Bicycle battery pack with replaceable pouch cells

Master Thesis Fabian Wilschut

Thesis report

Bicycle battery pack with replaceable pouch cells

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Battery research and consultancy

Report summary

This report covers the findings and considerations for the development of a reconfigurable bicycle battery pack with replaceable pouch cells.

On the path to net zero, electric vehicles will play a major role in the energy transition. As a result, battery demand is expected to rise significantly in the coming decade. To reduce the need for critical materials and prevent e-waste, it is essential to establish circular supply chains and implement effective end-of-life strategies.

Bicycle batteries consist of multiple cells, yet entire battery packs are often discarded when only a few cells fail, despite the remaining cells being perfectly reusable. One of the reasons is the excessive use of glue and solder in battery pack designs, which complicates both reuse and recycling.

In partnership with EAGLEBAT, this report explores the development of a battery pack that allows for the replacement of individual cells. Additionally, the design utilises pouch cells developed by EAGLEBAT instead of the conventional cylindrical cells typically used in bicycle batteries.

First, the context of battery design is explored, with a focus on existing bicycle batteries, their disassembly challenges, and their safety features. This phase also includes a comparison of pouch cells with other cell types, an introduction to EAGLEBAT's pouch cell technology, and an evaluation of alternative joining techniques to replace soldering.

Second, boundaries are established to define the scope of the battery design. A vision for a reconfigurable system based on 12V modules is introduced, followed by the selection of a Battery Management System structure and an overview of the 12V module's cell layout. Finally, design principles are formulated.

Third, ideation is started by dividing the design problem into sub-problems. Solutions for each sub-problem are generated and consequently compiled into a morphological chart. This chart, guided by design the design principles, serves as the basis for developing initial concepts. After evaluating these concepts, the focus shifts to the challenge of creating a durable, reversible tab connector. Three tab connector options are explored and through the DATUM method, the laser-welded flexible PCB tab connector is selected as the most suitable.

Ultimately, a final design concept is proposed as a demonstrator, integrating previous insights from the project. The laser-welded flexible PCB tab connector plays a central role in this design concept. The design is elaborated at cell, module, and battery pack levels, concluding with an evaluation of its overall performance.

The report then ends with a discussion of the project and with several recommendations toward the realisation of the design.

A note of gratitude

This project marks the end of more than seven years at the faculty of Industrial Design Engineering. During this time, I have been able to develop myself on a personal and professional level thanks to the many opportunities that I have been offered. Studying in England for a semester, and being a board member of BlueDot are only a few of the wonderful adventures that I got to experience.

During this Master Thesis, I unfortunately faced the challenges of a concussion. Although my recovery, and therefore the project, took significantly longer than I had anticipated, I am proud that I am now able to complete my Master's thesis. However, this journey would not have been possible without the support of several people, whom I would like to sincerely thank.

First and foremost, I would like to thank my supervisors, Ruud Balkenende and Mascha Slingerland, for their invaluable support throughout this project. Beyond their expertise, I deeply appreciate their patience and understanding. While I was sometimes eager to push forward too quickly, they consistently reminded me that prioritizing my health was even more important. They encouraged me to produce high-quality work, but never pressured me to exceed my limits.

I would also like to extend my gratitude to EAGLEBAT, and in particular Walter Legerstee. Not every company would take on such a commitment, and I am truly grateful for their trust and belief in me.

Finally, I want to thank my family and friends. Their unwavering support carried me through this year, especially during the most difficult moments when I felt overwhelmed or doubted myself. They continuously reassured me that I was on the right path and that everything would work out in the end. It is no surprise that they were right.

So once again, from the bottom of my heart, thank you all.

Fabian Wilschut

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1. Introducing the project

Context

On the world's path to net zero, electric vehicles (EV's) are set to play an increasingly vital role in the energy transition. Consequently, battery demand for these vehicles is expected to increase tenfold over the next 10 years (IEA, 2024).

This surge in EV battery demand is consequently the primary driver behind the rising demand for critical metals like lithium. In 2023, battery demand for lithium reached approximately 140 kilotons (kt), representing 85% of total lithium demand and marking an increase of more than 30% compared to 2022. Similarly, cobalt demand for batteries grew by 15%, reaching 150 kt, which accounts for 70% of the total demand. Battery demand growth also contributes to the rising demand for nickel, albeit to a lesser extent, comprising over 10% of the total nickel demand. In 2023, battery demand for nickel stood at nearly 370 kt, up almost 30% from 2022. Significant investment in mining and refining over the past five years has ensured that global supply can comfortably meet current demand, not only for EVs but also for historical markets such as portable electronics, ceramics, metals, and alloys. However, to meet future demand, avoid supply chain bottlenecks, and enhance resilience to potential disruptions, continued growth in mining and refining is essential. Another key strategy in achieving these objectives is reducing the dependence on these critical materials altogether. (IEA, 2024).

As the EV stock and its batteries ages, implementing effective end-of-life strategies, including recycling and reuse, is essential to creating circular supply chains and mitigating the demand for critical minerals. The battery recycling sector, will therefore be crucial to the future of EV supply chains and to maximizing the environmental benefits of batteries. However, the concept of lithium-ion battery circular economy is still in its early stages. One reason this topic has taken time to gain attention is the current demand. At the moment, the supply of used lithium-ion batteries entering the secondary and end-of-life markets remains limited (Warner, 2024). Most vehicles using lithium-ion batteries have only recently been introduced, so these batteries are still relatively new .

On the other hand, Oeser et al. (2018) conducted an analysis on 396Wh (36V, 11Ah) bicycle batteries and found that after 1480 cycles, the State of Health had decreased to 83%. In a scenario where someone commutes to work 5 days a week and fully charges their electric bicycle each night after, this decline would occur over approximately 5 years. Considering that the battery capacity will continue to decrease, likely leading to an even faster decline because of fewer time between charges, it's reasonable to expect that many used bicycle batteries will enter the market in the coming decade. This does not mean we should wait until then with developing end-of-life strategies for lithium-ion batteries. Right now is the perfect time to start!

EAGLEBAT

They are a young start-up developing a circular battery system for electric vehicles, starting with small vehicles such as bicycles. Their mission is to reduce the loss of critical materials (such as cobalt and nickel) by increasing the repairability and longevity of battery packs. Central to their mission is their innovative pouch cell technology, which allows for better regulation of cells, thereby extending their lifespan. This technology might eventually also open the possibility of using other, less critical materials in future battery packs. Ideally, EAGLEBAT can replace each individual component of their battery pack to increase the longevity of their product even more.

They conducted market research that showed that it would be hard to bring their product directly to the saturated consumer market. This is partly due to the fact that consumers often get their first battery pack accompanied with the product (such as a bicycle), thus having no need to buy another battery pack. For this reason, a business-to-business model seems appropriate, directly delivering their system to battery-package-builders. This means that EAGLEBAT wants to develop the inside of the battery packs, whilst companies themselves still define the outer body with the appropriate brand form factors. EAGLEBAT wants to develop their batteries for a variety of different electrical vehicles. They therefore envision a system in which cells with their new technology can be easily connected to each other in order to gain the required voltage and current outputs for different applications.

