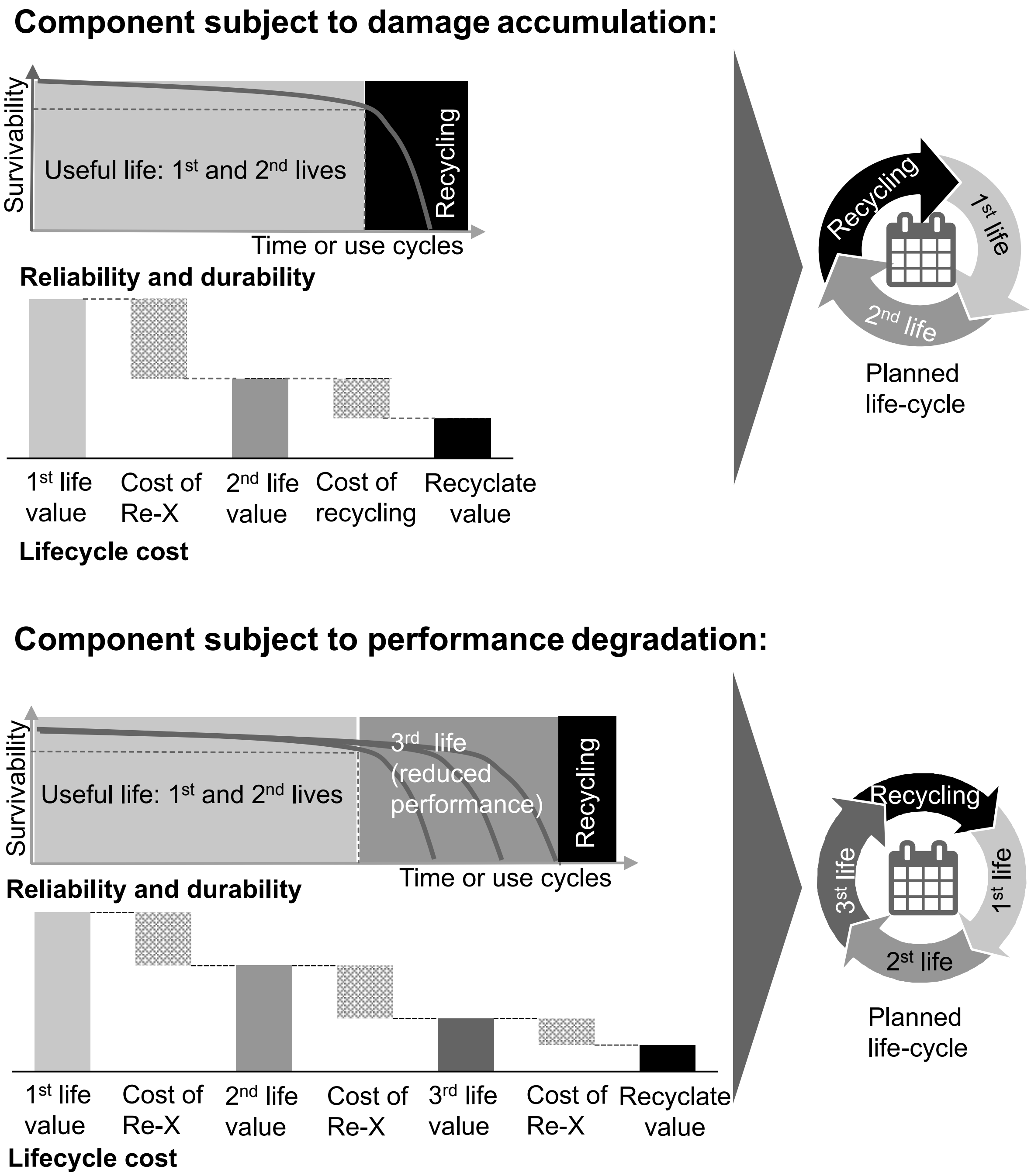


Figure 5.2: Example of component life-cycle planning according to reliability and LCC

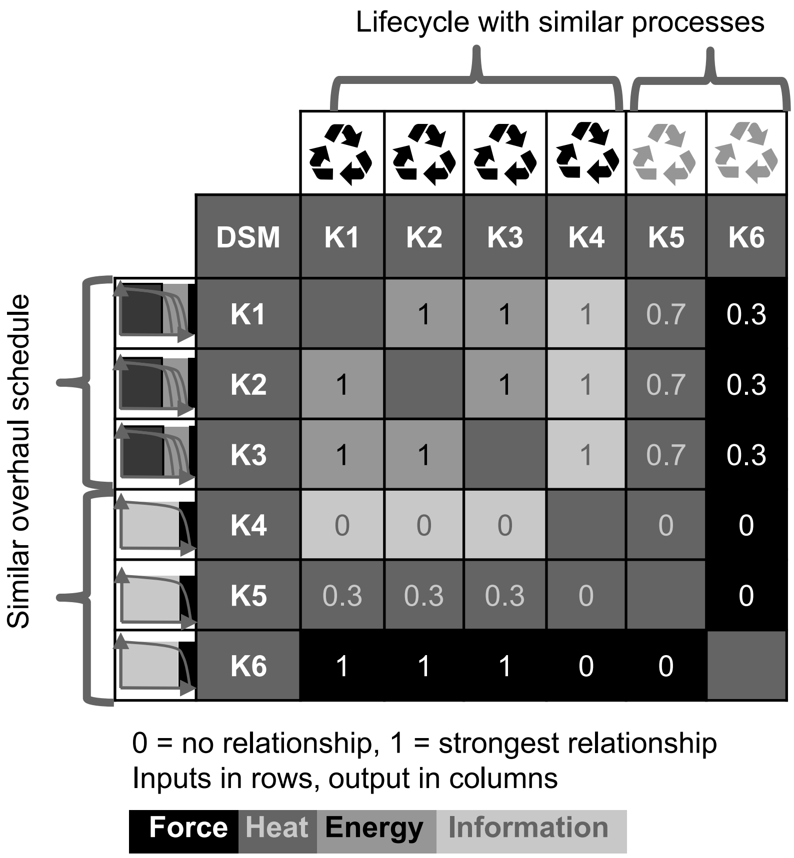


Figure 5.3: DSM to assess both component relationships and commonalities in the life cycle and overhaul schedule

5.2.2 Design structure matrix

At this stage, the product architecture must be structured to enable the preferred component life cycles: Ideally, components with similar lifetimes and EoL strategies should be clustered together, components that need frequent replacement should be easily accessible, and trade-offs need to be made between these often-conflicting goals while ensuring that functional requirements are satisfied.

For this purpose, the components that have been identified in the initialization module—and whose preferred life cycles have been outlined in section5.2.1—are analyzed in terms of their interactions by means of a design structure matrix (DSM).[459]

The relationships between components should be expressed in a numerical, non-binary form on a continuous scale from 0 to 1[460]. The durability and EoL strategy could be noted close to the component name to make them visible when applying DSM methods for clustering components into sub-assemblies, as figure 5.3 shows for components labeled K1 to K6. The connections between components are classified as "force," "en-

[459] Pimmler et al. (Integration Analysis of Product Decompositions) 1994, p. 9.
[460] Eppinger et al. (Design structure matrix methods and applications) 2012, p. 5.

ergy," "heat," and "information." Although some implementations of DSM use a specific row and column for each of these, the present methodology proposes simplifying and prioritizing the connections, such that those that impose stricter requirements on the product structure hide the others. If, for example, two connections exist between two components, a force and an information connection, only the force connection will be represented in the DSM, because it is assumed that there is a way (cable or wireless) to transfer the information around sub-assemblies. According to this logic, the priorities are force, energy, heat, and information.

As figure 5.3 shows, beyond the standard DSM features, components are characterized by the classification criteria from section 5.2.1. One row is added to the top for classification according to the EoL criterion, and one column is added on the left for classification according to the reliability criterion. If two or more components are compatible according to both criteria, they should be preferentially clustered in the same sub-assembly for reuse, repurposing, or recycling. If two or more components are only compatible according to the reliability criterion, they should be preferentially clustered in the same sub-assembly, which will be disassembled after removal from the product during an overhaul.

These two additional criteria can be considered two further dependency relations in the DSM, relations that only come into effect at the product EoL. They visualize when a product overhaul would be convenient to recover the components and what EoL strategy should be adopted. For this reason, they could, in principle, be represented similarly to other relationships by a number between 0 and 1 and be prioritized according to the standard DSM method. However, they are visualized separately to highlight their role in defining the product structure. From the life cycle perspective, it would be advantageous to cluster the same sub-assembly components with similar reliability and EoL strategies to recover them with the minimum depth of disassembly. From a functional perspective, it would be advantageous to cluster components with the strongest dependencies, such that they interact without involving more components than necessary.

By considering this trade-off, a tentative product structure can be derived that makes it clear which sub-assemblies should be prioritized at which service interval.

An example of a tentative product structure appears in figure 5.4. Multiple structures are possible according to different design priorities, and for each an LCA and an LCC can be performed with relatively low effort with the available information collected in the initialization module, before specialized IPPD teams put substantial development effort into component development. After the clustering of the DSM, the subassemblies are still considered separable (physically independent according to GÖPFERT[461]), and the joints will be defined later—in the synthesis module, as explained in section 5.3.2.

[461] Göpfert (Modulare Produktentwicklung) 1998, pp. 104-105.

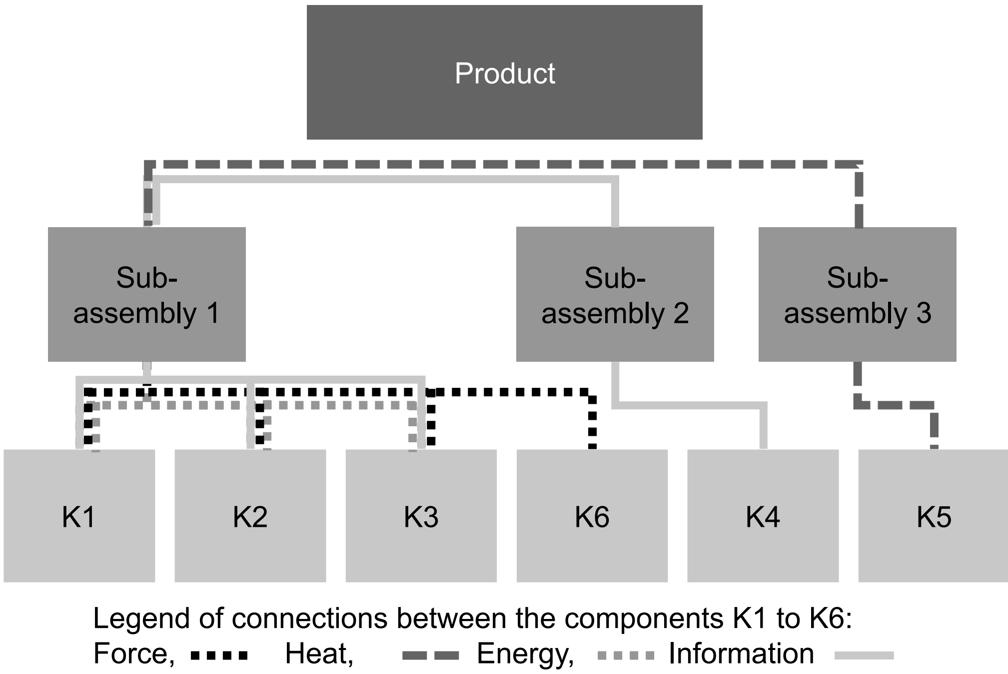


Figure 5.4: Tentative product structure derived from the DSM, with the connections color-coded

5.2.3 Summary of the analysis module

The analysis module classifies the components identified during the initialization modules according to a reliability criterion and an EoL criterion and considers these two criteria as dependencies within the framework of the DSM method to determine a tentative product structure that sees components grouped into sub-assemblies not only on the basis of functional dependencies but also as a trade-off with the optimal life cycle of the components. The consequences of this trade-off can be either an increase in the number of subassemblies or longer paths for the transmission of force, heat, or energy when these are compatible with the product's function. Ultimately, because not all components can always follow an optimal life cycle, this module provides the elements for prioritization based on LCC and LCA criteria.

5.3 Synthesis module

The synthesis module will present methods for improving the tentative product structure mapped by the analysis module. After clarifying the relationships between components, a product structure needs to be determined to fulfill product functions and make possible the desired component life cycles. The synthesis module does this in two steps. First, it organizes the product structure to decrease the necessary depth of disassembly for the prioritized components. Then, it lays out the joints and their accessibility.

5.3.1 Derivation of product structure

The accessibility of the components to be removed during the same overhaul should aim for the least depth of disassembly. Here, the disassembly precedence matrix (DPM)[462,463] is employed to improve the tentative product structure.

Each row and each column of the DPM represents a component, and the entries represent dependencies in the disassembly sequence (i.e., if a component needs to be disassembled before another component). The DPM method finds an optimal disassembly sequence by reordering the matrix to make it triangular, such that the last components that can be removed are at the top and the first to be removed are at the bottom.

At this stage in the design process, the joints have not been defined, so the matrix will have many zeroes, and multiple disassembly sequences are possible. This means that it is possible to prioritize the depth of component disassembly, which must be recovered during an overhaul. This should be either at the bottom of the matrix or part of a sub-assembly that is at the bottom of the matrix. For simplicity, sub-assemblies can be

[462] Tao et al. (Partial/Parallel Disassembly Sequence Planning for Complex Products) 2018, pp. 3-5.
[463] Laili et al. (Product Representation for Disassembly Sequence Planning) 2022, p. 30.

DPM	K1	K2	K3	K4	K5	K6	Total	Order
K1		0	0	0	0	-1	0	4
K2	0		0	0	0	-1	0	4
K3	0	0		0	0	-1	0	4
K4	0	0	0		0	0	0	3
K5	1	1	1	1		1	5	1
K6	1	1	1	0	-1		2	2

Each element of the matrix b_{ij} represents precedence relations for the disassembly of components *i* and *j*

- 0 if *i* and *j* can be disassembled in any order,
- 1 if *j* must be disassembled **after** *i,*
- -1 if *j* must be disassembled **before** *i,*

Instead 1 and -1, *x* and –*x*, *y* and –*y*, *z* and –*z* can be used to express direction of disassembly

Figure 5.5: DPM made on the basis of tentative product structure: The first elements to be disassembled are those with the highest sum total unless they are blocked by other antecedent components

represented as single components and analyzed recursively.

Sometimes certain components are interdependent and must be extracted together, as is the case for K1, K2, and K3 in the example shown in figure 5.5.

To address such cases, the concept of ”service sub-assembly” is introduced in the methodology. Whenever some components need to be part of the same sub-assembly during handling and manufacturing operations, but must not be linked together in the product, a ”service sub-assembly” is made. For this kind of sub-assembly to maintain its integrity, some tools and fixtures are needed; otherwise, it collapses. This way, the need for module housings, typical of modular designs, is reduced, as are the number of joints and assembly and disassembly times. In the example in figure 5.5, the housing K6 could be avoided if K1, K2, and K3 were kept in place by a service sub-assembly until they are kept in place by K5. This has a similar effect of reducing the depth of disassembly, as K123 (the service disassembly comprising K1, K2, and K3) can be disassembled as soon as K5 is removed and the holding fixture is released. For simplicity, the service sub-assemblies can be collapsed into a single component, and the DPM can be used recursively top-down from the product to the sub-assemblies.

The result of this first operation is represented by the rearranged matrix that appears in figure 5.6

It is important to note that this methodology is usually employed in the context of ex-

DPM	K123	K4	K6	K5	Total	Order
K123		0	0	-1	-1	4
K4	0		0	0	0	3
K6	1	0		-1	0	2
K5	1	1	1		3	1

Figure 5.6: DPM rearranged by swapping components and aggregating service sub-assemblies

DPM	K123	K4	K6	K5	Order
K123		x	z	-z	4
K4	-x		y	0	3
K6	z	-y		-z	2
K5	z	z	z		1

Figure 5.7: DPM with prevalent access direction z

isting products, where every component is constrained by joints. The proposed design methodology differs because, at this stage, only the dependencies between components related to their function and life cycles are present. Hence, many zeroes will identify degrees of freedom in the direction of assembly, degrees of freedom that will be useful for the layout of the joints in the next step.

5.3.2 Direction of access and layout of joints

The product structure alone is insufficient to guarantee ease of disassembly because interference between components could prevent tool accessibility and interfere with the component extraction trajectory. As such, the disassembly of further components might be needed. This step considers the directions for assembly and disassembly with the goal of increasing the degrees of freedom in the assembly and disassembly sequences by assigning the assembly and disassembly sequences of some components to specific directions, making them independent of one another. Where possible, the components that need to be recovered during the same overhaul should be assigned to the same direction of assembly and disassembly.

This step elaborates the product structure from section 5.3.1 by considering the di-

DPM	K123	K4	K6	K5	Order
K123		x	x	-z	4
K4	-x		y	0	3
K6	-x	-y		-z	2
K5	z	z	z		1

Figure 5.8: Rearranged directional DPM allows the integration of K4 and K6 because of the same access direction

rections for assembly and disassembly by means of a geometrically based DPM[464].

Following the component priority from section 5.2, a direction of access is assigned to the components with consideration of the following criteria:

- Access from the same direction is preferred unless the goal of reducing the depth of disassembly of a shadowed component is precluded.
- Access from multiple directions reduces the depth of disassembly to reach some components.
- Fixation from a direction affects the tolerance chain in that direction and in perpendicular directions; every time the access direction changes, a loss of precision occurs.

According to these needs, the DPM should be completed with the direction of access, which results in different assembly sequences and requirements for the manufacturing equipment.

The geometrically based DPM can now be rearranged to improve the depth of disassembly of the prioritized components by exploiting the extra degrees of freedom. The example shows two possibilities, one in figure 5.7, with access from multiple sides, and one in figure 5.8, which has been manipulated for access to both K4 and K6 on x. Because the two components share a similar durability and life cycle, they can be integrated into a sub-assembly.

In this step, the product structure is modeled with placeholder models in a CAD environment, with the access direction of components highlighted and the space needed for component assembly and disassembly—including the necessary tolerances—also represented.

[464] Moore et al. (Disassembly Petri net generation in the presence of XOR precedence relationships) 1998, pp. 13-15.

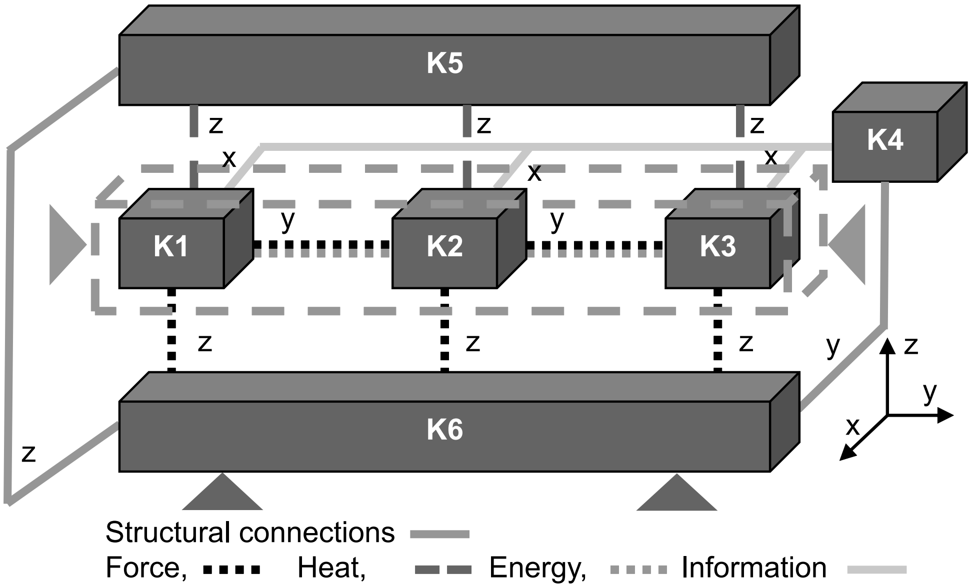


Figure 5.9: Representation in space of product structure resulting from prioritizing access from direction z

The top component of the DPM must have fixtures and references to the manufacturing environment, and the components mounted on that component (frame) should be referenced to the datum and precisely positioned. Further components are subject to tolerance stack-ups.

Figures 5.9 and 5.10 show the two possible representations in space of the proposed exemplary product structures derived from the DPM in figures 5.7 and 5.8.

At this stage, many alternatives appear possible, but not all of them might be feasible because of the necessary space needed for the layout of joints selected from the available technologies identified in section 5.1.2.1 and for tool access. This can be quickly verified by CAD placeholders.

Figure 5.11 shows an example of a top-down CAD model of the product made from placeholder components, including accessibility requirements for tools.

The available space is now visible for joints and their accessibility, such that they can be engineered at the lowest sub-assembly level in an IPPD framework with special attention to the requirements for:

- Space and fixtures for the joint itself;
- Tooling access and force transmission for the joint's realization;
- Access for the quality inspection of the joint at the end-of-line and during inspections;
- Access and other requirements of the joint separation process.

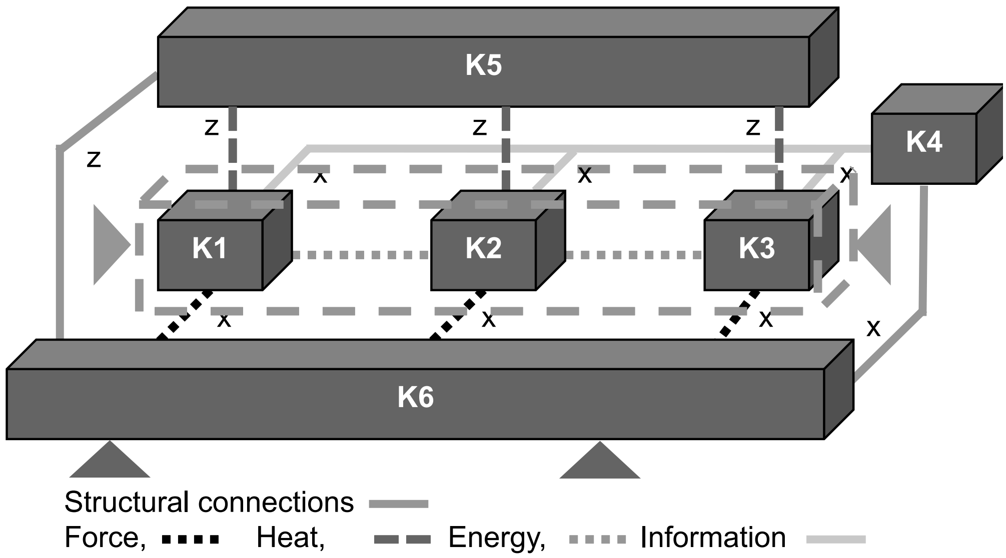


Figure 5.10: Representation in space of product structure resulting from prioritizing access from direction x

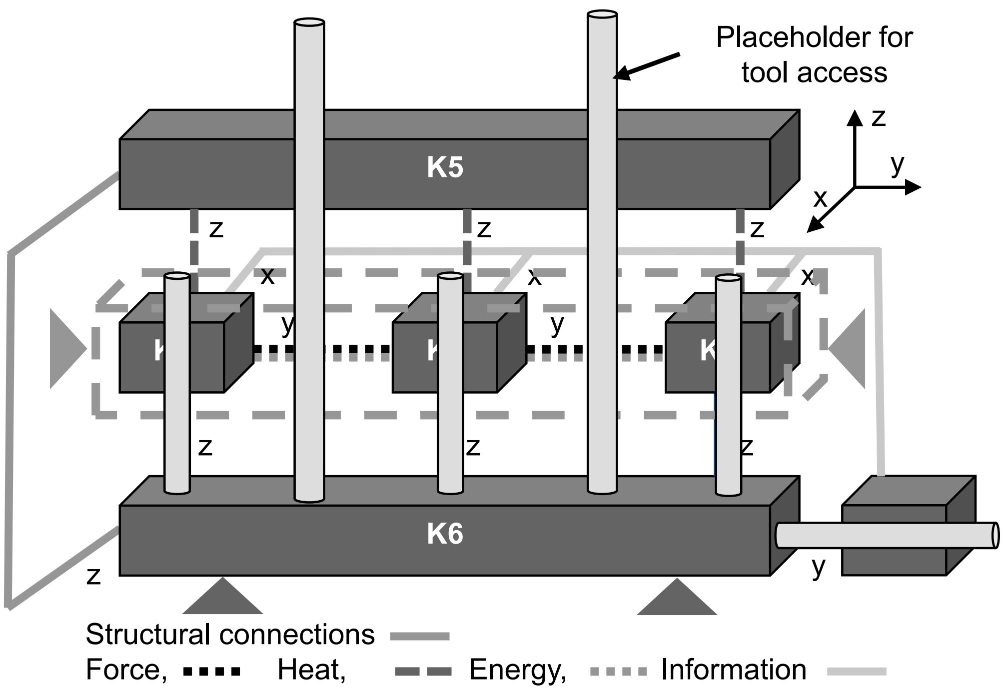


Figure 5.11: Top-down skeleton with placeholders for tool access

In the layout of the joints, it is important to consider that some components can be reused only a limited number of times, which means that their joints do not need to be detached indefinitely. This requirement introduces the possibility of using non-detachable joint technologies, where a part is sacrificed in the detachment and replaced in the reconnection of the joint. This approach implies added requirements for joint space and accessibility and for handling the extra sacrificial part.

5.3.3 Summary of the synthesis module

Given the prioritization of components to be easily recovered and the tentative product structure derived in section 5.2, the synthesis module provides a methodology for optimizing the depth of disassembly of prioritized components. This involves first arranging the disassembly sequence in general and then considering the problem of accessibility in possible directions. The disassembly sequence can be run separately in each direction, thus further decreasing the depth of disassembly for prioritized components. Finally, the product structure is represented in CAD by placeholders, with the mounting precision of each component and the tool accessibility considered according to the requirements derived in sections 5.1.2.2 and 5.1.2.1. Such a model is then sufficient to perform detailed design of each component according to the requirements derived from sections 5.1.2.3 and 5.1.2.4 by independent development teams. The connection and detachment of the most-critical joints can also be developed independently on small-scale prototypes.

5.4 Assessment module

The proposed methodology should allow a viable solution to be found within the first iteration. However, that solution is not optimized with regard to any other goals. Instead, it only ensures a certain life cycle for certain components and that a subset of components can be easily replaced. There is the possibility that other product variants that prioritize other components are advantageous from some perspective or that future product life-cycle scenarios tilt the risk-opportunities balance in favor of some product variant.

The assessment stage allows for the evaluation of certain metrics that can be used to evaluate alternatives as early as possible in the design process to avoid unnecessary effort being exhausted on unpromising concepts. Furthermore, it enables early experimentation on joint connection, detachment technologies, and component recycling. Figure A.16 shows when different aspects can be evaluated during development with the proposed methodology.

5.4.1 Design evaluation

At the end of the synthesis module, the overall package space of the product, the component placement, the force paths, and the heat, energy, and information flow are defined, enabling evaluation and comparison with similar products with similar specifications. On this basis, it should be possible to evaluate whether the trade-offs made to optimize for component life cycles have engendered significant disadvantages compared to designs that neglect such aspects.

Furthermore, accelerated aging tests can be performed at the component level to evaluate component lifespans and, hence, their value for reuse and repurposing based on comparisons with components featuring similar specifications when new. As such, decisions can be made regarding whether to over-dimension some components to allow their reuse multiple times.

5.4.2 Evaluation of cost and sustainability

The proposed methodology allows the derivation of a (BOM) before the actual design starts, allowing overall cost and approximate weight to be estimated soon enough to discard unacceptable alternatives. The information about the components gathered in the initialization and analysis modules is sufficient to perform LCC and LCA at the component level at a very early stage (when a design change can be implemented at a low cost). Meanwhile, with the information about component life cycles, disassembly sequences, and accessibility, it is possible to calculate assembly and disassembly times and, therefore, the cost of each component's life cycle, enabling EoL decisions. Furthermore, the necessary productive capacity over time can be estimated according to EoL scenarios, according to which—along with the LCC of each component and its estimated residual value when reused—it is possible to assess the economic viability of the design method from an early phase in the design process.

An example of a hypothetical evaluation appears in figure A.17

5.5 Interim summary

The framework outlined in section 4.2, has been detailed in this chapter, with focus on the requirements on the methodology listed in section 4.1.3.

The methodology consists of four phases: the first two are descriptive models which capture the components' properties and their interdependence. The third phase is a decision model which assists the designers in arranging the product structure to optimize for the life-cycle of single components. The fourth phase is a description model, which is aimed at benchmarking the current product iteration on the basis of cash flows, GWP and to assess the impact of its modularity on the development time.

Based on the phases of the proposed methodology, a workflow of the design process is mapped across four modules to be followed sequentially. Each module comprises two steps.

The first module consists of two stages: the definition of a tentative product architecture and the collection and organization of information about possible components and available manufacturing technologies.

The second module consists of two analyses: an analysis of necessary component relationships for the product function and another analysis focused on the relationships between reliability life cycles of each component.

The third module consists of the determination of the assembly and disassembly sequence in the first stage, and in the spatial arrangement of components in the second stage.

The fourth module evaluates the necessary time to develop a product with the selected degree of modularization and accessibility in the first stage, and evaluates the LCC and LCA of the product in its envisioned life cycle scenarios.

The proposed methodology assists the designers in achieving the necessary degree of products modularisation and component accessibility to optimize the life-cycles of its most valuable components and to quantify the development effort as well as the potential costs in the very early stage of product development. As such, it provides a cost-effective answer to the questions regarding trade-offs in DfE.

6 Application and validation of the methodology

The following chapters demonstrate three use cases of the proposed design methodology, enabling proof-of-concept battery designs that enable an OSR life cycle of battery cells. Two use cases have been developed as part of the BatteReMan project and one as part of the LiVe research project. Some results have been anticipated in the Journal of Remanufacturing.[465] The present chapter will expand on the results presented in that paper by focusing on the application of the proposed design methodology to define the problem and find the solution. The results are evaluated in terms of life-cycle improvements and potential costs or difficulties encountered during development.

6.1 Use case: Battery module with prismatic cells

The simplest application of the proposed methodology is to validate an existing design, highlight necessary changes, and find a solution to make the OSR life cycle possible. For reference, a standard module with PHEV2-sized prismatic cells—shown in figure 6.1—has been re-engineered.

Because an example of the product is available, the first step is to understand the functions of existing components and their interactions.

6.1.1 Initialization module

The solution space is represented by the possible properties of components, joining and detaching technologies, manufacturing, handling, and recycling technologies.

Because the product structure is given, component identification is trivial. Hence, although some choice is available with respect to materials and manufacturing technologies, the relevant information on components is collected in figure A.1.

Meanwehile, the relevant information on joints, handling, manufacturing, and recycling is collected in figures A.2, A.3, A.4, and A.5.

[465] Kampker et al. (Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells) 2021, pp. 10-19.

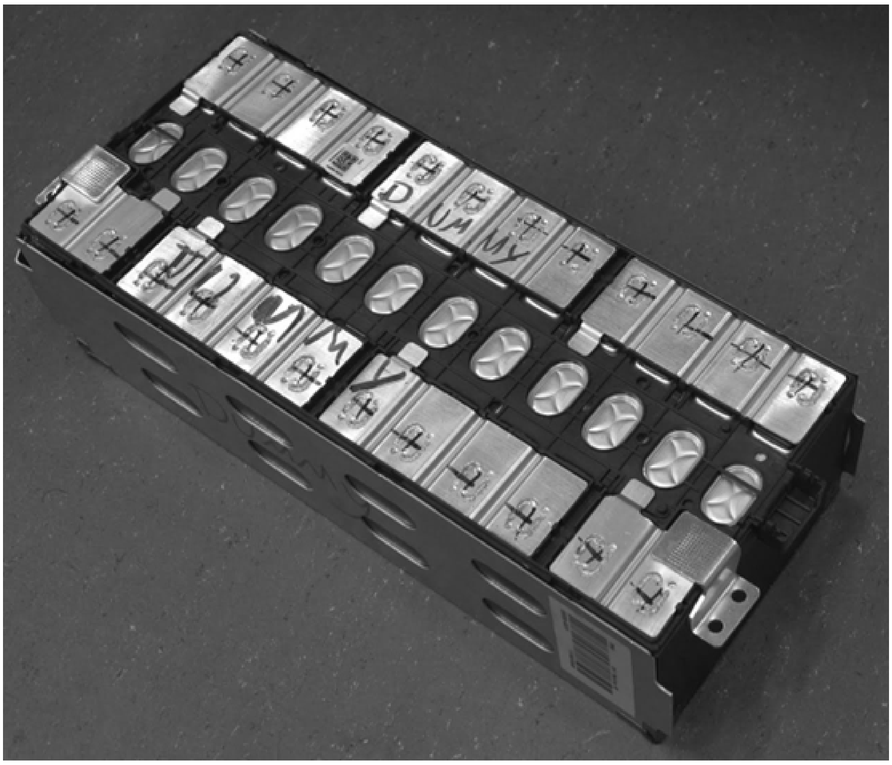


Figure 6.1: Dummy module with prismatic cells to be re-engineered

6.1.2 Analysis module

Cells are subject to aging, as explained in section 2.3, but they can be reused at least once more. This module is a dummy, but analogies suggest that one can expect more than 10 years for the longer-lasting cells and about 3-4 years for the first failures. The working hypothesis about a cell's life cycle is that a first life ($100\% > SoH > 80\%$), a second life ($80\% > SoH > 60\%$), and a third life ($60\% > SoH > 50\%$) will be possible, all in modules with the same housing and BMS shape as this one. Because cells are by far the highest value and least durable component, their life cycle determines the module's overhaul interval. For this reason, apart from functional safety, each cell's SoH is constantly monitored. The CSC boards are prone to electronic failures, which can be diagnosed. Moreover, CSC can be tested at each overhaul and inspected to detect mechanical or thermal damage. The CSC can be reused many times under these assumptions and then recycled as E-waste. The CSC carrier can be made of plastics, separated, and recycled when the CSC is recycled. Head plates and side plates should ideally be reused at least three times and recycled with the cells. Alternatively, they can be recycled at each overhaul and replaced with new ones. The cells are isolated from each other and from the sides by isolation foils, which are glued all around the cells. A better life cycle would be enabled by gluing these with a light adhesive to the head, side, and bottom plates. Among the cells, rubber gap pads could be used and stacked to keep the pressure uniform among the cells, with only a very light adhesive required