Problem description

The main problem is that current battery packs consist of cells glued and welded together. This makes it impossible to access individual cells and the whole battery pack is thrown away. This is an issue because it prevents recycling or reuse. Reusing cells is a possibility because often the battery pack only malfunctions because of a couple bad cells, whilst the others still work properly. When cells are thrown away before their end-of-life or when they are not recycled, critical materials get lost. In order to get the right voltage and current output, the cells must be connected in specific configurations. However, the battery housing body is different for every brand and application. Creating an internal battery structure that fits different form needs whilst still being able to easily access all components, composes an interesting design challenge. The battery structure must also be held firmly in place in the body as to increase its longevity and to prevent safety risks such as short circuits.

Design goal

"The aim of this project is to design and build prototypes that explore ways for a reconfigurable battery system that enables the possibility of replacing individual battery cells during repair."

The design will integrate the EAGLEBAT pouch cell technology with the aspiration to create more sustainable lithium-ion batteries for electric bicycles. This approach aims to enhance battery longevity and improve repairability, whilst also taking safety into consideration. The project will be looking at the following research questions:

- How can we develop a reversible electronic connection for battery pouch cells to allow replacing of individual cells?
- What will a reconfigurable battery structure look like for the application of EAGLEBAT?
- How will the Battery Management System be integrated into the battery structure?
- How will all design elements fit into a safe structural design?

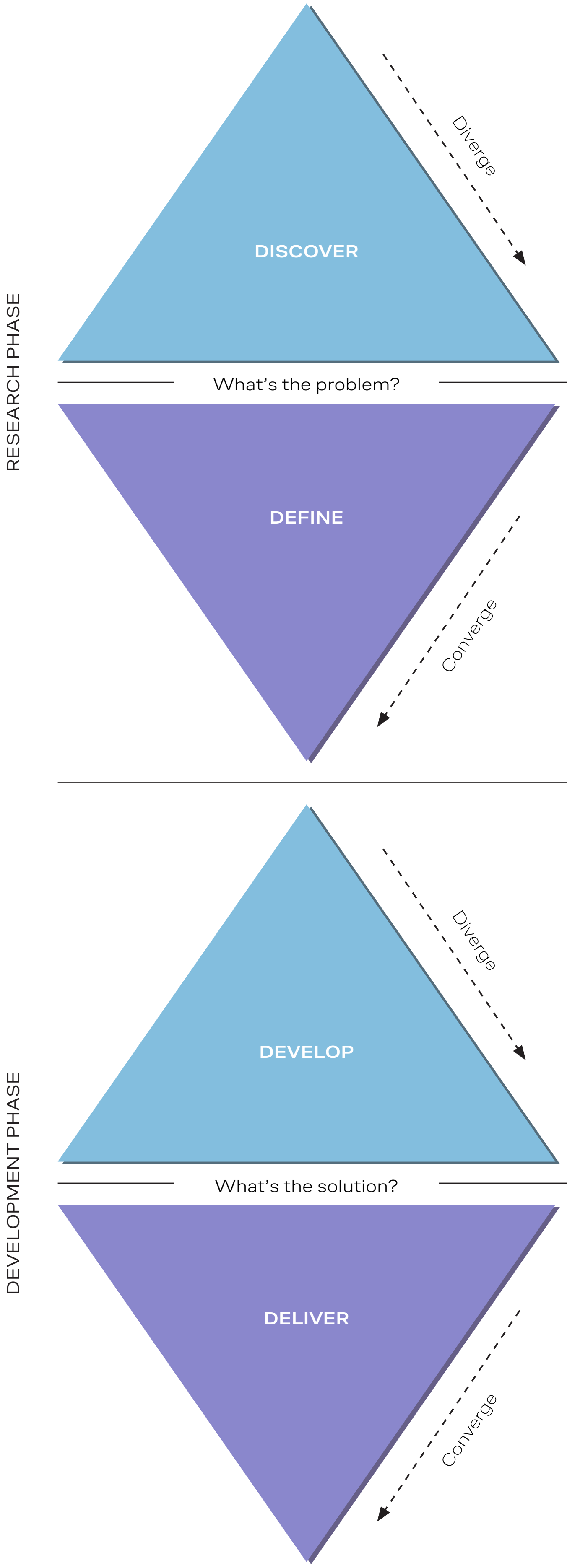
Structuring the design process – a reading guide

This report outlines a creative and iterative process in which various activities occur simultaneously, with frequent interactions between design and research. The project was approached primarily as an industrial design challenge for two key reasons. The first obvious reason is that the project is conducted as a Master's thesis at the Faculty of Industrial Design Engineering. The second reason is to provide the client company, EAGLEBAT, with new perspectives on their emerging technology. By applying a different skillset, the project seeks to help EAGLEBAT transform their innovative technology into a tangible and feasible product.

The project is organized into four stages, based on the double-diamond framework: Discover, Define, Develop, and Deliver (Design Council, 2019). These stages, which form the core of the document, are outlined in the four main sections of the report and can be roughly categorized into a research phase (first diamond) and a development phase (second diamond). Each diamond starts off with diverging and ends with converging. During every stage, a continuous cycle of design loops will take place. Where applicable, additional research and evaluation methods are further detailed throughout the report.

Figure 1 on the next page provides an overview of the complete design approach for this project. Furthermore, a terminology list with words that are used often can be found at the end of the report.

Throughout the report, insights that are key to the project are summed up briefly in boxes like this one.



PROBLEM EXPLORATION

Chapter 2

Gain a thorough understanding of the context of the design challenge. Research includes:

- Battery terminology
- Current bicycle batteries & safety
- Pouch cells
- EAGLEBAT's pouch cell
- Joining techniques

RESEARCH TOWARDS THE SOLUTION

Chapter 3

This section serves as the foundation for ideation. Challenges have been identified and the following boundaries have been defined:

- Reconfigurable modules
- Battery Management System
- Cell layout
- Design principles

CONCEPT DEVELOPMENT & SELECTION

Chapter 4

This phase is primarily focused on working toward feasible concepts that comply with the previously identified design principles. Methods and activities performed are:

- Brainstorming & How-To's
- Morphological chart
- Concept creation
- Design considerations explained
- Reversible connector selection using DATUM

FINAL DESIGN CONCEPT

Chapter 5

The last section details the final design concept. The design is elaborated on cell, module and battery pack level. Design activities include:

- Design development
- CAD modelling
- Renders
- Design evaluation

Figure 1: the project design approach is based on the Double Diamond framework, in which the designer alternates between diverging and converging. The four phases also lay the foundation for the main chapters of this report..

Figure 2: cylindrical cell battery pack

2

Problem Exploration

This chapter explores the challenges involved in creating a battery pack, offering a deeper understanding of its inner workings. It starts with an overview of different battery levels, followed by a detailed examination of a typical e-bike battery, pointing out the limitations of existing design, such as the use of spot-welding and adhesives, complicating the repair and recycling processes. The chapter then discusses safety issues and how to mitigate them. A comparison of various cell types is presented, highlighting pouch cells as a preferred option due to their high energy density and flexibility, while also addressing the mechanical challenges associated with them. Then, EAGLEBAT's pouch cell technology is introduced, along with its limitations. Finally, the chapter evaluates various joining techniques, with a focus on reversible connections that allow for easier cell replacement.

2.1 Battery levels

Before we can delve further into the project, it is essential to have an understanding of how a basic battery is structured and its corresponding terminology.

Figure 3 illustrates the essential components required to construct a battery pack, which is organized into three primary levels. At the foundation are the cells, which store energy and serve as the basic building blocks of the battery pack. Since each cell generates only a limited amount of voltage and current, combining them is necessary to meet the desired battery specifications. Cells can be connected either in series, parallel or both to form a module. Grouping cells into these modules allows for more manageable and serviceable units. Series connections increase the overall voltage output, while parallel connections boost the current. Ultimately, the complete battery pack can be assembled, consisting of one or more modules along with higher-level components such as a Battery Management System, a Thermal Management System, electrical interfaces, connectors, and an enclosure (Zwicker et al., 2020).