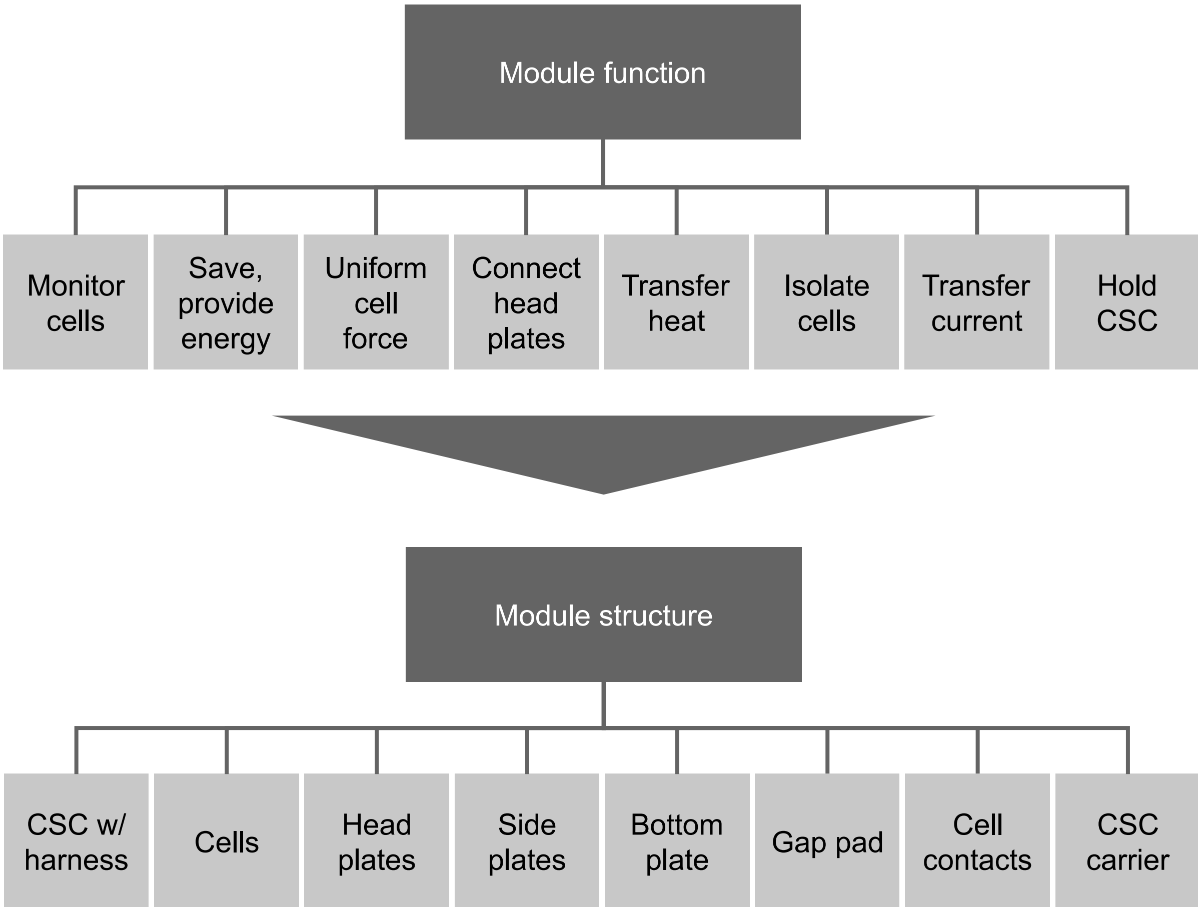


Figure 6.2: Product architecture of battery module

to keep the cells in place during cell stacking. Cell contacts are made of aluminum and can be recycled with either the cells or the housing.

Given the assumptions of the previous section, several simplifications can be made:

- The CSC and the CSC carrier can be considered one sub-assembly because they are separated only before recycling.
- The cell isolation foils can be considered a part of the head, side, and bottom plates for the same reason.
- The side and the bottom plates can be considered together because they are identical, and only the direction of assembly differs.

With these simplifications, the DSM appears in figure 6.3.

The dependency structure of the force connections requires that the cells and the housing be contained in one sub-assembly, with the contacts and the CSC clustered together because they are loosely linked by information connections, as demonstrated by the tentative product structure in figure 6.4

In this tentative structure, the force connections have been prioritized over the energy and information connections because the latter require fewer fixtures, some of which are provided by the housing structure itself to enable easier performance at a later stage.

DSM	Cells	Gap pads	Head plates	Side plates	CSC	Contacts
Cells		0	0	1	1	1
Gap pads	1		1	0	0	0
Head plates	1	0		0	0	0
Side plates	0	0	1		0	0
CSC	0	0	0	0		0
Contacts	1	0	0	0	1	

0 = no relationship, 1 = strongest relationship
Inputs in rows, output in columns

Force Heat Energy Information

Figure 6.3: DSM of prismatic cells module

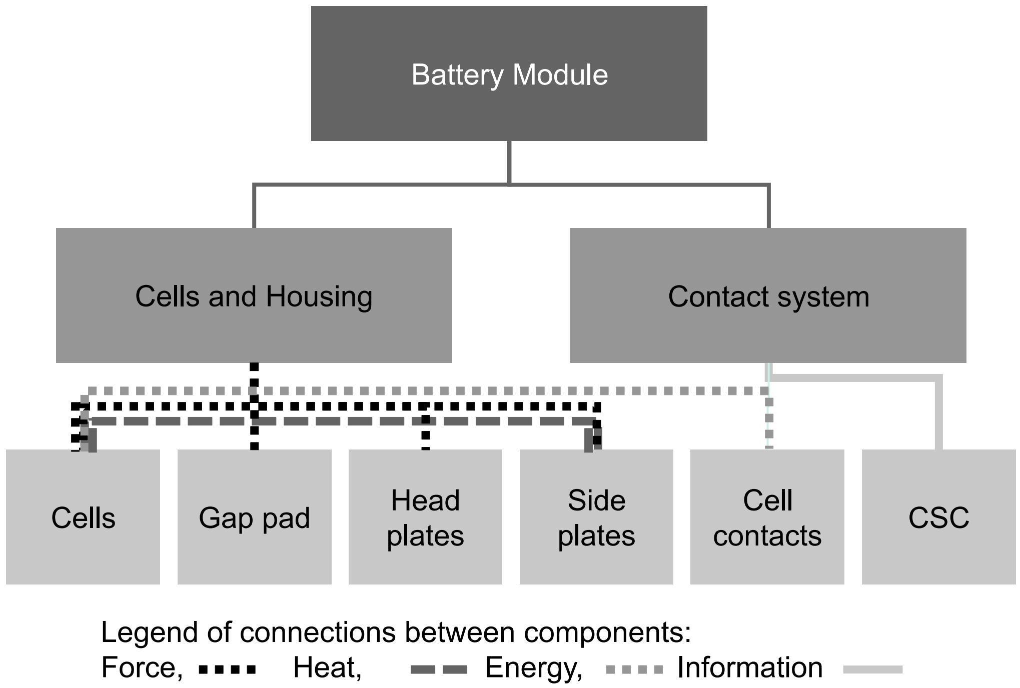


Figure 6.4: Tentative product structure of prismatic cells module

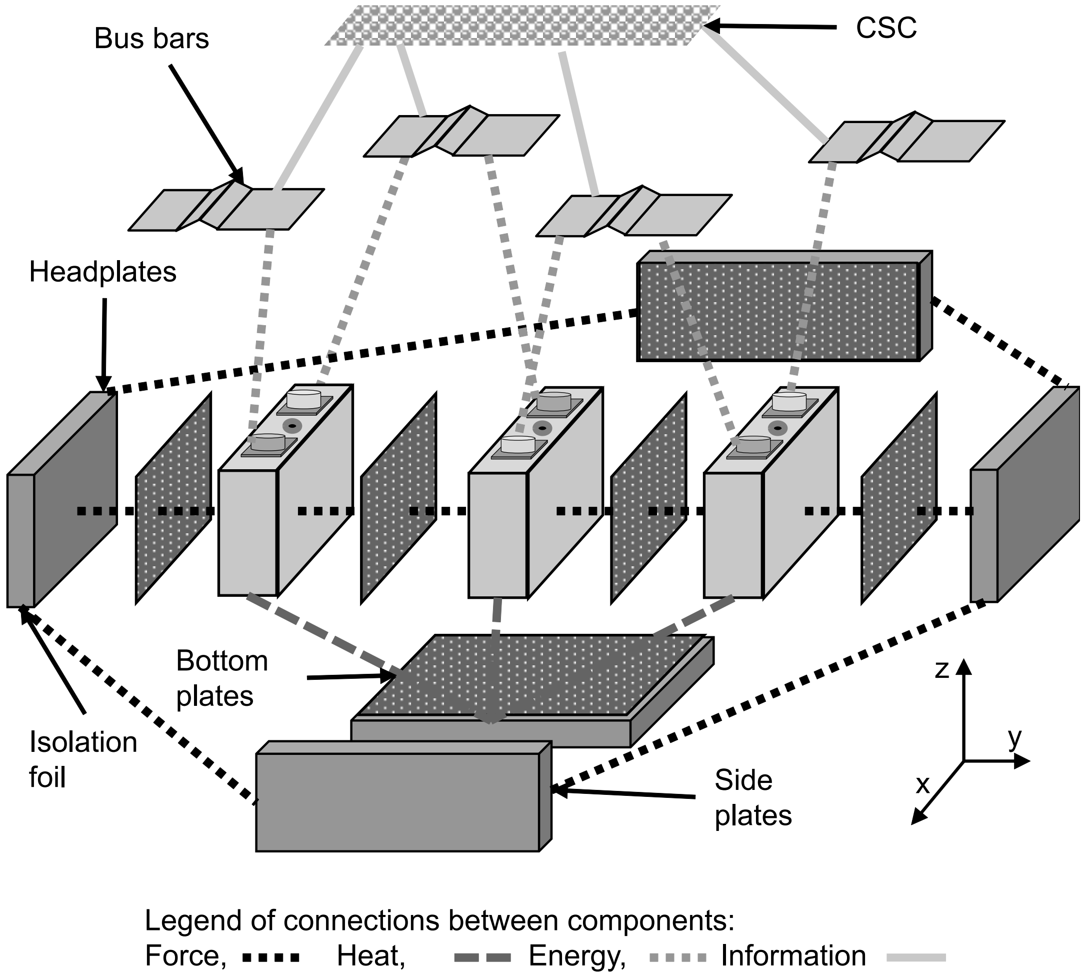


Figure 6.5: Tentative product structure of prismatic cells module in space

6.1.3 Synthesis module

Given the cells' geometry and the housing function, not many degrees of freedom arrange the components in space, as 6.5 shows.

The DPM, in figure 6.6, is characterized by a cluster comprising cells, gap pads, and head plates, representing a service sub-assembly during the stacking phase (when the side plates are connected to the head plates).

Tool access is given from the sides to welded side plates and from the top to contact the cells and CSC, as figure 6.7 shows.

In both cases, the access for the joint, inspection, and detachment processes are the same, indicating that the problem is reduced to setting up these processes, as shown by KAMPKER[466]

Figure 6.8 shows the necessary tooling for module assembly.

[466] Kampker et al. (Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells) 2021, pp. 11-13.

DPM	Cells	Gap-pad	Head plates	Side plates	Cells contact	CSC	Total	Order
Cells		1	1	-1	-1	-1	-1	4
Gap-pad	1		1	-1	-1	-1	-1	4
Head plates	1	1		-1	-1	-1	-1	4
Side plates	1	1	1		-1	-1	2	3
Cells contact	1	1	1	1		-1	3	2
CSC	1	1	1	1	1		5	1

Figure 6.6: Disassembly precedence matrix of prismatic cells module

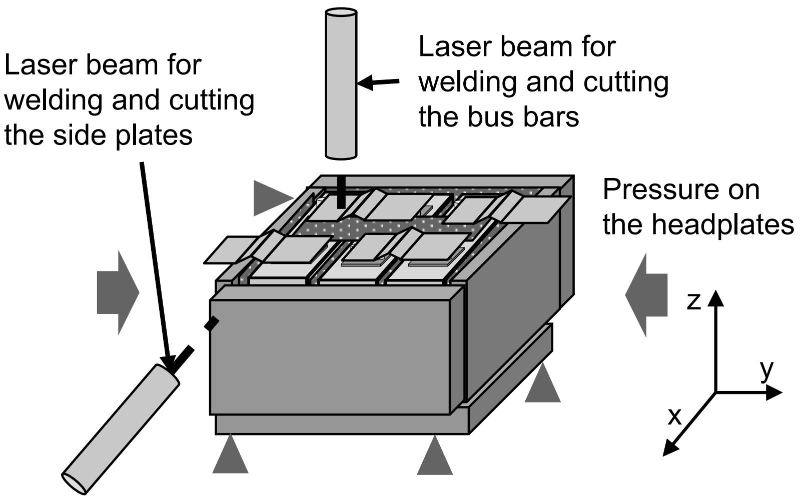


Figure 6.7: Tool access to prismatic cells module

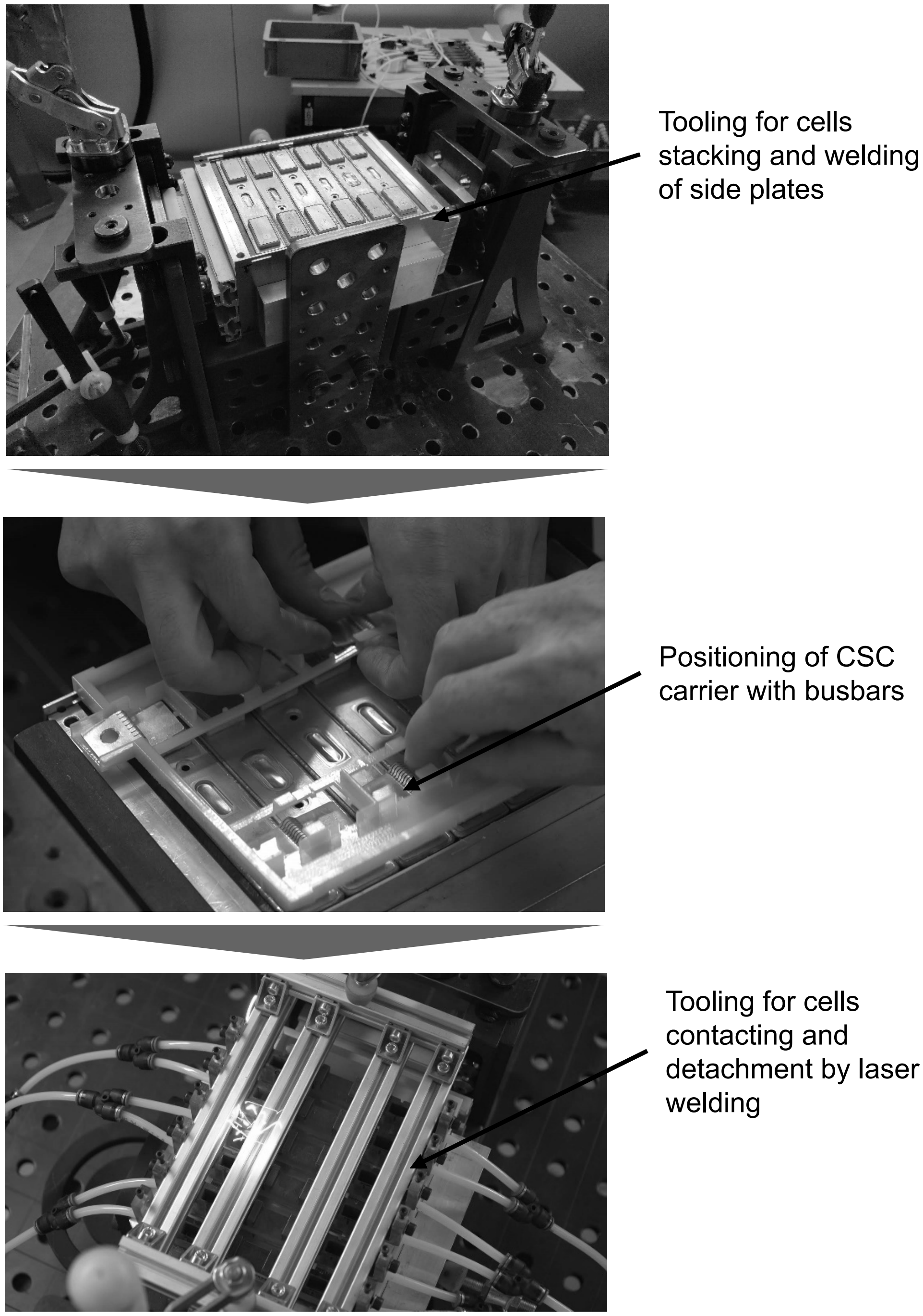


Figure 6.8: Tooling for module assembly and cell contacts welding

6.1.4 Assessment module

The design changes with respect to the basic module have been very limited, mostly focusing on the cell contacts and the tooling to allow cell joint and detachment. However, the cell-stacking process must be developed with the constraint of a light, removable glue in the gap pads, limiting the additional design effort, while improving the life cycle seems promising. The workflow of the design methodology identified the need for the development of detachable welded joints immediately in the initialization module, making it compatible with IPPD and a return-on-engineering approach, whereby the time to set up the processes and tooling is allocated early in the project, reducing technical risk. The volume and weight of the module should increase only marginally and only in the second-life variant, such that there are no foreseeable counterarguments to adoption provided pack safety is granted.

6.1.5 Discussion

The application of the proposed methodology to this simple use case to recover single usable cells at EoL has confirmed the basic layout of the original module, which differs from the state-of-the-art in several aspects. In the initialization module, the methodology allowed some critical reflection on the welded joints between the cells and the identification of the lack of a detachment technology, which could accommodate a limited number of reconnections. Therefore, some experimental effort was put into the combined development of the cell welding and cutting processes very early in the project, such that their requirements were clear in the synthesis module and they were reliable at the time the prototype was built.

In the analysis module, the force path between the cells and head plates was identified as the main structural connection, such that, in the synthesis module, these components were treated as a service assembly until the side plates were welded in place. The analysis of the force and tolerance path resulted in the choice of gap pads between the cells, instead of wrapped isolation foils, and the housing was isolated with isolation foil, such that no glue was applied to the cells.

In applying the proposed workflow to an existing product, it was possible to focus on several aspects. These have been highlighted in the various modules, enabling a creative solution to be found. In some steps, there was not much potential for improvement, with the methodology demonstrating that the existing methodology was already mostly appropriate. The application has been proven to not yet require a big effort and to offer some life-cycle improvements. The next use cases will apply to less constrained designs.

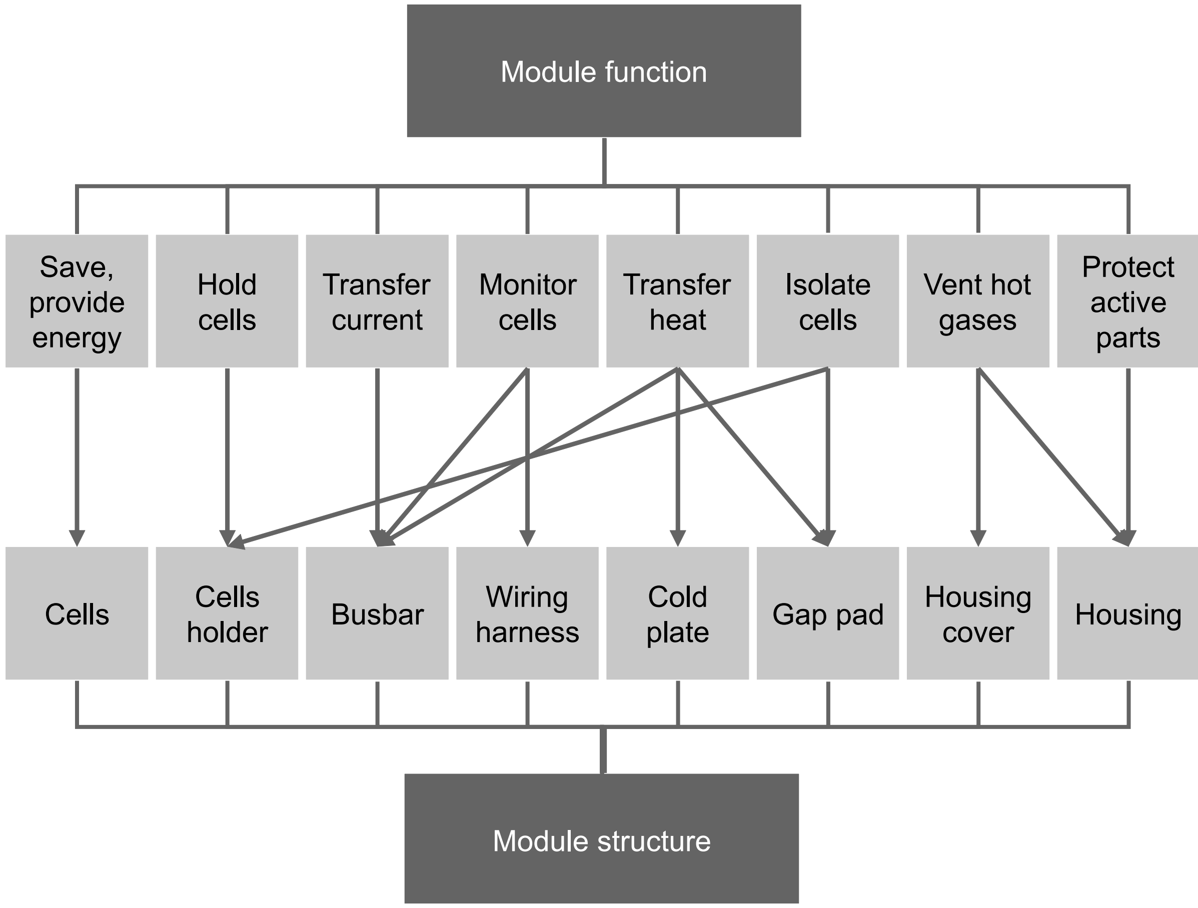


Figure 6.9: Product architecture of battery module

6.2 Use case: Battery module with round cells

A further level of difficulty is the design of a module with round cells, with the shape and the larger number of cells allowing for more diverse designs.

A battery module with round cells needs to perform most of the same functions. However, there are several differences:

- The cells are smaller and connected in parallel. Cell monitoring is only possible for each string of cells in parallel.
- Some percentage of cells is expected to fail during the module's lifetime and some even to vent, requiring that hot venting gases be expelled without overheating the neighboring cells.
- Cells need to be kept in place and isolated by holders, which restricts the availability of cell side surfaces for cooling.

The first step is to understand the functions of components and their interactions, given that most components are known in principle. The tentative product architecture appears in figure 6.9.

The increased degrees of freedom compared to the prismatic cell module is demonstrated by the arrangement of cells in strings, how the strings are connected, the orientation and busbar design of the cells, the shape and function of the cell holders, and how the heat is transferred and split between the cell holders and the busbars.

6.2.1 Initialization module

Given the product architecture, relevant information about components, joints, handling, manufacturing, and recycling appears in figures A.6, A.7, A.8, A.9, A.10

Regarding manufacturing technologies, 3D printing has only been used to manufacture rapid prototypes, so its use is not relevant to component life cycles. Because 3D printing is an additive technology, it could be used to refurbish used components. For the purpose of the proposed design methodology, additive technologies are relevant to component life cycle only if they are used to refurbish used components. For this reason, 3D printing in the context of a 3D-printed cell holder is not considered an additive technology, because 3D printing is used in this case as a substitute for molding plastic parts.

6.2.2 Analysis module

The cells are connected in strings, so the failure of a few cells leads to higher currents in the remaining ones. Although the system's reliability is increased by this redundancy, a damaged string ages faster and should be replaced. Because a string voltage can be measured but no information about single cells is available, a whole string must follow the same life cycle. The working hypothesis about string life cycles is the same as that of cell life cycles in the previous use case: A first life ($100\% > SoH > 80\%$), a second life ($80\% > SoH > 60\%$), and a third life ($60\% > SoH > 50\%$) will be possible. The cell-holders and busbars are expendable because of their low value, ease of separation, and existing recycling methods. Because cell strings are by far the highest-value and least-durable component, their life cycle determines the module's overhaul interval. For this reason, cells belonging to the same cells should be held by the same cell holder, and these should all be fixed in the same way to facilitate assembly and disassembly. The cell holder must isolate the cells from each other and prevent side wall rupture in the event of venting.[467] Each string terminal must be connected to the next by busbars that are welded to the cells and to the next string. Both of these joints must be easy to inspect and detach. The busbars should be isolated from other parts and allow cells to vent. Furthermore, cells should transmit heat via a combination of busbars and cell holders. Because used cells pose an elevated venting risk, cell holders should

[467] Darcy (Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells) 2018, pp. 16-18.

completely surround the cell sidewalls, leaving heat transmission entirely to the busbars. A cell holder with PCM might be advantageous, but this is outside the scope of this proof-of-concept demonstration. A cover must be able to dissipate part of the energy and heat of cells venting and transmit it outside, avoiding propagation to other cells.

The DSM relative to component functions and interactions appears in figure 6.10.

The cluster made of cells, the cell holder, and the busbars of a cell's strings is the most interconnected component, so it must be easy to remove. The gap pads are expendable, and the other parts can be reused.

The clear differences in component life cycle make the product structure straightforward: The cell strings belong to one sub-assembly and the housing to another, with the wiring harness and gap pad representing interfaces between the two that can interchangeably belong to one or the other. 6.11

In this tentative structure, the force connections are mostly internal to each sub-assembly, resembling a classical modular structure. The connections within the sub-assembly are mostly energy, heat, and information, optimal conditions for easy assembly and disassembly.

6.2.3 Synthesis module

Given that the cell holders must have the same geometry, they should also have the same orientation to allow tool access from the same direction.

The connection between strings must also be on the accessible side, meaning that the busbars on the positive and negative side must differ. This simplifies the positions of the cold plate and the top cover on opposite sides, as figure 6.12 shows.

The DPM in figure 6.13 is characterized by a cluster comprising cells, cell-holders, and busbars, which are assembled on the cold plate and later joined.

Tool access is given from the top, as 6.14 shows. The strings can be detached by laser cutting or milling only the welding seam, leaving space for a new one in the event that the string is reused.

Because access for the joint, inspection, and detachment processes are identical, set-up costs are shared between all these processes, as demonstrated by Kampker[468]

[468] Kampker et al. (Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells) 2021, pp. 15-16.

DSM	Cells	Cell holders	Busbars	Gap pad	Wiring harness	Cold plate	Housing	Cover
Cells		0	1	1	0	0	0	1
Cell holders	1		1	1	0	0	0	0
Busbars	1	0		1	1	1	0	0
Gap pad	0	0	1		0	1	0	0
Wiring harness	0	0	0	0		0	0	0
Cold plate	0	0	0	0	1		0	0
Housing	0	1	0	0	0	1		1
Cover	0	0	0	0	1	0	0	

0 = no relationship, 1 = strongest relationship
Inputs in rows, output in columns
Force Heat Energy Information

Figure 6.10: DSM of round cells module

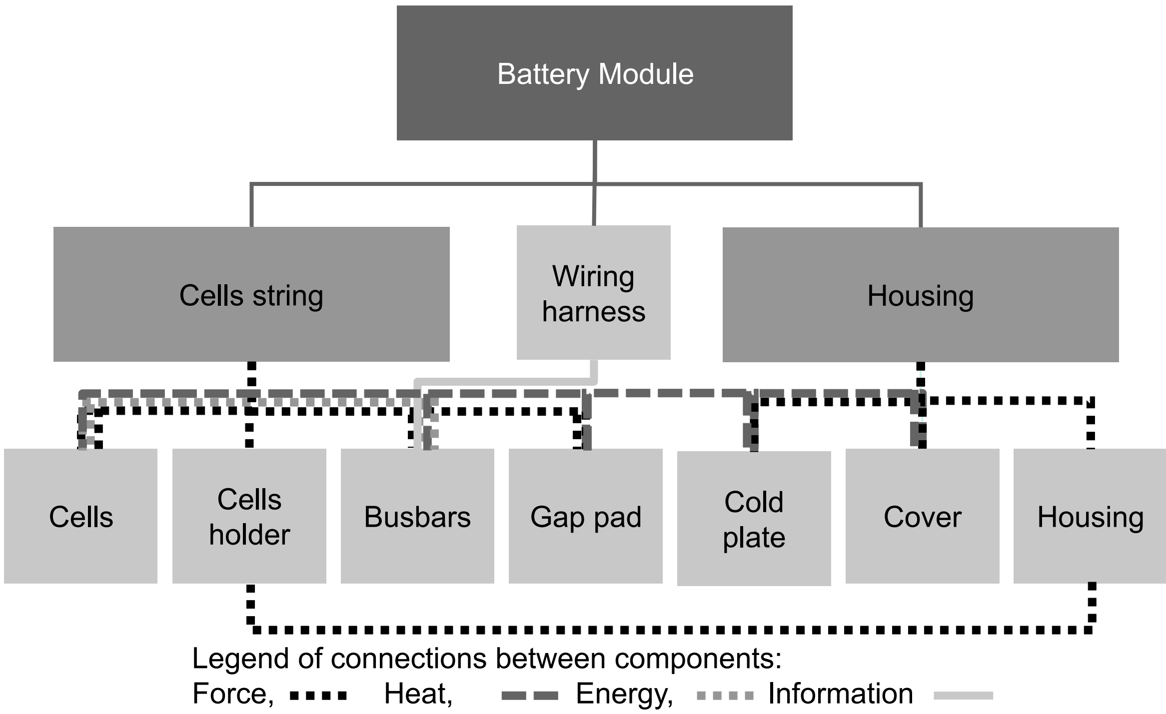


Figure 6.11: Tentative product structure of round cells module

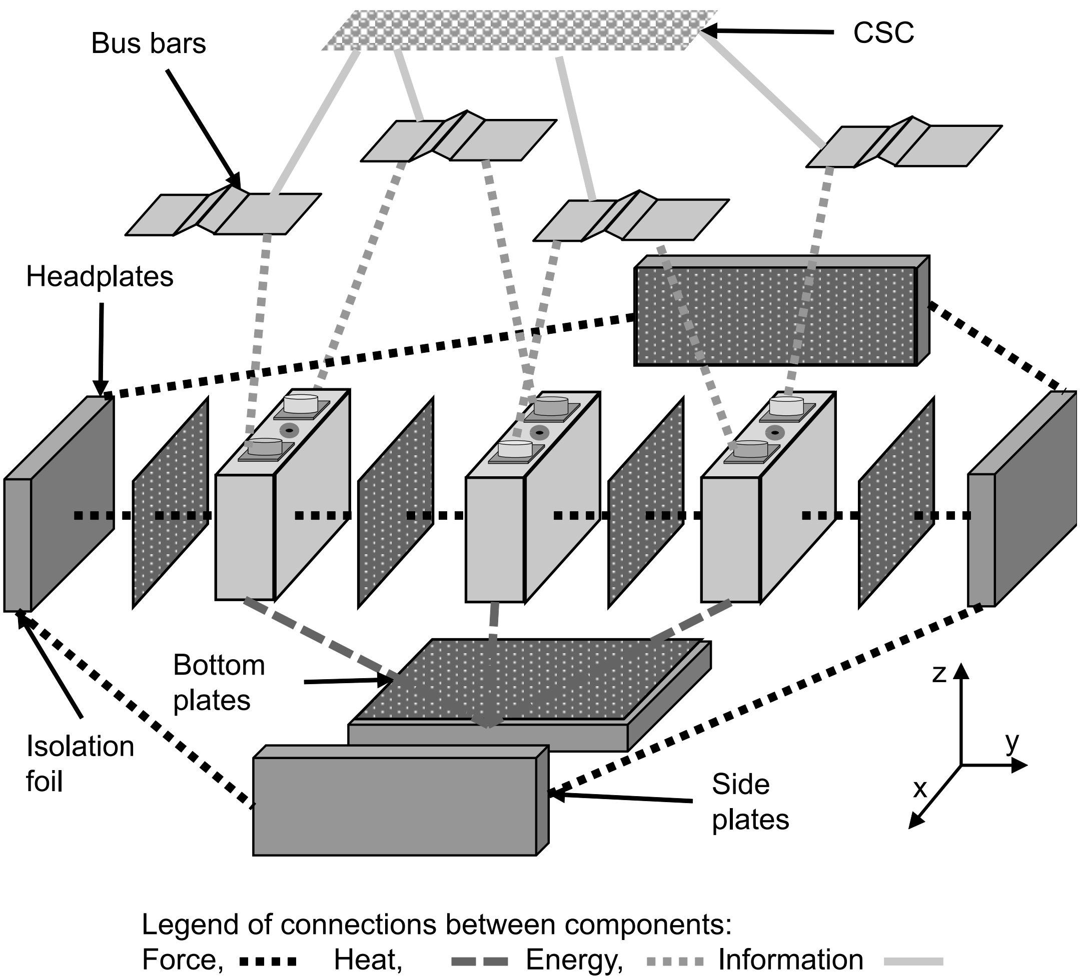


Figure 6.12: Tentative product structure of round cells module in space

DPM	Cells	Cell holders	Busbars	Gap pad	Wiring harness	Cold plate	Housing	Cover
Cells		-1	-1	-1	-1	-1	0	-1
Cell holders	1		-1	-1	-1	-1	0	-1
Busbars	1	1		-1	-1	-1	0	-1
Gap pad	1	1	1		1	-1	0	-1
Wiring harness	1	1	1	1		0	0	-1
Cold plate	1	1	1	1	1		1	-1
Housing	1	1	1	1	1	1		-1
Cover	1	1	1	1	1	1	1	