Main insights

- The battery system is structured from the smallest to the largest level. Cells at the base, followed by modules, and finally the complete battery pack at the top level.

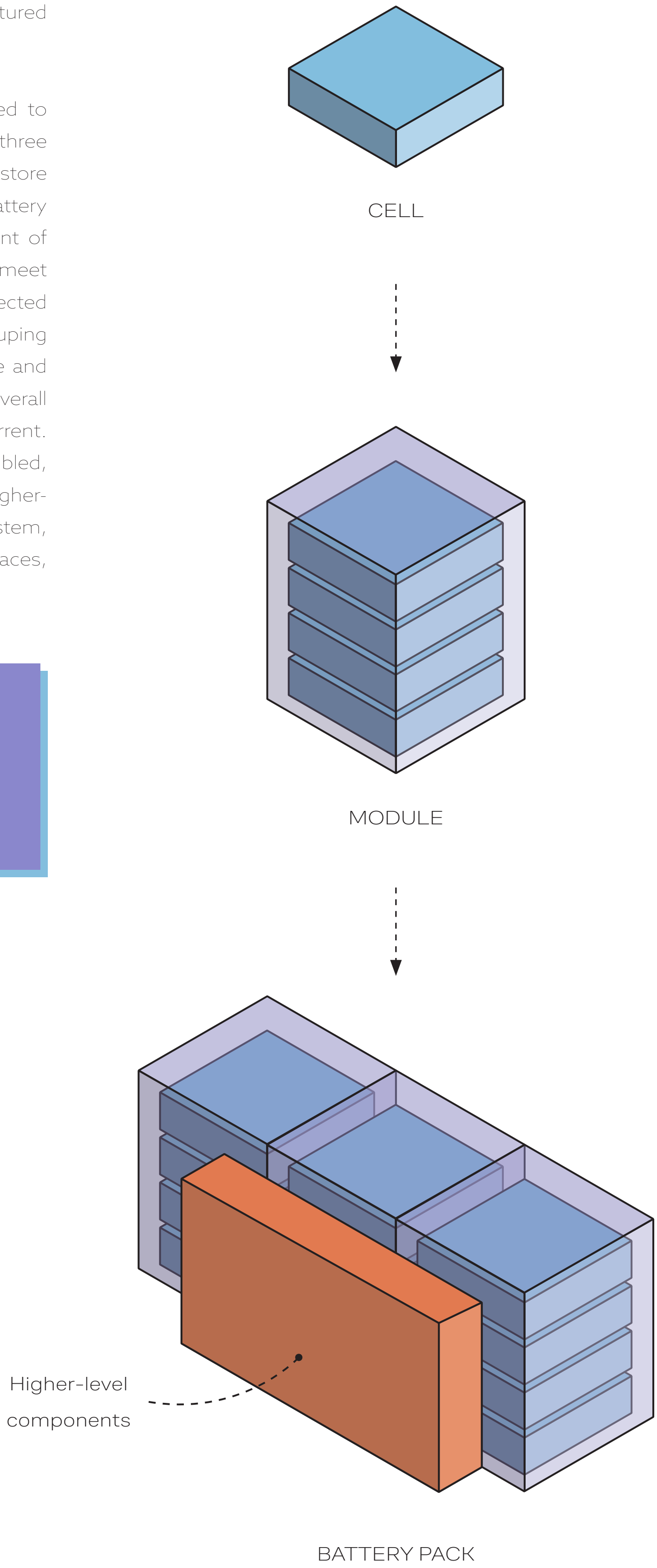


Figure 3: battery levels from smallest to biggest.

2.2 Examination of a bicycle battery

To be viable in the e-bike market, new battery designs must meet industry standards for performance and specifications. Most e-bikes use batteries rated at 36V or 48V, with capacities ranging from 10 Ah to 14 Ah. This project focuses specifically on rear-mounted batteries. To gain a better understanding of these batteries, a Gazelle battery has been examined (figure 4).

Specifications Gazelle Gold

Dimensions: 365 x 120 x 60 mm
Weight: 3.7 Kg
Voltage: 36 V
Capacity: 11.25 Ah
Location: rear-end

Inside a Gazelle Gold battery

The Gazelle Gold battery features 50 cylindrical lithium-ion cells of the type 18650. They are configured in a 10S5P arrangement, meaning they are connected in a grid of ten cells in series and five in parallel. Each cell has a nominal voltage of 3.6V and a capacity of 225 mAh, producing a total output of 36V and 11.25 Ah for the whole battery pack.

The cells are interconnected using nickel sheets, with tabs spot-welded to ensure robust and reliable connections. A Battery Management System (BMS) monitors the cells, maintaining safety and performance. These components are housed in ABS and then encased in an aluminium shell with the brand identity of Gazelle. The battery's construction relies heavily on adhesives to enhance durability and structural integrity, though this design makes disassembly and recycling challenging (figure 5).

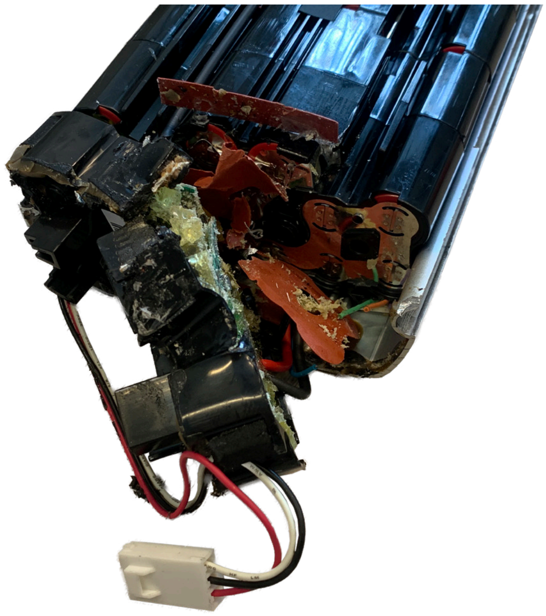


Figure 5: spot-welding and the use of glue make reuse or recycling difficult.

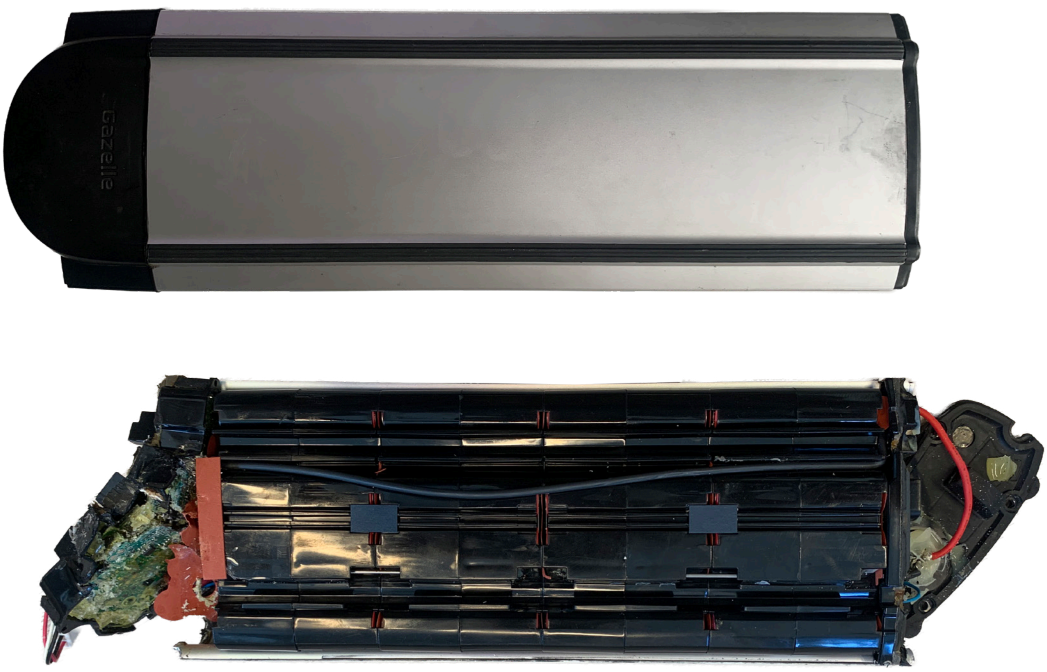


Figure 4: the inside of a Gazelle Gold battery, cylindrical cells in a robust plastic casing, control components visible on the left.

Challenges for disassembley

The Gazelle Gold battery is a design focused on cost-efficiency, durability, and large-scale manufacturability. While these priorities benefit production and reliability, they also make the battery challenging to repair and recycle. The use of spot welding, extensive adhesives, and a design philosophy centred on streamlined production over repairability reflect the trade-offs inherent in such an approach.:

1. Spot welding, though efficient and reliable for mass production, complicates disassembly by creating fixed connections that are difficult to separate. While alternatives like mechanical connectors would allow for easier repairs, they come with drawbacks such as higher costs, increased space requirements, and reduced durability under vibration and shock. As a result, spot welding remains the preferred method for ensuring structural integrity and efficient manufacturing, even though it hinders repairability.

2. Repairing damaged batteries by replacing individual cells introduces additional complications. Mixing new cells with older degraded ones, creates performance imbalances, accelerates the deterioration of the new cells and shortens the battery's overall lifespan. This issue, combined with the heavy use of adhesives in the battery's construction, makes component replacement nearly impossible without risking damage to the assembly.

3. From a commercial perspective, the design prioritizes new product sales over repairability, aligning with a business model that emphasizes repeat purchases. While this approach supports streamlined production and profitability, it comes at the expense of sustainability and consumer-friendly repair options. The result is a product that is efficient to manufacture but challenging to repair or recycle, raising questions about long-term environmental impact.

The Gazelle Gold battery is a design optimized for cost-effective production and durability, but highlights significant challenges in repairability and recycling. While not all bike batteries are as hard to reuse or recycle as the Gazelle Gold, it underscores the need for more sustainable and repairable solutions in the e-bike industry.

Main insights

- The design choices for current batteries are based on durability, reliability and safety, but lack in repairabilty.
- The combination of spot welds and extensive glue usage must be avoided as it makes it impossible to access individual cells.

2.3 Battery safety

Safety is of the utmost importance when designing a battery. It is not enough to only protect the battery against external factors like shocks, vibrations, rain, and dust; the design must address potential internal risks as well. Internal disruptions pose significant hazards, with the outbreak of fire as the primary concern. This can occur due to several factors, including overheating, physical damage to the cells, excessive current flow, or short circuits within the pack. The Bosch battery in figure 6 serves as an example of how to mitigate such risks effectively. The main safety measures are:

- Install fuses between cells or sections to provide protection against excessive current.
- Use flame-retardant plastic casings to shield the battery from physical shocks and to contain fire in the event of an outbreak. If the outer body is made of a conductive material like aluminium, the plastic casing also serves as insulation to prevent electrical conductivity through the outer housing.
- Incorporate separators between the cells or sections of the pack to prevent the spread of heat and reduce the risk of overheating between individual cells.
- Design air gaps within the battery structure to allow for controlled gas leakage, ensuring pressure buildup can be safely managed if necessary.

Main insights

- External safety risks are shocks, vibrations, rain and dust.
- Internal safety risks are excessive currents, overheating and pressure build up.

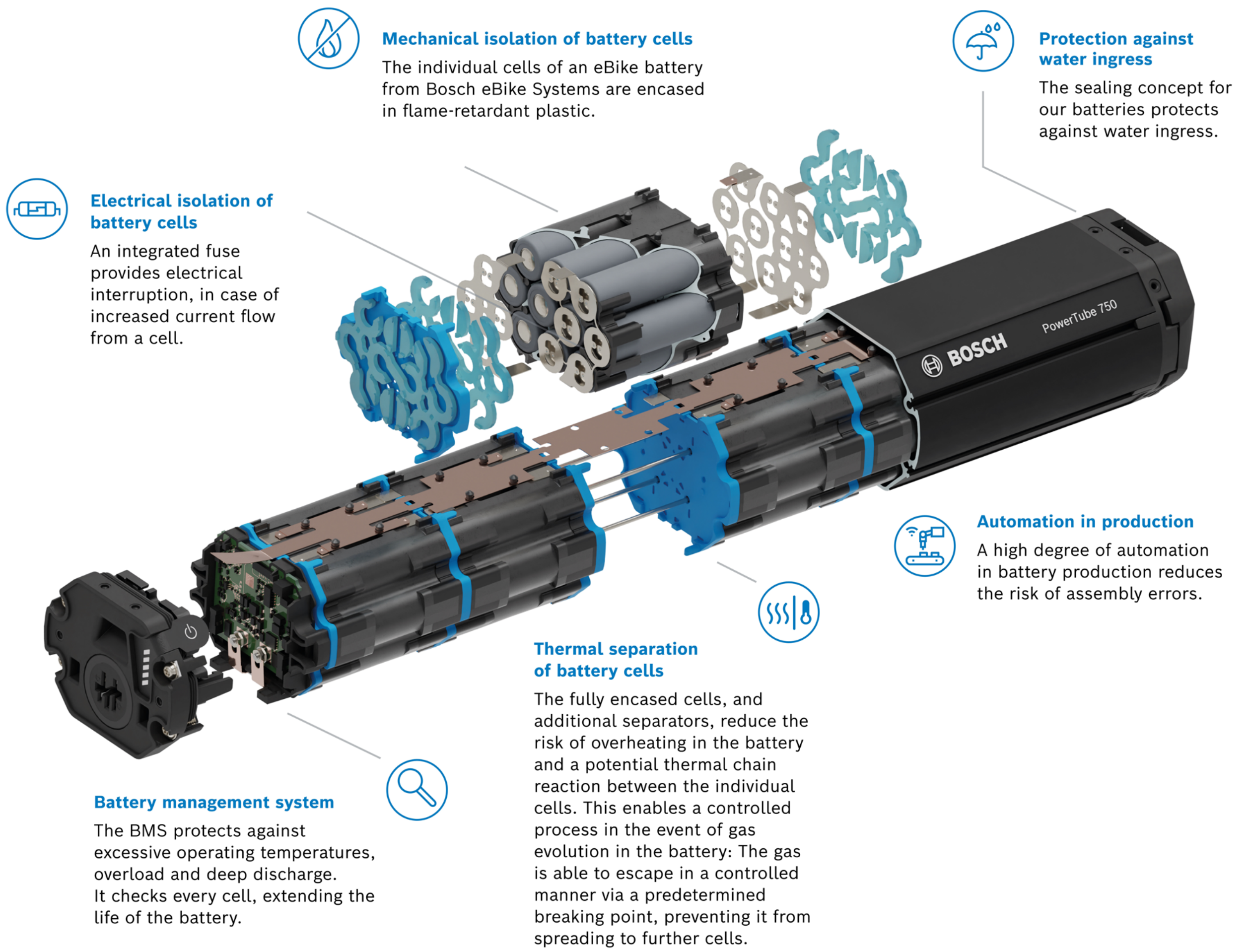


Figure 6: safety measures within a Bosch bicycle battery (Bosch E-bike, 2024).