Figure 6.13: Disassembly precedence matrix of round cells module

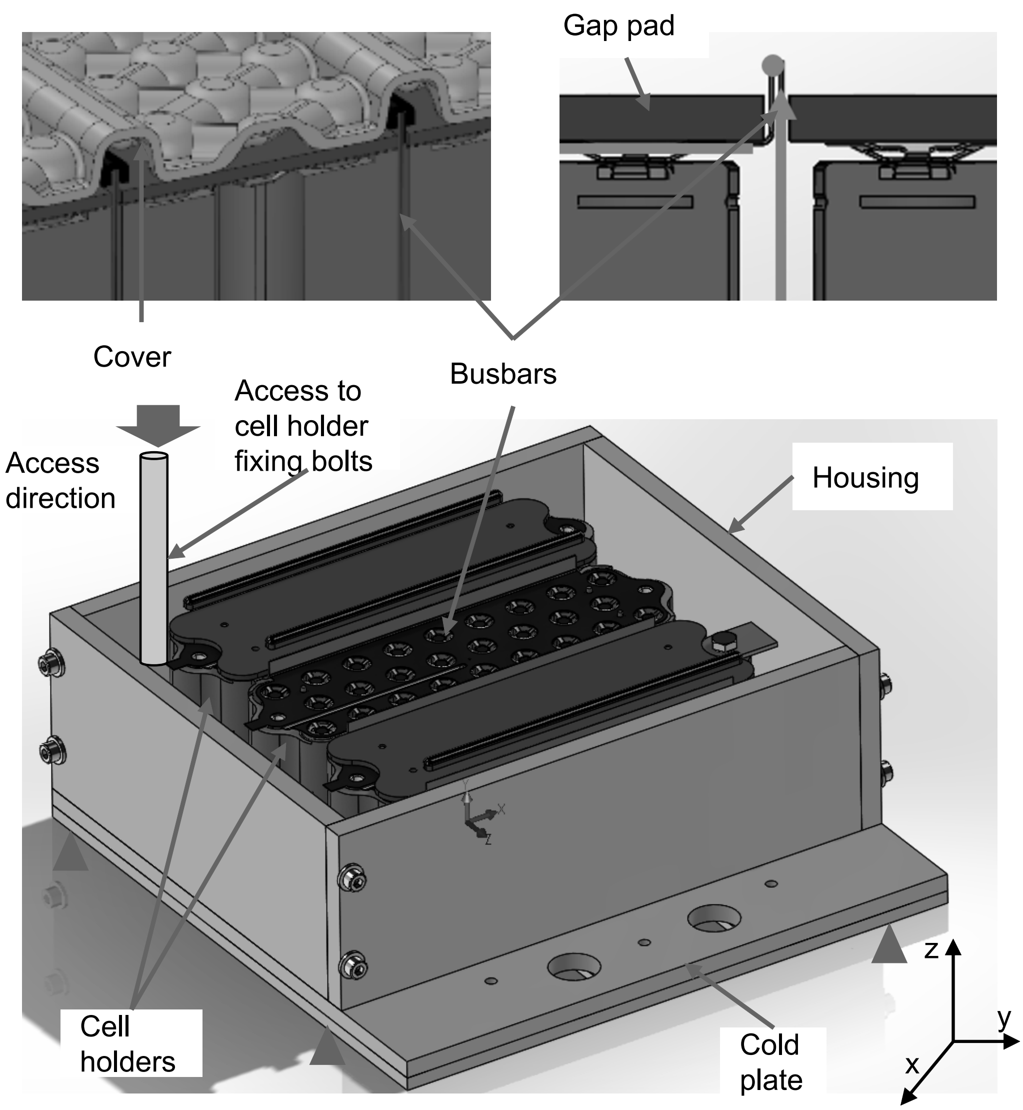


Figure 6.14: CAD design with tool access of round cells module

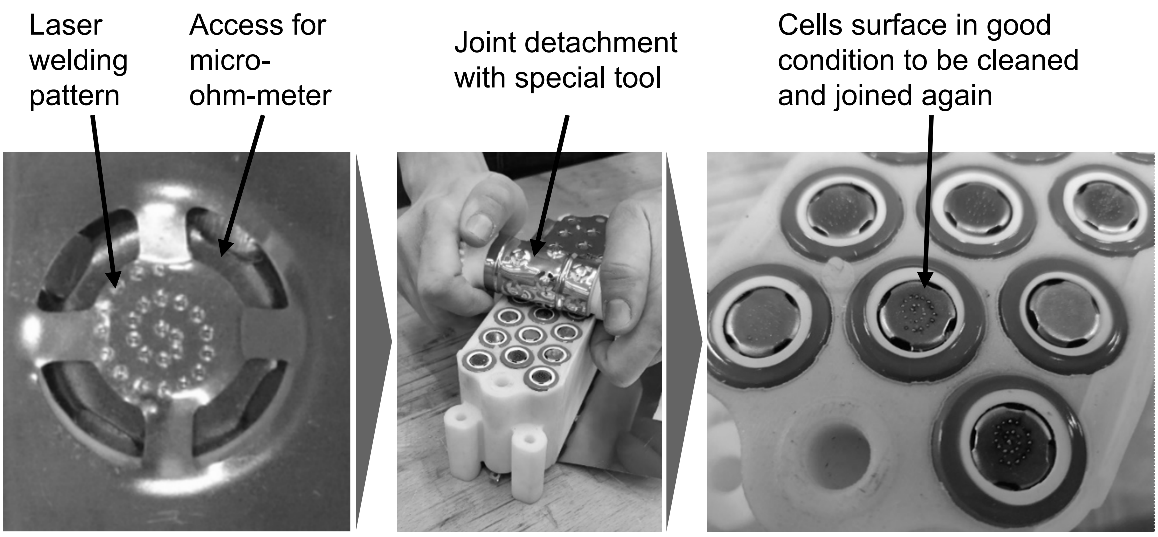


Figure 6.15: Joint design for laser welding and detachment

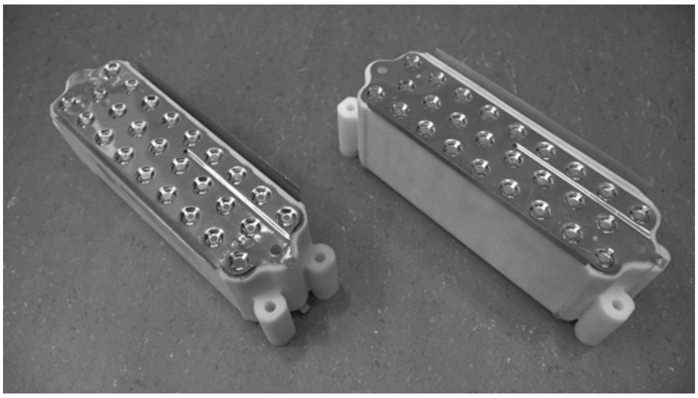


Figure 6.16: Rapid prototypes of cell strings

6.2.4 Assessment module

The design workflow allowed the identification of cell strings as a target sub-assembly to be recovered, and prioritized its access over easy bus-bar design, whereby a conventional design for modules with round cells would prioritize easy busbar design and manufacturing. A slight increase in volume resulted, which might be compensated by the possibility of gaining space by cooling the busbars from the bottom.

Two string sub-assemblies appear in figure 6.16

Another interesting aspect is the quality control of the welded joints, which is enabled by measuring the electrical resistance between cell and busbar instead of the mechanical resistance on samples demonstrated by KAMPKER. This allows the process to be set up for minimal electrical resistance because the control method is more precise.[469]

6.2.5 Discussion

The most interesting findings produced by the application of the methodology were made in the analysis module by recognizing that a cell string is the smallest cell assembly that can be diagnosed before disassembly. The life cycle was mapped to facilitate the replacement of cell strings and the recovery of single cells from each string after the removal of each string has been removed because each cell must then be tested singularly. The orientation of the strings, the provision for venting ducts, and tab cooling on opposite sides represent the consequences of the synthesis phase. The proposed design features slightly higher height and busbar weight than a comparable design without such features, but offers the potential for better life cycles, especially with large cells, proving that the methodology can contribute to the generation of a qualitatively good trade-off. The next use case uses quantitative life cycle data to assess whether life-cycle improvements can be justified.

469 Kampker et al. (Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells) 2021, pp. 14-15, 18.

Figure 6.17: Battery pack of LiVe2 delivery truck

6.3 Use case: Battery module with pouch cells

The final use case involves designing a battery pack for a fleet of delivery trucks for the purpose of reducing overall ownership costs.

The pack design is straightforward and shown in figure 6.17. The details of the cooling system were presented at the iTherm Conference 2019.[470]

This use case substantially resembles the one examined in section 2.4.3, which demonstrated the OSR life cycle for battery cells to have the most potential because of the large cell size. The result of the model design appears in figure 6.18.

The tentative architecture is derived straightforwardly from the functions in figure 6.19

6.3.1 Initialization module

The product architecture resembles the previous two use cases. The relevant information about components, joints, handling, manufacturing, and recycling is gathered in figures A.11, A.12, A.13, A.14, and A.15.

The cells are connected in parallel pairs, so failure of one cell does not lead to immediate failure of the other but allows a short operation at limited power. The cells have been tested for nail penetration, and the separator is capable of shutting down the propagation of an internal short circuit. For this reason, flame-retardant gap pads are inserted to delay cell-to-cell thermal propagation.

[470] Heimes et al. (Cell Tab Cooling System for Battery Life Extension), pp. 1126-1127.

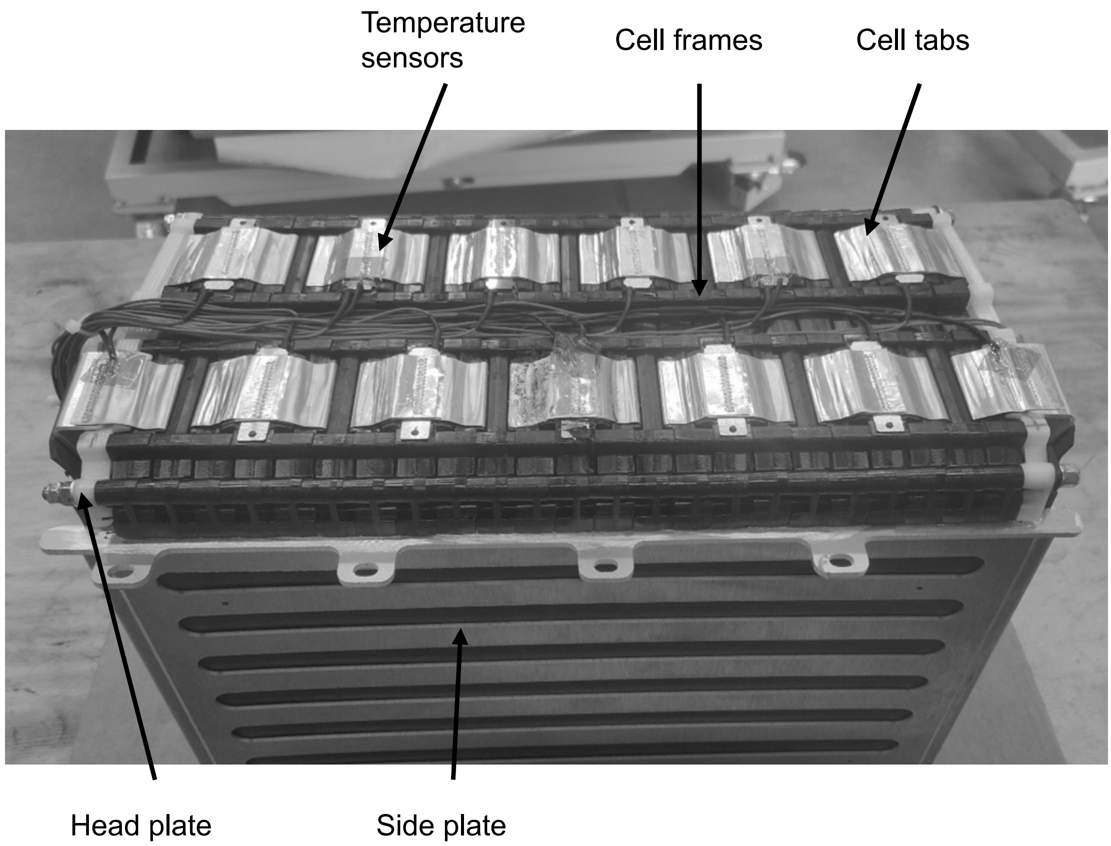


Figure 6.18: Battery module of LiVe2 delivery truck

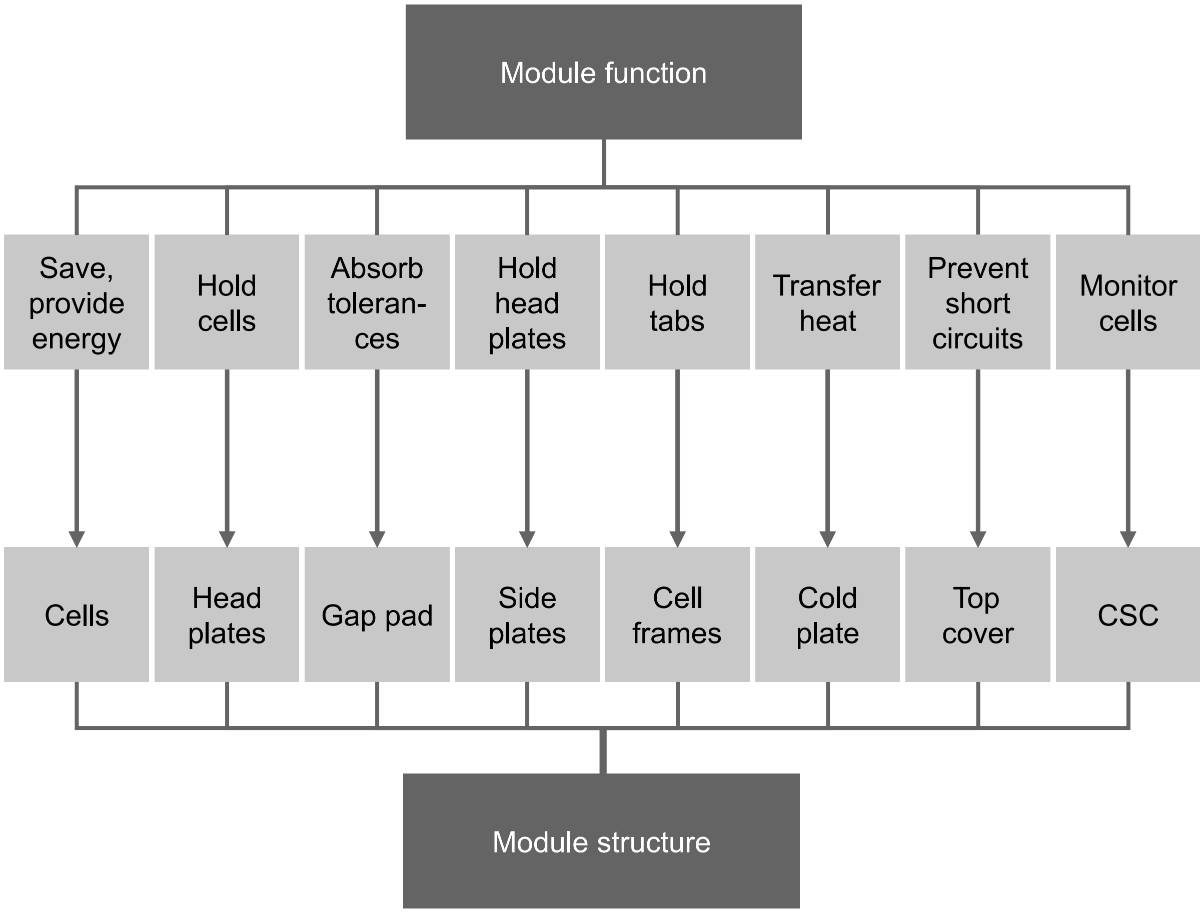


Figure 6.19: Product architecture of battery module

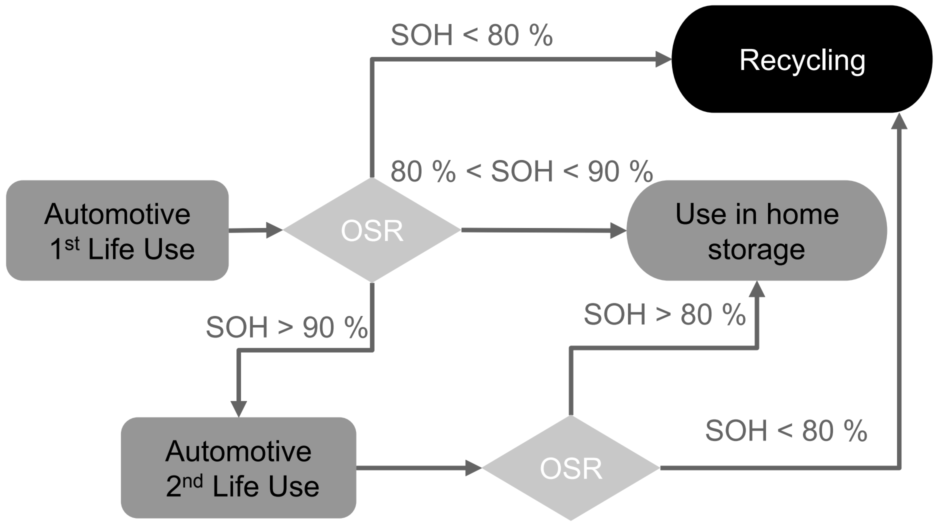


Figure 6.20: Life cycle of cells in Live2 battery pack

6.3.2 Analysis module

The requirement for cell life cycle is that each cell must be reused three times, each time with reduced power output. Cell frames are expendable at each overhaul. Cell condition determines the time for overhaul.

Figure 6.20 shows the life cycle of LiVe2 battery cells, and, consequently, the battery packs. The latter are overhauled as soon as they reach $SoH = 90\%$. Then, the cells are sorted, and those with $SoH > 90\%$ are used in a second automotive life, with those between 80% and 90% used as stationary storage.

Figure 6.21 shows the reliability of new cells, taking $SoH = 80\%$ as the failure criterion, Pinson's model of aging, and a Weibull distribution with $\beta = 5$, as well as the reliability of used cells, which are recovered from an overhaul with $SoH = 90\%$.

The sum of first and second lives' MTTF exceeds that of a longer single life without overhaul. Furthermore, some usable cells are left over for stationary use.

Head plates hold the stack made of cells and gap pads together at a fixed stack height, allowing the cells to change in volume. The cells must be in contact with the cold plate—in this case, through the tab—to increase temperature homogeneity and, therefore, durability. The cold plate must be made of plastics or isolated by thermally conductive, electrically isolated tape.

The side plates must oppose the force from the cell stack and isolate the cells together with the top cover.

The resulting DSM is shown in figure 6.22.

The dependency structure of the force connections among the head plates, cells, and gap-pad stack, including the cell frames, require that these components form one sub-assembly. Meanwhile, the housing and the CSC can be assembled later, as shown in the tentative product structure in figure 6.23.

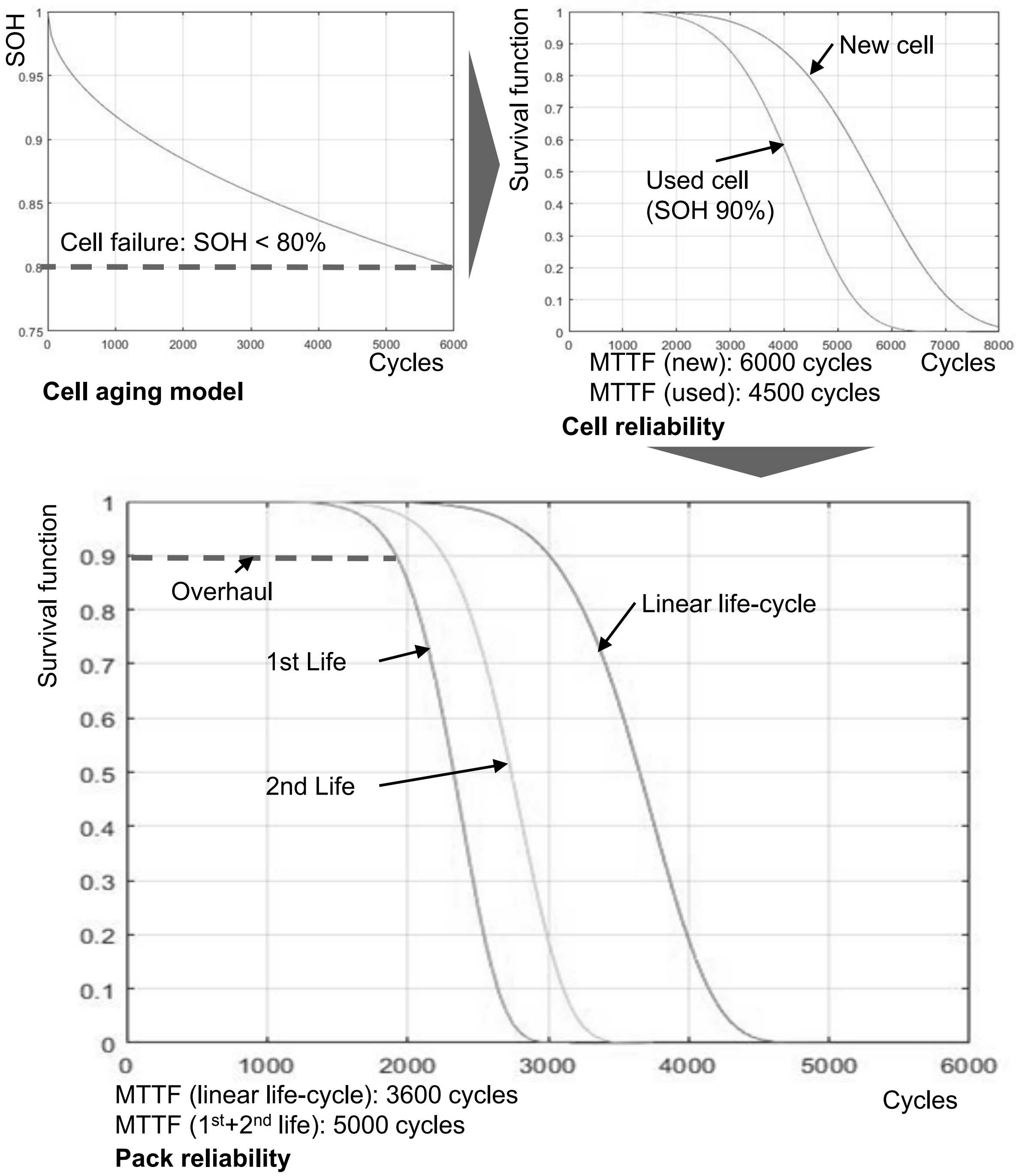


Figure 6.21: From the reliability of new and used cells to pack durability

DSM	Cells	Gap pads	Cell frames	Head plates	Top cover	Side plates	CSC	Cold plate
Cells		1	1	0	0	0	1	1
Gap pads	1		1	0	0	0	0	1
Cell frames	1	0		0	0	0	0	1
Head plates	1	1	0		0	0	0	0
Top cover	0	0	0	0		0	0	0
Side plates	0	0	0	1	1		0	0
CSC	0	0	0	0	0	0		0
Cold plate	1	0	1	1	0	0	0	

0 = no relationship, 1 = strongest relationship
Inputs in rows, output in columns
Force **Heat** **Energy** **Information**

Figure 6.22: DSM of pouch cells module

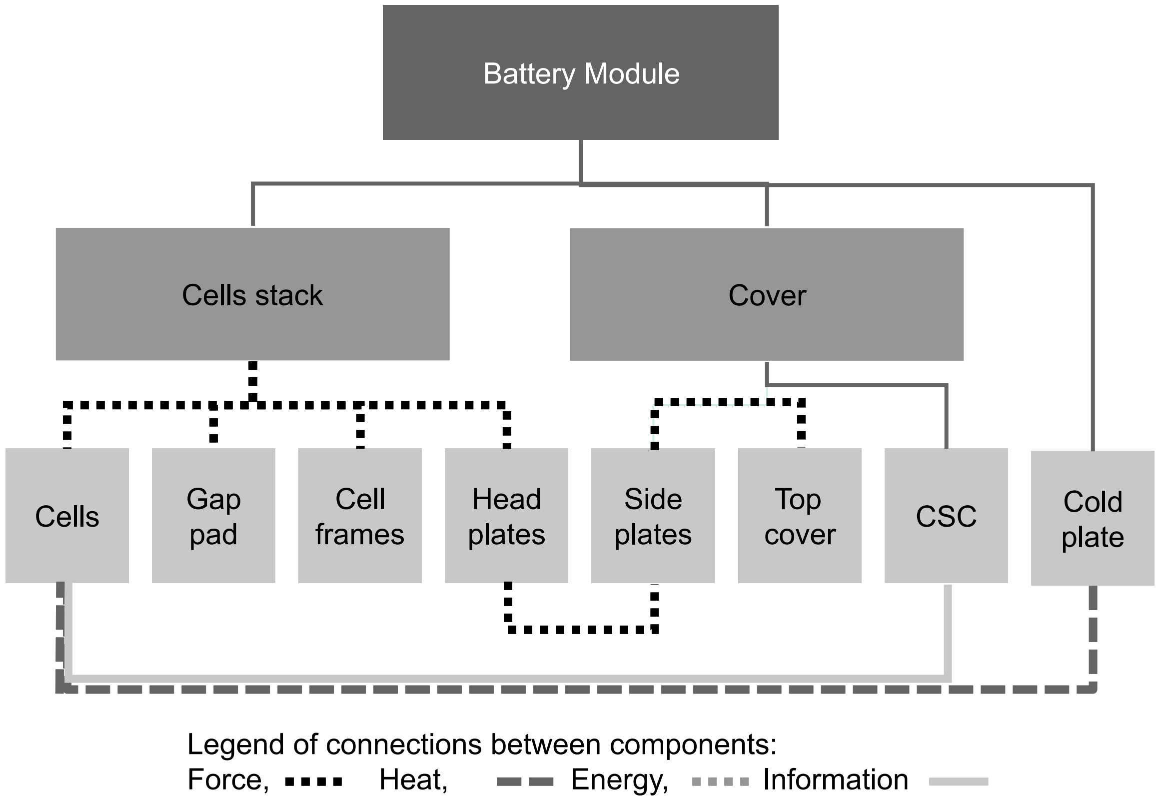


Figure 6.23: Tentative product structure of pouch cells module

In this tentative structure, the only force connection outside the cell stack sub-assembly is with the cold plate. Otherwise, there are only heat and information connections out of the stack sub-assembly.

6.3.3 Synthesis module

The DPM in figure 6.24 is characterized by a cluster comprising cells, gap pads, and head plates. These represent a service sub-assembly during the stacking phase (when the side plates are connected to the head plates).

Given the geometry of the cells with the tabs on one side, few degrees of freedom exist to arrange the other components in space, as figure 6.25 shows.

While the cell stack is held together by a gripper—as shown in figure 6.27—the perpendicular directions are free. This means they can be used to slide the side plates onto rails in the head plates. The top cover can then lock these in place, as figure 6.26 shows.

Because the cell tabs must be connected, they need to be pressed together during welding regardless of the process. This means the tabs need to be bent along a tool that acts as an anvil that presses them against another welding tool. Because the cutting process has been considered beforehand, this ”anvil” is necessary to stop the laser

DPM	Cells	Gap-pad	Head plates	Cell frames	Side plates	Top cover	CSC	Cold plate	Total	Order
Cells		0	-1	-1	-1	-1	-1	-1	-6	6
Gap-pad	0		-1	-1	-1	-1	-1	-1	-6	6
Head plates	1	1		-1	-1	-1	-1	-1	-3	6
Cell frames	1	1	1		0	0	-1	-1	-1	5
Side plates	1	1	1	1		0	0	-1	3	4
Top cover	1	1	1	1	1		0	0	5	3
CSC	1	1	1	1	1	1		0	6	2
Cold plate	1	1	1	1	1	1	1		7	1

Figure 6.24: DPM of prismatic cells module

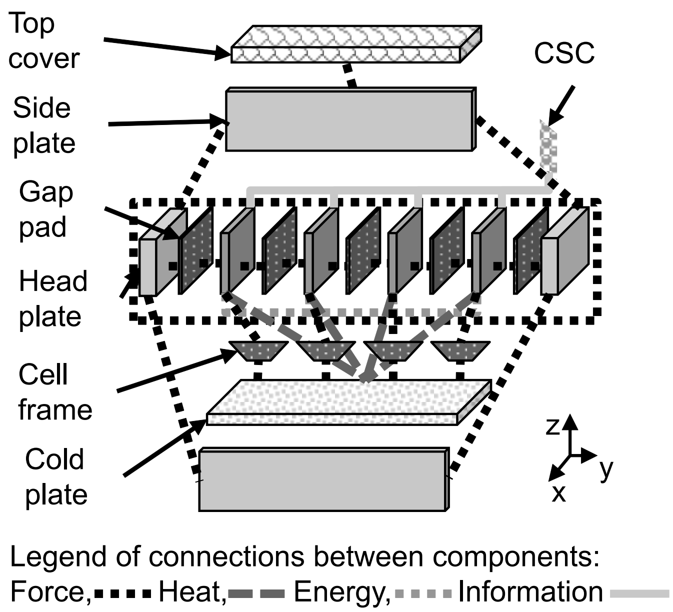


Figure 6.25: Tentative product structure of pouch cells module in space

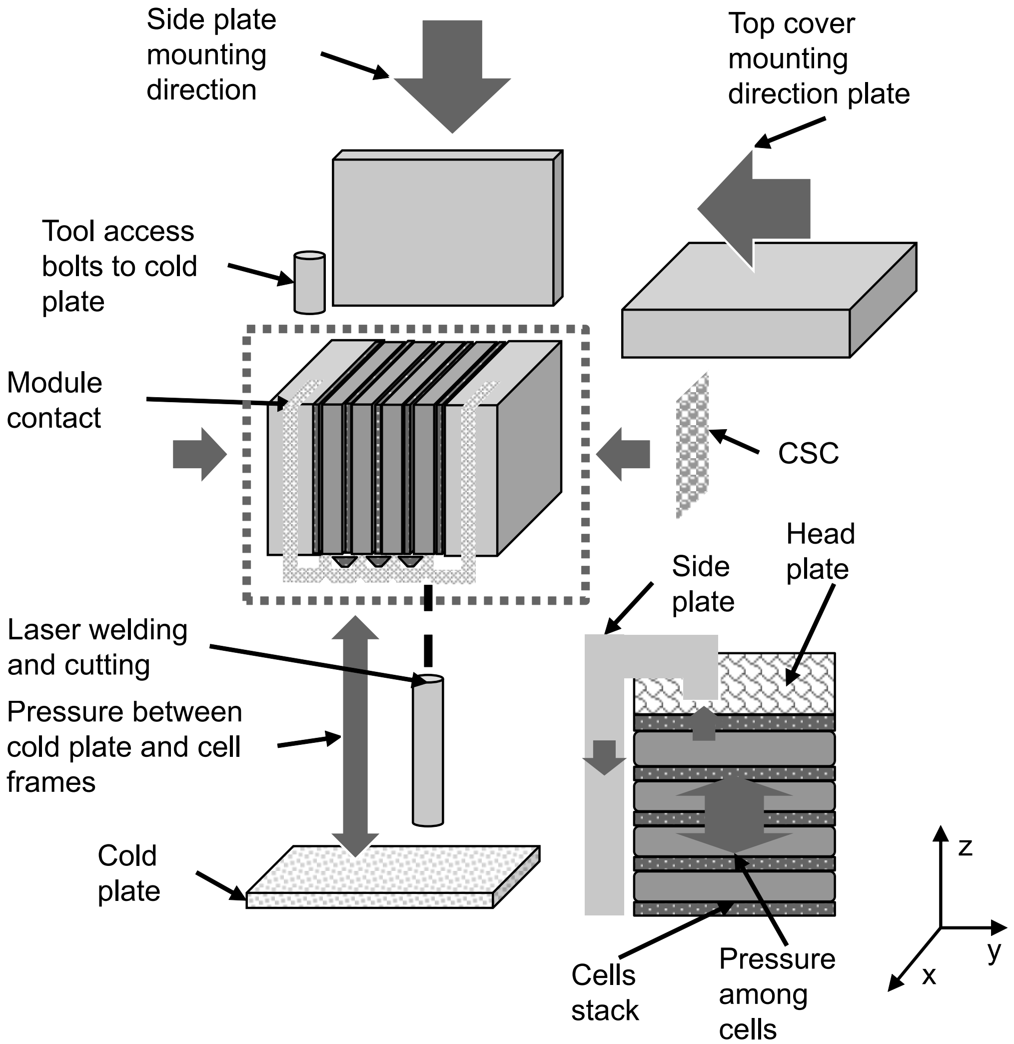


Figure 6.26: Tool access for module assembly and disassembly

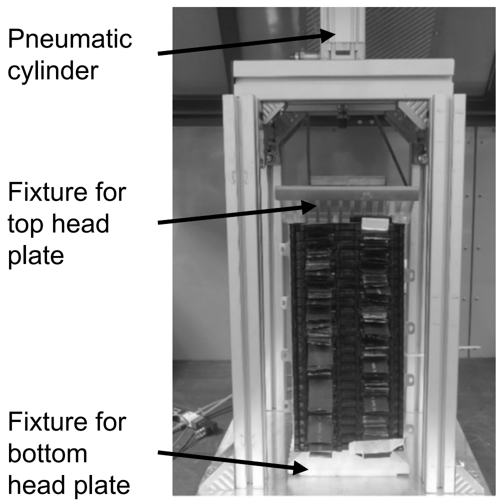


Figure 6.27: Service sub-assembly held together by a pneumatic piston, for the insertion of side plates

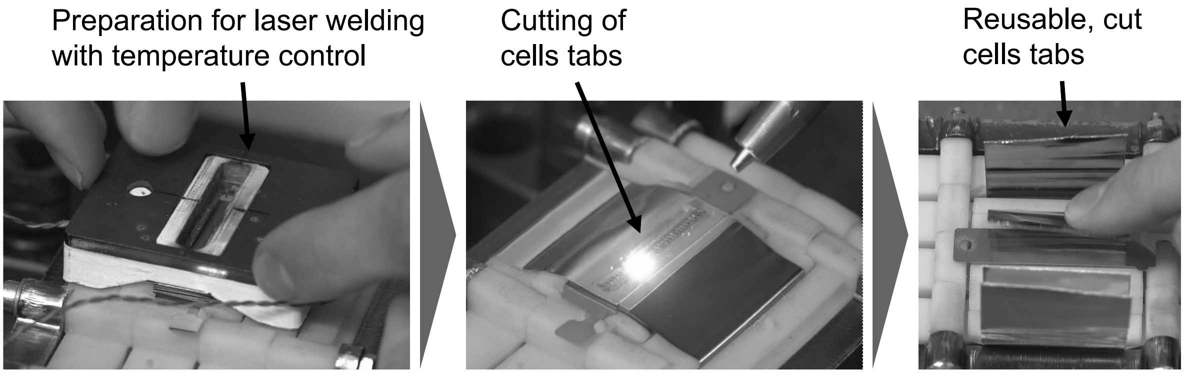


Figure 6.28: Laser welding and cutting process of cell tabs

cutting beam from hitting the cells. As such, it has been incorporated into the design in the form of cell frames. At this point in the application of the design methodology, a partial iteration is necessary because these new components have been introduced. However, the extra effort is limited because the product structure and tool access are sufficiently clear to develop this new component within a narrow scope of simple and clear specifications. In particular, the shape of the cell frames allows the maximum tab length to be used, meaning that the cells remain usable, even with a reduced tab length, after multiple welds and cuts, as figure 6.28 shows, as claimed in the patent WO2020064807A1[471], and as explained in the Journal of Remanufacturing[472].