2.4 Pouch cells

Types of cells

There are three primary lithium-ion cell types used in electric vehicle applications: cylindrical, prismatic, and pouch cells, each with distinct advantages and disadvantages. Table 1 illustrates the key differences among these options regarding structural design considerations (Arora et al., 2018).

The 18650 cylindrical lithium-ion cell is the most commonly used in bicycle batteries (Rebatt, personal communication, May, 2024). Its cylindrical shape provides enhanced safety, mechanical stability, and strength. Additionally, its design facilitates mass production, leading to economies of scale and lower manufacturing costs. Conversely, prismatic cells are less common in bicycle batteries due to their lack of standard sizes, which increases production costs. Additionally, the rigidity of prismatic cells makes them less flexible and harder to implement into the battery design.

For this project, the battery pack will be designed using pouch cells, as EAGLEBAT's technology focuses on this cell type. Although pouch cells are not yet widely used in bicycles, this chapter explores their advantages and the design challenges associated with their use.

CRITERIA	POUCH CELL	PRISMATIC CELL	CYLINDRICAL CELL
ENERGY DENSITY	High	High	Low
WEIGHT	Light	Moderate, dependent on casing	Moderate, dependent on casing
CONNECTIONS	Tabs that are clamped, welded or soldered	Threaded hole for bolt	Welded nickel or copper strips, threaded studs
RETENTION AGAINST EXPANSION	Requires retaining plates at the end of the battery	Requires retaining plates at the end of the battery	Inherent from cylindrical shape
DELAMINATION	Highly possible	Possible	Not possible
CASING	Aluminium soft bag	Semi-hard plastic or metal	Metal
COMPRESSIVE FORCE HOLDING	Extremely poor	Poor	Excellent
LOCAL STRESS	Yes	No	No
SAFETY	Poor, no safety features included	Good, due to integrated Positive Temperature Coefficient	Good, due to integrated Positive Temperature Coefficient

Table 1: characteristics of the three primary lithium-ion cell types.

Advantages

Among the three cell types, pouch cells offer the highest individual cell capacity and often exhibit superior energy density compared to cylindrical cells of the same chemistry (Empower Greentech, 2024). The use of soft aluminium casings in pouch cells, rather than rigid metal or semi-hard plastic casings, enables manufacturers to maximize active materials and achieve greater energy storage per unit volume. This results in longer runtimes and extended operating periods for devices powered by pouch batteries. In electric vehicles, the higher energy density of pouch cells contributes to an increased driving range, addressing a key challenge for broader electric vehicle adoption. Additionally, the lightweight nature of pouch cells allows for lighter and more portable designs without sacrificing battery capacity or performance.

Furthermore, unlike the other types, pouch cells have great flexibility in shape and design, making them very suitable for applications where shape and size constraints are paramount, such as on electric bicycles. They are typically flat for two main reasons: First, a flat design requires fewer internal layers, which lowers production costs per cell. Second, it allows for more effective heat dissipation during charging and discharging cycles, reducing the risk of thermal runaway and extending battery lifespan. Additionally, the larger surface area of pouch cells improves cooling efficiency (Empower Greentech, 2024).

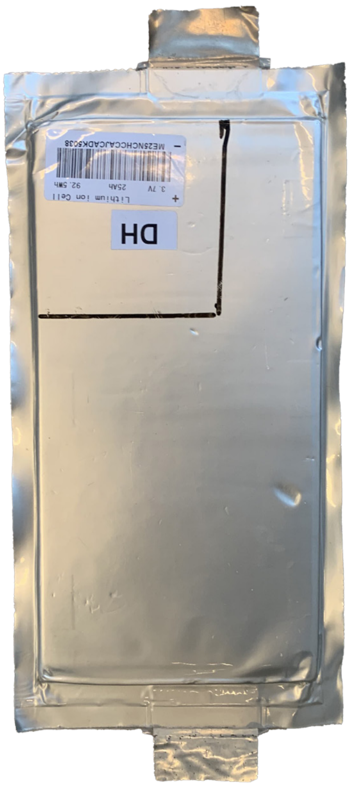


Figure 7: example of a pouch cell displaying the soft nature of the aluminium casing.

Design challenges

Although pouch cells appear ideal for electric bicycle battery packs, they present specific challenges primarily due to their soft aluminium casings (Arora et al., 2018).

The flexibility of the pouch cells' packaging affects the structural stability of the battery pack. The soft casing, as illustrated in figure 7, necessitates careful handling during assembly to prevent local stress that could damage the cell structure. Additionally, the casing's softness makes it difficult to secure the cells in place, requiring robust holding structures and retention mechanisms to counteract cell expansion. Without proper support, the cells may experience delamination of electrode layers due to extreme shocks or continuous vibrations, which are not uncommon during bicycle operation. Therefore, structural members are needed to provide external compressive force, vibration isolation, and shock resistance.

Pouch cells also tend to swell over time. Although EAGLEBAT has developed a technique to mitigate this issue, some bloating is inevitable. Sufficient spacing between cells is necessary to accommodate slight swelling and as well as to ensure effective heat management. While pouch cells generally have excellent heat dissipation, they require air gaps or conductive materials between cells to manage heat effectively. Unlike cylindrical or prismatic cells, pouch cells lack a Positive Temperature Coefficient safety feature, which increases electrical resistance with temperature rise. Consequently, external components must be included in the battery pack to ensure proper heat management and safety. Furthermore, pouch cells use tabs for their positive and negative connections, which requires different joining techniques compared to cylindrical or prismatic cells.

In summary, it is clear that a robust mechanical structure is necessary. This structure must provide adequate spacing between cells while securely holding them in place and protecting them from external shocks and vibrations.

Main insights

- Pouch cells have a high individual cell capacity, are lightweight and have great flexibility in shape and design, making them suitable for electric bicycle battery packs.
- A robust mechanical structure is required that securely holds the pouch cells in place, leaves enough space between cells and protects them from external shocks and vibrations.

2.5 EAGLEBAT's pouch cell

A pouch cell dissected

A lithium-ion pouch cell is composed of cathodes (positive electrodes) and anodes (negative electrodes). Each electrode consists of a current collector coated with an active material. The cathodes and anodes are alternately stacked with a thin separator membrane between each layer, forming a single laminated pouch. The separator membrane allows ions to pass through while preventing physical contact between the electrodes. Furthermore, the cell is filled with an electrolyte, which facilitates the movement of lithium ions between the cathode and anode. This layered stack is then sealed within a soft aluminium outer layer. At the final stage, all tabs from the cathodes are combined into a single tab for the positive side, and similarly, all tabs from the anodes are combined into a single tab for the negative side, resulting in only two tabs per cell in a conventional pouch cell.

Pouch cell with sub-cells

EAGLEBAT's new concept involves subdividing the pouch cell into smaller sub-cells. These sub-cells are arranged in a stacked configuration within the pouch cell, with each sub-cell being separated by an isolator layer (Figure 8). EAGLEBAT combines multiple sub-cells into a single pouch cell because providing each sub-cell with its own individual aluminium pouch is not economically feasible. These tabs are individually connected to MOSFETs, which are used to actively manage the operation of each sub-cell, enabling them to be switched on or off as required. The sub-cells are then connected in a parallel configuration, which allows the pouch cell composed of sub-cells to function similarly to a standard pouch cell in terms of energy output.

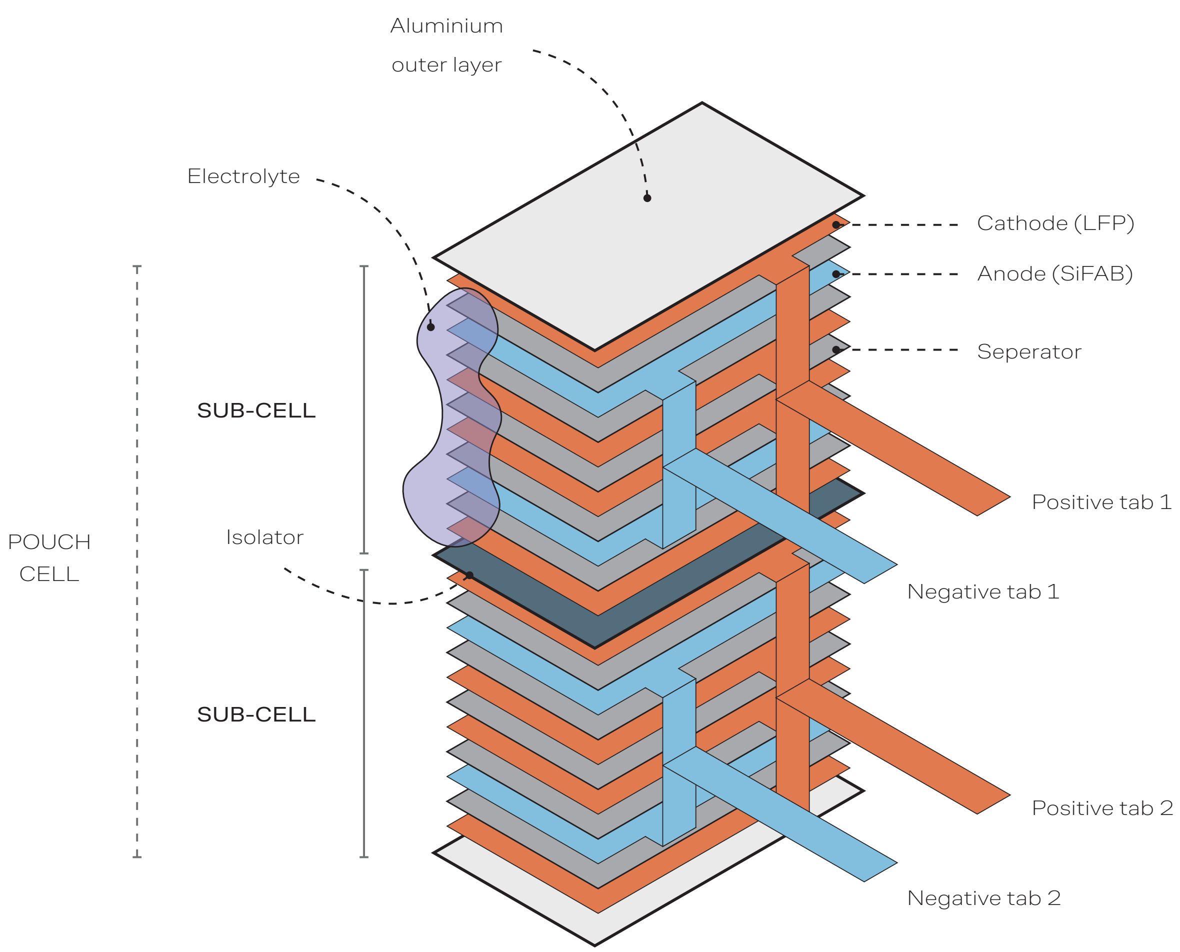


Figure 8: *cell layer configuration in the EAGLEBAT pouch cell with sub-cells (example has two sub-cells, but more is also possible)*

Advantages

Firstly, this new approach utilising sub-cells allows for greater control over which parts of the cell are engaged at any given time, promoting a more uniform decline in State of Health across the cell. Secondly, it enables periodic resting periods for the sub-cells, allowing material redistribution within the cell and thereby extending its overall lifespan. Despite the subdivision, the peak current remains consistent with the original cell, as all sub-cells can be activated when high peak currents are needed. Lastly, this method may also facilitate more precise temperature regulation within the cell.

Design considerations

Unlike traditional designs with just 2 tabs, this configuration uses 12 tabs (figure 9), which limits space and increases the risk of short circuits if not properly managed. To mitigate this risk, tabs can be strategically placed to ensure that positive and negative tabs are sufficiently separated. Furthermore, Lee et al. (2020) advise to place the tabs from the anodes and cathodes on opposite sides of the pouch cell for better heat distribution within the cell and for increased cell longevity. Additionally, each tab connects to its own MOSFET before connected in parallel, adding complexity to the wiring. Lastly, the design offers flexibility in adjusting the cell's width, length and depth. However, a thin cell with a large surface area is preferred as this has better heat dissipation and requires fewer layers, lowering the possibility of a production error whilst stacking layers.

Main insights

- The EAGLEBAT pouch cell is divided into 6 sub-cells, resulting in 12 tabs per pouch cell.
- Tab locations can be adjusted, but it is advised to put anode and cathode tabs on opposite sites of the cell for optimal cell longevity.
- MOSFETS are used to regulate the sub-cells. Each tab must first be individually connected to a MOSFET before being connected in parallel, adding complexity to the wiring.
- There is flexibility in the cell's dimensions, but a thin cell with a large surface area is preferred for better heat dissipation and fewer production errors.

Figure 9: an EAGLEBAT pouch cell prototype displaying the many tabs required because of the sub-cells.

2.6 Joining techniques

A battery pack for an electric bicycle consists of numerous cells that need to be both structurally secured and electrically connected. Establishing these electrical and structural connections involve several challenges. The connections can be categorized into cell-level joining and module/pack-level joining. For a pouch cell, cell-level joining refers to the process of combining all the tabs of cathodes or anodes into a single tab, which conventionally occurs during the production of the pouch cell using ultrasonic welding (Das et al., 2018). However, this chapter focuses on module/pack-level joining, examining the techniques that can be employed to connect the 12 tabs of the EAGLEBAT pouch cell to the corresponding required MOSFETs.

Reversible connections

The connections between the cell tabs and other components face multiple challenges, including the need to avoid potential damage during the joining process. Moreover, once in use, these connections must endure heat, mechanical and electrical stress, while maintaining high durability, as bicycles are regularly subjected to vibrations and shocks (Zwicker et al., 2020).

Additionally, EAGLEBAT's mission introduces another key requirement: the ability to replace individual cells at the end of their life cycle. This necessitates that the connections to the pouch cells are reversible. To minimize replacement time, the connection and the cell must be easily accessible without interference from surrounding components. For instance, it would be inefficient if three functional cells had to be removed to access a faulty fourth cell. Creating individual, reversible connections for each of the 12 tabs per pouch cell presents a unique challenge in this context.