Given that the cell frames can apply pressure perpendicularly to the cells, it is possible for the tabs to transfer heat, as explained by HEIMES.[473]

6.3.4 Assessment module

To evaluate the results, assumptions regarding cell degradation have been made according to the literature[474], and the value of used cells has been considered against that of new cells with similar specifications (adjusted for the same lifetime). Thus, a life cycle for battery packs and cells has been mapped and total ownership costs have been calculated.

The use case for the battery pack has been economically analyzed: The costs of component manufacturing have been evaluated using simple formulas and compared to similar parts[475], and the assembly and disassembly times of the prototype have been measured and estimated in an automated environment.

471 Maltoni (Battery module and method for producing same) 2019, p. 1.
472 Kampker et al. (Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells) 2021, pp. 18-20.
473 Heimes et al. (Cell Tab Cooling System for Battery Life Extension), pp. 1126-1127.
474 Pinson et al. (Theory of SEI Formation in Rechargeable Batteries: Capacity Fade, Accelerated Aging and Lifetime Prediction) 2013, p. A243.
475 Kor (Management industrieller Produktion) 1996, pp. 142-144.

	Sub-assembly		Materials	Manufacturing	Total cost
			Unit cost in [€]		
1st life production	E/E box	1x	416,00	0,00	416,00
	Housing	1x	260,00	0,00	260,00
	Cooling system	1x	506,55	32,06	538,61
	Battery module	9x	122,18 x 9	58,91 x 9	1.629,81
	Assembly	1x	268,20	70,27	338,48
	Battery cells	216x	19,74 x 216	0,00	4.263,84
	Total		6.814,25	632,53	**7.446,78**

	Sub-assembly	Materials	Re-manufacturing	Total cost
		Unit cost in [€]		
2nd life production	Housing	67,60	0,00	67,60
	E/E box	208,72	58,91	267,63
	Battery module	222,35	58,91	281,26
	Home storage	1.015,87	305,92	**1.321,78**
	DC-AC inverter	901,00	0,00	901,00

Figure 6.29: Cost of production of first and second life battery packs

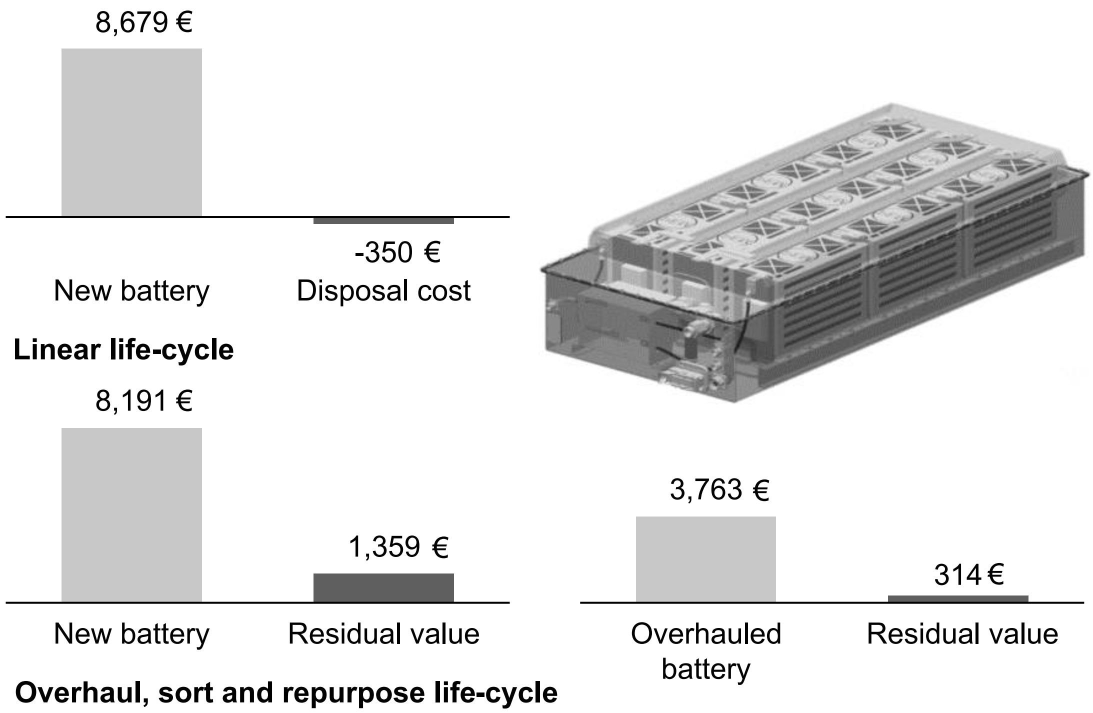


Figure 6.30: Comparison between production costs and the residual value of battery packs in the case of a linear or OSR life cycle

Figure 6.29 shows the cost of production of the first- and second-life automotive packs. Given an estimation of cell value based on a comparison with new cells of similar performance and the added pressure of decreasing assembly time, the pack designed for the OSR life cycle retains its residual value after both the first and second life, meaning that no disposal costs occur, as figure 6.30 shows.

6.3.5 Discussion

In this use case, the tools of the methodology identified some similarities to the first use case in terms of the product structure. The difference is that the pouch cells need to be compressed together, which leads to the early development of tooling to realize the service sub-assembly made of the cell stack and head plates, which could be slide-fit into the side plates. The need to offer a force to resist welding and a sufficient length to cut the tabs was also recognized early enough to develop the process and file a patent on the joint layout for assembly, disassembly, and cooling. The analysis module was used to predict the possible life cycles in the event of reuse and repurposing. This functioned as a basis for calculating the LCC over such life cycles. This aspect of the assessment module could have been completed by a sensitivity analysis with respect to the time of the overhaul and the percentage of cells to be repurposed or reused.

6.4 Interim summary: application of the methodology to battery design

Given the challenges posed by the development of automotive batteries that can be effectively serviced and dismantled at EoL, the present work has mapped and validated a design methodology that adds some key heuristics of product design for a circular economy to establish design in manufacturing methods.

Particular properties of battery systems have been highlighted for which the classic approaches of remanufacturing do not apply, requiring a change in the approach to focus on the life cycle of single cells, moving away from traditional emphasis on the life cycle of whole battery packs. Although batteries are serviced according to predictive maintenance, the aim is to maximize the aggregate residual value of single cells. As such, battery packs are required to be disassembled a certain number of times up to cell level. If the SoH differs from one to another, different EoL decisions are justified for different cells.

Although this approach has been proven applicable for heavily used automotive battery packs, such as those of delivery trucks, it can be extended to other products that demonstrate similar battery-cell properties. In particular, this relates to the high value of battery cells in proportion to the total value of the product, their relatively predictable degradation, and their suitability for repurposing in other contexts at a lower performance level.

A design methodology for products with similar life cycle properties to those of automotive batteries that emphasizes component life cycles and the possibility of recovering components easily by reducing the depth of disassembly from the early design concept phase has been proposed that combines tools from the design and manufacturing disciplines to deliver a workflow that does not require many design iterations and facilitates adoption by development teams operating under the framework of integrated product and process design for sustainable manufacturing. For these reasons, the applicability of the requirements in the context of automotive batteries have been met, at least insofar as enabler technologies are available (e.g., to diagnose the state of used battery cells).

The methodology was applied to three use cases of automotive battery modules and has proven suitable for used in an IPPD framework. It highlights the technological challenges associated with optimizing component life cycles and developing detachable joints very early in design projects such that they can be addressed by specialized technical teams and validated experimentally on a small scale. As such, this characteristic has been proven in the facilities of PEM, and it certainly enables the mitigation of the technical risks associated with the extra requirements of sustainability and circularity over standard products without such requirements. The extra effort to meet these requirements can be made in parallel to other activities and without detriment to the TTM.

The proposed methodology has been used in only one use case to estimate the lifespan of automotive cells quantitatively. There, it was proven to be relatively uncomplicated in terms of deriving an economic evaluation for recovered used components upon which to build a business case. The level of detail, surely based on assumptions regarding similar components, can sufficiently establish scenarios and adapt the EoL strategies according to the products on the market. In any case, at least a few components can be identified for which a small depth of disassembly should be prioritized to enable their reuse or ease their recycling.

The design of the product structure according to planned overhaul operations features a few steps and requires critical judgment at every step because the methods based on DSM and DPM are based on strong simplifications. However, because they allow for potential improvements in the depth of disassembly for the prioritized components early in the project, they are congruent with the overall goal of usability. The transition to a CAD design was not problematic because the spatial product structures can be represented as the first step in a top-down approach to 3D modeling, and the space reserved for tool accessibility represents an implicit means of establishing such requirements from the beginning.

In the use cases considered, the proposed methodology produced results that improved the life cycles of components with very little compromise on performance. This is because it directs development efforts toward both goals, focusing on high-impact synergies.

Broadly speaking, the methodology has proven applicable to both new products and reiterations of existing products, thus meeting the requirements regarding the fulfillment of design objectives, at least in cases where enabler technologies, such as appropriate detachable joints, are available.

7 Conclusion

7.1 Summary

The urgent need to reduce GHG emissions across the economy has led to rapid changes in the automotive industry, with staggering growth in electric mobility observed. At first, the industry has focused on introducing new BEV designs and then scaling up production and infrastructure. However, addressing the environmental impact caused by the batteries was not the initial focus.

Recycling processes have been developed for lithium-ion batteries, which can scale but only recycle a fraction of strategic materials at a quality sufficient for reuse in battery production. New and improved processes capable of recycling a very high percentage of battery materials at sufficient quality require the cost-effective disassembly of the batteries at EoL to be economically viable. The longer the lifespan of batteries, the better their environmental footprint, especially as new, more cost-efficient recycling technologies become available. Furthermore, relying on importing strategic materials decreases as new disruptive battery materials are developed.

As a strategy for recovering the value of used automotive components, the common practice of producing spare parts by re-manufacturing has been applied to automotive batteries by some OEMs and independent companies to produce spare batteries. However, these efforts have been limited by the intrinsic reliability properties of batteries, with the aging or failure of a few cells determining the failure or diminished performance of the whole battery system. In contrast to products suited for re-manufacturing, early degrading cells cannot be identified beforehand, meaning that batteries cannot be designed to allow their easy replacement. Moreover, replacing failed cells with new cells would be expensive and preclude achieving a suitable performance outcome because other cells degrade too. Thus, replacing a few cells is not sufficient to enable a return to the original performance level. For this reason, the disassembly of spent batteries up to the cell level and the sorting of used cells together according to their properties is preferable if the goal is to recover the residual value. Meanwhile, although used batteries may not fulfill the specifications of new ones, they are valuable for other purposes, meaning that they can be employed in secondary markets, such as stationary storage. This goal contrasts with the tenets of classic DfRem: While the latter aims to reduce the required depth of disassembly needed to recover the components that need replacing by means of modular design, the depth of disassembly up to the cell level cannot be reduced by modularization alone. A key enabler technology is online diagnostics, which can perform end-of-life decisions while the battery remains in use. This prevents a few failed cells from accelerating the degradation of the remaining ones and avoids an overhaul in cases where all the cells degrade homogeneously, as in the case of calendar aging. A second set of enabler technologies is detachable joints between the battery cells and the housing, which incur no cost, negligible cost, or weight increase with respect to existing technologies and which do not delay the battery development process. A third set is a highly automated and sustainable manufacturing environment in which economies of scale are exploited between assembly and disassembly over circular life-cycles. This especially applies to product and process-development processes.

These enabler technologies do not only apply to automotive battery systems and can be effectively adopted only if they are considered from the early design phases of products and processes.

The design of automotive battery systems in recent years has been focused on reducing development times to reach the market with new products as soon as possible and on achieving more ambitious performance and cost goals by introducing disruptive technologies barely suited to the long-term maintenance objectives of a circular economy.

The present work acknowledges that adopting a circular framework for products with a high rate of innovation is dependent on the possibility of achieving similar performance without compromising on costs or development time.

Current product development approaches, such as design for manufacturing, DfR, DfRem, and DfE, have been analyzed in terms of their applicability to automotive battery systems and have been found to either not solve the problem of maximizing the residual value of used cells or to require so much data and information that they do not provide designers with practical support.

The present work has proposed a design method that utilizes those tools in a workflow that structures the development process and helps make design decisions on the basis of qualitative or scarce quantitative data. It achieves this not only without slowing down the development process but also by addressing key issues early on by identifying subproblems in the product architecture or joining technologies.

First, relevant information about component function, durability, and life cycle are gathered, alongside information about possible manufacturing and assembly technologies to define the scope of possible solutions.

Then, combining component reliability and life-cycle properties with component connections in a design structure matrix allows the identification of the components that can be prioritized for recovery by clustering them into sub-assemblies. The connections are prioritized with regard to their influence on product assembly and disassembly, such that decisions can be made on which components to recover together. The next step is a top-down design process in a CAD environment with the help of a spatial disassembly precedence matrix, with the desired disassembly sequence given as a design input. From this stage, multiple development teams can work independently on different sub-assemblies, iterating the method recursively on complex sub-assemblies. Considering joining, quality control, and detachment technologies together allows for consideration of tool access during this stage and allows the engineering and early prototype testing of such joints. The information collected during the initial phases and the experiences recorded by early prototypes contributes to the generation of LCC and LCA metrics during the development process. The proposed workflow is suitable for implementation in a product life-cycle management (PLM) and CAD system, enabling it to be easily used to reduce the development costs of products made in a sustainable manufacturing framework and facilitate the adoption of derived products made for a secondary market with reduced requirements.

7.2 Outlook for further research

The proposed methodology represents an overarching framework for the development process. As such, many aspects can be expanded further and made more usable.

At the initialization stage, the gathering of information regarding components, joints, and recycling technologies could be expanded and formalized into a requirement management system that considers safety aspects, prohibited materials, and changes in legislation. An efficient way to arrange such a library of requirements and cascade it properly across generic, yet-to-be-defined product architectures would certainly find application in the industry.

Further research could be done on integrating some of these methods in a CAD PLM environment to facilitate concept design and the definition of interfaces for teams working on different sub-assemblies and to provide the metrics needed for LCC and LCA.

The analysis module could be integrated into PLM software, enabling inclusion of data from a supplier's LCC and LCA alongside the measured assembly time and costs. Hence, data accumulation would improve the quality of life-cycle decisions at early stages and allow the precise field measurements collected by products to fine-tune such decisions once the product enters the market.

In a CAD environment, the development tool could directly represent the direction of assembly and disassembly in the form of exploded views by inputting the desired DPM to ultimately greatly improve the derivation of the product structure.