Joining techniques

Whilst there are many joining techniques, each with its unique applications, advantages, and drawbacks, three main techniques have been identified for pouch cells that could be relevant during this project (Das et al., 2018).

Laser welding is a fast and precise process that forms high-strength, low-distortion joints while minimizing heat input., which is important for heat sensitive batteries. It is particularly effective for thin materials and intricate designs, including applications with limited access, because it does not require physical contact, However, it demands precise alignment, specialized equipment, and strict safety measures due to high-energy laser beams. While it provides a permanent bond, making it ideal for specific connections, an additional technique should be considered if reversibility is needed.

Soldering is a widely used method, especially in electronics, due to its versatility in joining dissimilar materials. However, it typically forms an irreversible bond as well. While desoldering is an option, it is not ideal for frequent component replacement, such as in battery cells. Joint strength, localised heat damage and the risk of loosening due to vibration are also concerns if done improperly. Soldering can be useful for connecting various electronics in the battery pack, but might be harder to use to connect tabs.

Mechanical assembly is the only technique that is fully reversible, offering the advantage of easy disassembly, repair, and recycling. However, it may introduce additional weight, potentially increase resistance, and can become costly, particularly when numerous connections are involved. There is also a risk of mechanical damage, and over time, fasteners may loosen, compromising the stability of the assembly. Generally, pack level (e.g. module-to-module) connections are made with mechanical fasteners, but mechanical connections for tabs will be explored during this project as well.

Design implications

While both laser welding and soldering are suitable for connecting various components, mechanical connections are necessary to ensure the reversibility required for replaceable cells. Unfortunately, these mechanical connections could create potential weak points in the battery pack, particularly since each pouch cell requires 12 tab connections, each linked to its own MOSFET. Having individual connections for each of the 12 tabs could also greatly extend the time needed to replace a pouch cell due to many extra steps. However, the replacement time must be be minimised. Therefore, a strong mechanical connection is required that allows for efficient cell swaps without compromising the durability the design.

Main insights

- Each tab connection must be easily accessible, without interference from other components.
- Mechanical connections are the only fully reversible option and thus essential.
- The replacement time per cell must be minimised.

Figure 10: pouch cell production

3

Research towards the solution

This chapter establishes boundaries to narrow the design space for the complex task of designing a reconfigurable battery system that supports single-cell replacement. It begins by introducing EAGLEBAT's proposed 12V modular system, featuring modules that can be combined in various configurations to accommodate different voltage and current needs for electric bicycles. Next, the Battery Management System (BMS) is examined, with a preference for a hierarchical BMS structure that offers a balance between modularity and cost-efficiency. The chapter also defines the cell layout, providing examples of effective wiring for both cells and modules. Finally, it concludes with insights from the research phase, which help shape the design principles for the remainder of the project.

3.1 A reconfigurable battery system

EAGLEBAT is developing a battery system based on their new pouch cell technology to support a variety of electric bicycles, each with unique power requirements. Generally, most e-bikes operate on 36V batteries, though larger models may require 48V, while smaller ones may only need 24V. To address this range, EAGLEBAT envisions a flexible, modular design, using standardized 12V battery modules that can be connected in series and/or parallel configurations to reach the desired voltage and current levels (figure 11). This chapter presents several key challenges for a modular lithium-ion battery system.

Safe and error-proof connections

Each module must be easy to connect correctly by employees, whether in series or parallel. To prevent connection errors, which could result in dangerous short circuits, a design is required that is able to differentiate between these two distinct configurations. Ensuring that connections are both safe and foolproof is critical for lithium-ion batteries, making a reliable, user-friendly connection system essential.

BMS integration

All battery modules will need to integrate with a Battery Management System (BMS) to monitor cell balance and ensure safe operation (chapter 3.2). This presents challenges in wiring and modular compatibility to ensure the BMS accurately reads and manages cells across different configurations.

Voltage mismatch due to modularity

The EAGLEBAT pouch cell has a nominal voltage of around 3.2V. For a functional modular 12V system, it is crucial that the nominal voltage is close to 3.0V. The following example shows what would happen if higher voltage cells would be used:

Each 12V module contains four cells in series. If cells with a nominal voltage of 3.6V are be used, the result will be 14.4V per module, which is higher than the nominal 12V target. For example, to achieve 36V, three modules are used, which would sum to 43.2V (12 cells total), overshooting the desired voltage drastically. Ideally, 36V requires only 10 cells in this case, but a standardized 12V modular design cannot achieve this level of precision.

Possible solutions might include specialized control software or circuitry to manage this discrepancy, though these options may add complexity to the design. Smaller, lower voltage modules might offer a solution but would compromise the simplicity and universality of a 12V system. However, these solutions become unnecessary when the nominal cell voltage is around 3.0V. With 3.2V pouch cells, a 12V modular system remains feasible for EAGLEBAT, but it is recommended to avoid increasing the voltage gap further, as it would worsen the mismatch.

Space efficiency and cell placement

Space constraints within a bicycle battery compartment require an optimized layout to maximize energy capacity. Modular systems may introduce additional components, potentially limiting the number of cells that can fit into a rear-mounted battery compartment. Designing a layout that balances modular flexibility with space efficiency is thus a key consideration.

In summary, implementing a modular 12V system brings several challenges that must be thoughtfully addressed. By keeping an open mind, EAGLEBAT aims to evaluate the feasibility of this modular approach without prematurely dismissing its potential.

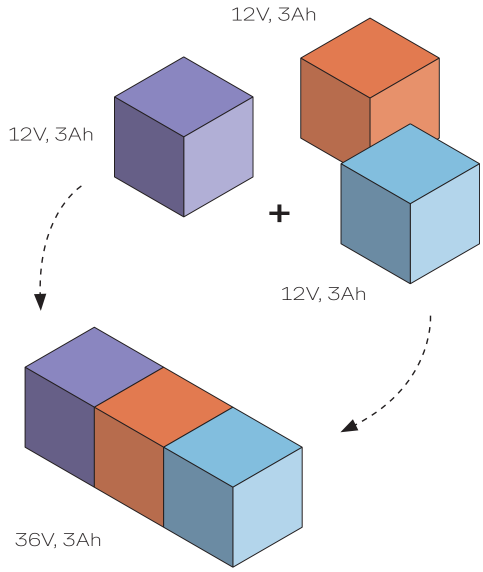


Figure 11: example of three modules combined in series to increase the total voltage of the system.

Main insights

- EAGLEBAT aims to create a versatile system using 12V modules to accommodate the various battery specifications needed for different types of e-bikes.
- A modular system introduces several challenges, including ensuring safe connections between modules, integrating a robust Battery Management System (BMS), managing voltage mismatches and overcoming space constraints.

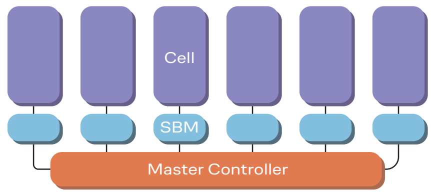
3.2 Battery Management System

The Battery Management System (BMS) oversees all control and management aspects related to energy storage and transfer in electric vehicle systems. These functionalities include battery cell monitoring, charge and discharge control, battery protection, communication, heat management, and many more (Hannan et al., 2018). This project will not involve designing the printed circuit boards (PCBs) required for a BMS, as this is beyond the scope. However, we will explore the BMS structure that would best suit our modular battery pack.