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A Appendix

A.1 Use case: battery module with prismatic cells

Compe nent	Reliability		Interface				Safety and Environment	
Name	TTF (y)	Failure mode	Force	Energy	Heat	Infor-mation	Hazards	Recycling process
Cell	5	Aging	2kN	4.8 kW	40W	V,T	various	Hydro
Head pl.	≥10	Mech. load	2kN	-	-	-	-	Melting
Side pl.	≥10	Mech. load	1kN	-	-	-	-	Melting
Bottom pl.	≥10	Mech. load	-	-	480 W	-	-	Melting
Gap pad	≥10	Short circuit	2kN	-	-	-	Toxic plastics	Remould (rubber)
Cell contact	≥10	Over-load	tbd	4.8 kW	-	-	-	Melting
CSC carrier	≥10	Over-load	tbd	-	-	-	-	Remould (plastics)
CSC incl. harness	≥10	Elec-tronic failure	-	-	-	V,T	Toxic metals	E-waste

Figure A.1: Information about module components

Joining			Inspection			Detachment		
Process	Fixture	Access	Process	Fixture	Access	Process	Fixture	Access
Laser welding	Joint clamp	From top	Ohm-meter	Small surface	From top	Laser cutting	Shiel-ding	From top
Snap fits	Not needed	From top	Visual	Not needed	From sides	Un-snap	Screw -driver	From side

Figure A.2: Information about joining and detachment of components

Opera tion	Recognition		Gripper or tool			Movement	
Process step	Recognition	Safety	Access	Fixture	Clamping	Trajectory	Max. Force
Fine handling	Features	Short circuit	Within profile	On part	On part	tbd	tbd
Rough handling	Shape	-	Out of profile	No need	On part	tbd	tbd
Cells handling	Shape	Short circuit	Stack	Cell profile	Cell stack	tbd	tbd

Figure A.3: Information about handling, assembly and disassembly of components

Manufac turing	Usability		Design requirements			Production	
Technology	Material	Preci sion	Parting	Thickness	Surface	Scale	Addictive ?
Cells production	Compos ite	0.8 mm	N/A	N/A	N/A	Yes	No
Electronics production	Compos ite	0.5 mm	tbd	tbd	tbd	Yes	No
Sheetmetal	Alumi-num	0.1 mm	No	2 mm	Even	Yes	No
Lamination	Plastic, rubber	0.1 mm	No	0.3-4 mm	Even	Yes	No
Injection molding	Plastic, rubber	0.3 mm	Yes	2-5 mm	Drafts	Yes	No

Figure A.4: Information about manufacturing of components

Recycling	Usability		Needed preparation			Production	
Technology	Target products	Material	Needed purity	Needed sorting	Particle size	Scale	Closed loop?
Hydro	Cells	Compo-site	High	Yes	Small	Yes	Yes
Remoulding	Carrier, Gap pad	Plastic, rubber	High	Yes	Coarse	Yes	Yes
Smelting	Housing	Metals	High	Yes	Coarse	Yes	Yes
Smelting	E-Waste	Metals	Low	Yes	Coarse	Yes	Yes

Figure A.5: Information about recycling of components

A.2 Use case: battery module with round cells

Compo nent	Reliability		Interface				Safety and Environment	
Name	TTF (y)	Failure mode	Force	Energy	Heat	Infor-mation	Hazards	Recycling process
Cell	5	Aging	2kN	4.8 kW	40W	V,T	various	Hydro
Head pl.	≥10	Mech. load	2kN	-	-	-	-	Melting
Side pl.	≥10	Mech. load	1kN	-	-	-	-	Melting
Bottom pl.	≥10	Mech. load	-	-	480 W	-	-	Melting
Gap pad	≥10	Short circuit	2kN	-	-	-	Toxic plastics	Remould (rubber)
Cell contact	≥10	Over-load	tbd	4.8 kW	-	-	-	Melting
CSC carrier	≥10	Over-load	tbd	-	-	-	-	Remould (plastics)
CSC incl. harness	≥10	Elec-tronic failure	-	-	-	V,T	Toxic metals	E-waste

Figure A.6: Information about module components

Joining			Inspection			Detachment		
Process	Fixture	Access	Process	Fixture	Access	Process	Fixture	Access
Laser welding	Joint clamp	From top	Ohm-meter	Small surface	From top	Laser cutting	Shiel-ding	From top
Snap fits	Not needed	From top	Visual	Not needed	From sides	Un-snap	Screw -driver	From side
Bolting	Anti - rotation	All sides	Torque measu-rement	Anti - rotation	All sides	Unscre wing	Anti – rota-tion	All sides
Thermal interface	Fea-ture	From top	Visual	Not needed	From sides	Peeling	Fea-ture	From Top

Figure A.7: Information about joining and detachment of components

Opera tion	Recognition		Gripper or tool			Movement	
Process step	Recognition	Safety	Access	Fixture	Clamping	Trajectory	Max. Force
Fine handling	Features	Short circuit	Within profile	On part	On part	tbd	tbd
Rough handling	Shape	-	Out of profile	No need	On part	tbd	tbd
Cells handling	Shape	Short circuit	Stack	Cell profile	Cell stack	tbd	tbd

Figure A.8: Information about handling, assembly and disassembly of components

Manufac-turing	Usability		Design requirements			Production	
Technology	Material	Preci-sion	Parting	Thickness	Surface	Scale	Addictive ?
Cells production	Compos ite	0.8 mm	N/A	N/A	N/A	Yes	No
3D printing	Plastics	0.5 mm	No	> 0.3 mm	Rough	No	No*
Sheetmetal	Alumi-num	0.1 mm	No	2 mm	Even	Yes	No
Lamination	Plastic, rubber	0.1 mm	No	0.3-4 mm	Even	Yes	No
Injection molding	Plastic, rubber	0.3 mm	Yes	2-5 mm	Drafts	Yes	No

* Despite 3D printing being an addictive manufacturing, it is not used to recondition used platic parts, so it is not considered "additive" for this purpose

Figure A.9: Information about manufacturing of components

Recycling	Usability		Needed preparation			Production	
Technology	Target products	Material	Needed purity	Needed sorting	Particle size	Scale	Closed loop?
Hydro	Cells	Compo-site	High	Yes	Small	Yes	Yes
Remoulding	Holder, Gap pad	Plastic, rubber	High	Yes	Coarse	Yes	Yes
Smelting	Housing	Metals	High	Yes	Coarse	Yes	Yes
Smelting	Cables	Rubber/ metals	Low	Yes	Coarse	Yes	Only metal

Figure A.10: Information about recycling of components

A.3 Use case: battery module with pouch cells

Component	Reliability		Interface				Safety and Environment	
Name	TTF (y)	Failure mode	Force	Energy	Heat	Information	Hazards	Recycling process
Cell	5	Aging	-	160 W	20W	V,T	Various	Hydro
Head plates	≥10	Mech. load	50 kN	-	-	-	-	Remould (plastics)
Gap pads	≥10	Mech. load	tbd	-	tbd	-	Toxic plastics	Remould (rubber)
Side plates	≥10	Mech. load	30 kN	-	-	-	-	Remould (plastics)
Cell frames	≥10	Mech. load	4 kN	-	120 W	-	-	Remould (plastics)
Cold plate	≥10	Mech. load	50 kN	-	200 W	-	-	Remould (plastics)
Top cover	≥10	Mech. load	-	-	-	-	-	Remould (plastics)
CSC	≥10	Electronic failure	tbd	-	-	V,T	Toxic metals	Melting (E-waste)

Figure A.11: Information about module components

Joining			Inspection			Detachment		
Process	Fixture	Access	Process	Fixture	Access	Process	Fixture	Access
Laser welding	Joint clamp	From top	Ohm-meter	Small surface	From top	Laser cutting	Shiel-ding	From top
Snap fits	Not needed	From top	Visual	Not needed	From sides	Un-snap	Screw -driver	From side
Bolting	Anti - rotation	All sides	Torque measu-rement	Anti - rotation	All sides	Unscre wing	Anti – rota-tion	All sides
Thermal interface	Fea-ture	From top	Force	Not needed	From sides	Peeling	Fea-ture	From Top

Figure A.12: Information about joining and detachment of components

Opera tion	Recognition		Gripper or tool			Movement	
Process step	Recognition	Safety	Access	Fixture	Clamping	Trajectory	Max. Force
Fine handling	Features	Short circuit	Within profile	On part	On part	tbd	tbd
Rough handling	Shape	-	Out of profile	No need	On part	tbd	tbd
Cells handling	Shape	Short circuit	Stack	Cell faces	Cell stack	tbd	tbd

Figure A.13: Information about handling, assembly and disassembly of components

Manufacturing	Usability		Design requirements			Production	
Technology	Material	Precision	Parting	Thickness	Surface	Scale	Addictive ?
Cells production	Composite	0.8 mm	N/A	N/A	N/A	Yes	No
3D printing	Plastics	0.5 mm	No	> 0.3 mm	Rough	No	No*
Sheetmetal	Alumi-num	0.1 mm	No	2 mm	Even	Yes	No
Lamination	Plastic, rubber	0.1 mm	No	0.3-4 mm	Even	Yes	No
Injection molding	Plastic, plastic-metal co-molding	0.3 mm	Yes	2-5 mm	Drafts	Yes	No
Electronics production	Compo-site	0.5 mm	tbd	tbd	tbd	Yes	No

Figure A.14: Information about manufacturing of components

Recycling	Usability		Needed preparation			Production	
Technology	Target products	Material	Needed purity	Needed sorting	Particle size	Scale	Closed loop?
Hydro	Cells	Compo-site	High	Yes	Small	Yes	Yes
Remoulding	Carrier, Gap pad	Plastic, rubber	High	Yes	Coarse	Yes	Yes
Smelting	Housing	Metals	High	Yes	Coarse	Yes	Yes
Smelting	E-Waste	Metals	Low	Yes	Coarse	Yes	Yes

Figure A.15: Information about recycling of components

A.4 Examples of assessment documentation

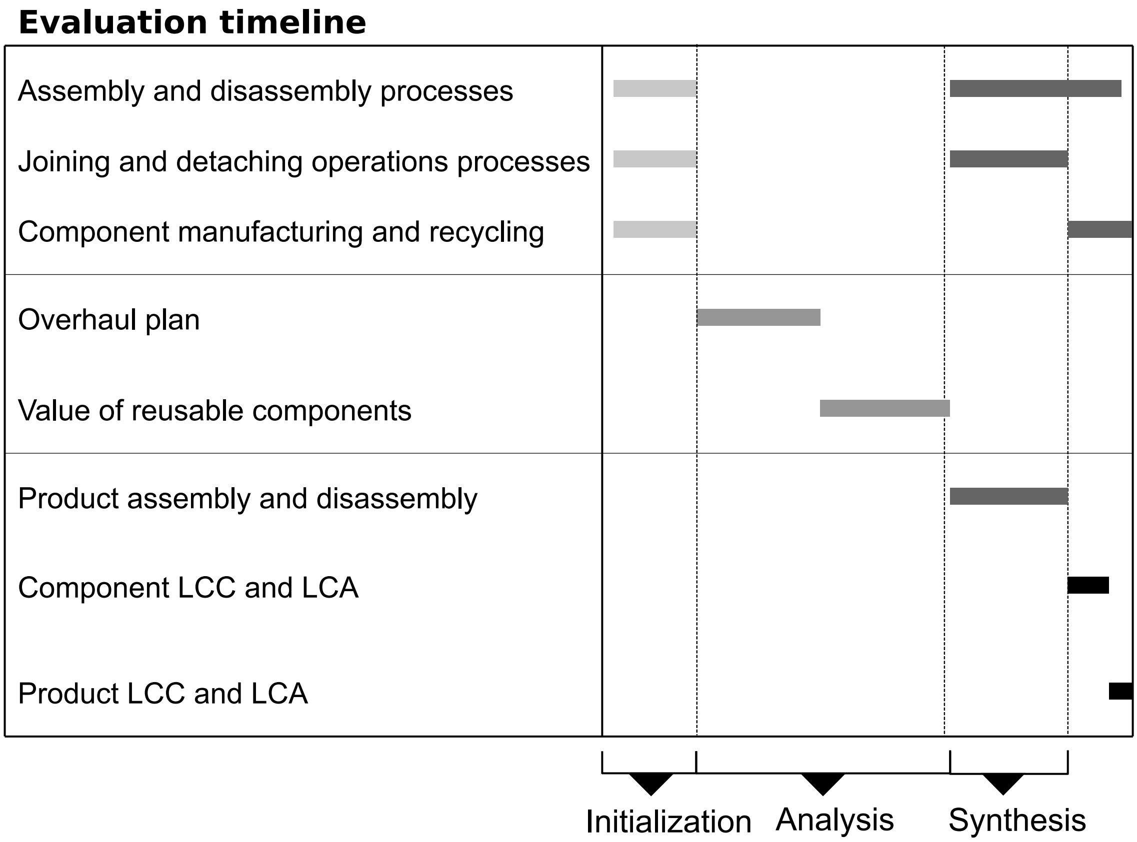

Figure A.16: Example of evaluation timeline along the development process

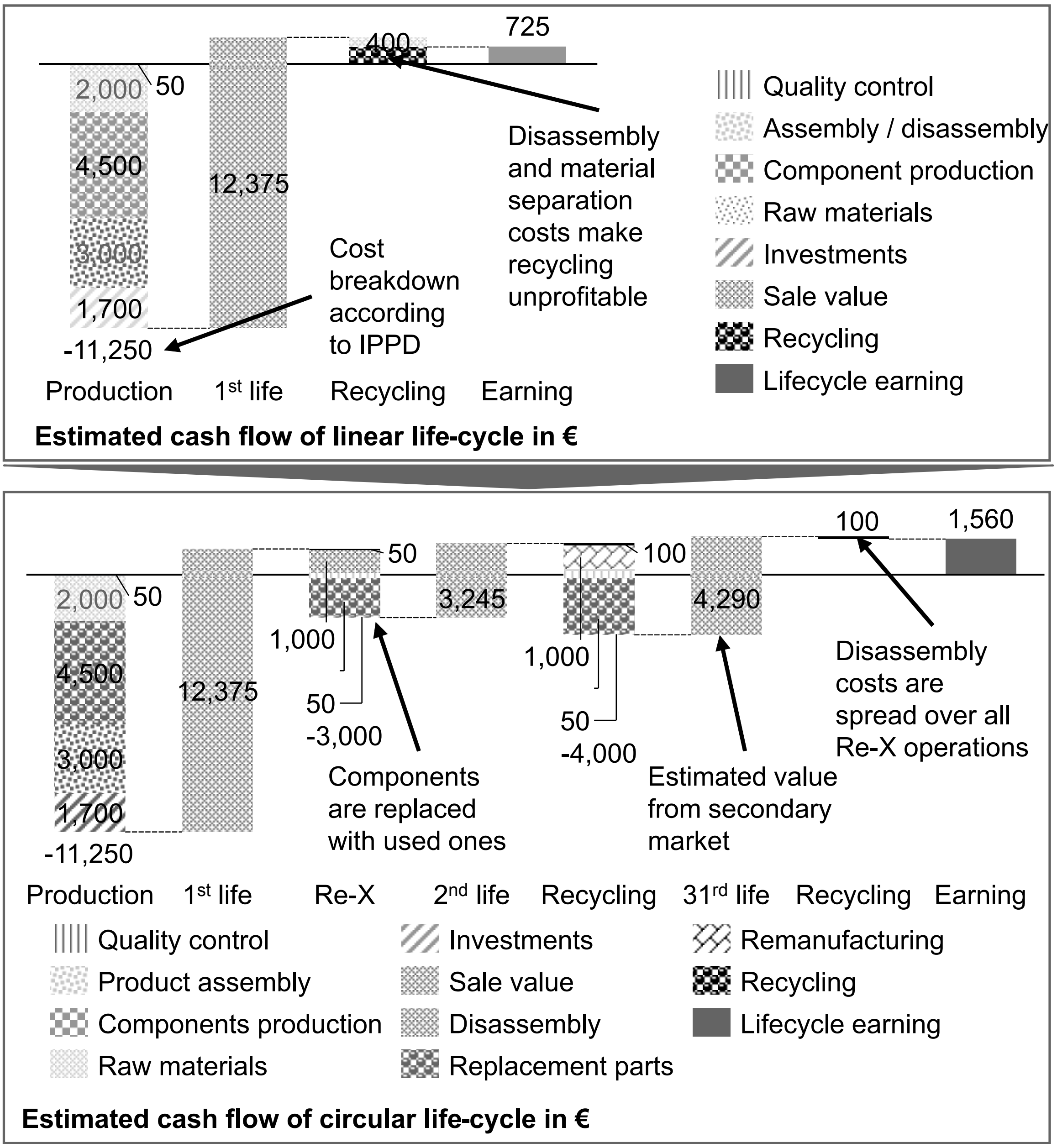

Figure A.17: Example of available information for evaluation of product and life-cycle concepts

A.5 Templates for the initialisation module

Component	Reliability		Interface				Safety and Environment	
Process	TTF	Failure mode	Force	Energy	Heat	Infor- mation	Hazards	Recycling process

Figure A.18: Table for the collection of information about component interactions within the proposed model

Joining			Inspection			Detachment		
Process	Fixture	Access	Process	Fixture	Access	Process	Fixture	Access

Figure A.19: Table for the collection of information regarding joining, inspection and detachment technologies

Operation	**Recognition**		**Gripper or tool**			**Movement**	
Process step	Recognition	Safety	Access	Fixture	Clamping	Trajectory	Max. Force

Figure A.20: Table for the collection of information about handling, assembly and disassembly operations

Manufacturing	**Usability**		**Design requirements**			**Production**	
Technology	Material	Precision	Parting	Thickness	Surface	Scale	Addictive ?

Figure A.21: Table for the collection of information about available manufacturing technologies

Recycling	**Usability**		**Needed preparation**			**Production**	
Technology	Target products	Material	Needed purity	Needed sorting	Particle size	Scale	Closed loop?

Figure A.22: Table for the collection of information about available recycling technologies