Narayanaswamy et al. (2018) identifies four distinct trends in BMS structures (Figure 12): centralised (a), hierarchical (b), partially distributed (c), and fully decentralised (d). Traditional rigid battery packs commonly employ centralied or hierarchical BMS topologies, utilizing a single central unit to manage the entire pack. However, these conventional topologies present scalability challenges. Each wire must be precisely connected to a specific location within the pack, leading to a highly integrated electrical architecture closely tied to the underlying cells and their parameter specifications. Consequently, the addition of new cells or modules to the system is not easily facilitated and often requires a complete redesign of the battery pack. The computational capabilities of the architecture do not scale proportionally with the number of cells as well. Another limitation is that conventional structures typically rely on energy-inefficient passive techniques for balancing, as more efficient active balancing approaches require a complex control scheme that cannot be accommodated by a single master controller while simultaneously fulfilling other critical pack-level BMS functions.

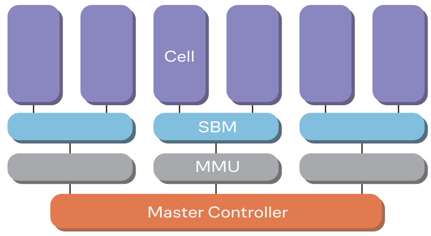
However, EAGLEBAT intends to actively balance its sub-cells and therefore already plans to implement a PCB per module, making a partially distributed or fully decentralised solution more appropriate. These decentralised solutions utilise local controllers to handle cell-level functions such as temperature measurements and cell balancing, which aligns with EAGLEBAT's intended approach. Adopting a decentralised structure would also address scalability issues and better suit a modular system. Other advantages of such structures include reduced wire complexity, a decreased number of connectors, and enhanced safety and reliability, as each module operates independently and prevent single-point failures. The main difference between the two is that unlike a partially distributed BMS, a fully decentralised structure does not require a Master Controller for communications and safety functionalities and executes all operations at a local level (Rao et al., 2023).

a



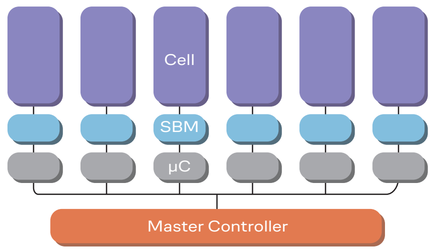
Centralised: each cell has its own Sensing and Balancing Module (SBM). The individual SBM's are controlled by a single Master Controller, which maintains safe operation of each cell and performs pack-level functions.

b



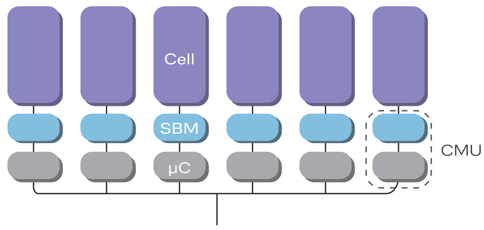
Hierarchical: an intermediate control layer in the form of Module Management Units (MMU's) manages the properties of a certain group of cells, relieving the Master Controler for performing only pack-level functions.

c



Partially distributed: each cell is monitored with a dedicated cell-level control unit (μC) that is in turn connected to a Master controller. Local controllers perform cell-level functions, including individual balancing, while the Master Controller only performs system-level BMS functions.

d



Fully decentralised: local cell-level controllers (μC) together with the SBM form an autonomous Cell Management Unit (CMU), which manages all the parameters of the cell it is attached to. The CMUs together perform pack level functions eliminating a central controller.

Figure 12: four distinct BMS trends. Greater decentralisation in the BMS increases the freedom in scalability, but also adds cost and complexity.

While a fully decentralised solution could maximize design flexibility and modularity by eliminating the need for a Master Controller, it presents significant challenges in software and control complexity given current technology. For large, complex battery systems, a partially distributed structure is generally recommended. This approach reduces the computing load on the Master Controller, as each module manages itself independently through localized monitoring, balancing, and charging calculations on a semi-autonomous basis (Narayanaswamy et al. ,2018). Meanwhile, the Master Controller, ensures proper coordination across modules.

In contrast, for smaller systems like a bicycle battery, a partially distributed structure is not recommended because "the increase in autonomy per module does not justify the added costs of implementing more complex chips in each module" (M. Verwaal, personal communication, October 8, 2024). In these cases, a centralised Master Controller can handle all necessary calculations effectively. Therefore, in collaboration with EAGLEBAT, the hierarchical structure has been selected for this project. In this setup, each component within a module is connected to a simple local chip mostly for sensing. Consequently, the single Master Controller will be responsible for coordinating module operations and performing the primary computations. The hierarchical solution is chosen over a fully centralised structure as it makes it easier to scale the number of cells without redesigning the systems architecture whenever the amount of cells changes.

Main insights

- The more decentralised the BMS, the greater the freedom in scalability.
- For a relatively small battery structure like a bicycle battery, the added costs and complexity of a (partially) decentralised structure are not justified.
- In collaboration with EAGLEBAT, the hierarchical BMS structure has been chosen for the rest of the project, as this is the most viable option to implement for EAGLEBAT at this time.

3.3 Cell layout

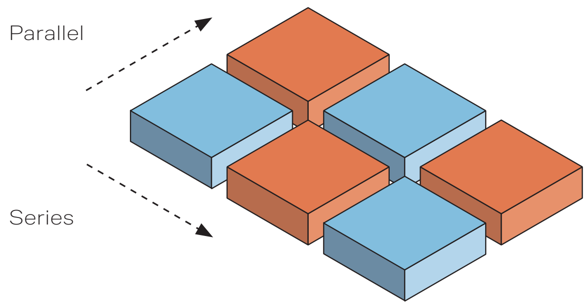
Module layout

Let's outline the cell layout for a system that integrates EAGLEBAT's pouch cell technology with a modular, reconfigurable design consisting of 12V modules. Starting at the smallest level:

1. Each pouch cell is divided into six sub-cells.
2. The tabs of each sub-cell are individually connected to a corresponding MOSFET.
3. Once the MOSFETs are in place, the six sub-cells are connected in parallel to function as a single pouch cell.
4. These fully assembled pouch cells are then connected in series to form a 12V module (figure 13).

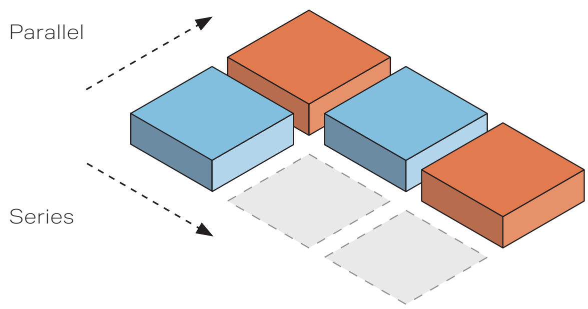
Connecting modules in a grid

When designing a battery system, modules must be connected in a balanced "rectangular" configuration (figure 14a). In series connections, module voltages add up, but capacity (Ah) remains unchanged (e.g., three 12V, 10Ah modules in series yield 36V, 10Ah). In parallel connections, capacity increases while voltage stays constant (e.g., three 12V, 10Ah modules in parallel yield 12V, 30Ah). To scale both voltage and capacity, identical series strings must be added in parallel. Each row must match in module count and specifications. Adding a single module to a series string (figure 14b) causes imbalance, leading to uneven voltage, stress, and damage (Andrea, 2010). Connecting the modules in the correct configuration ensures balanced voltage and current distribution, preserving the system's performance and reliability.



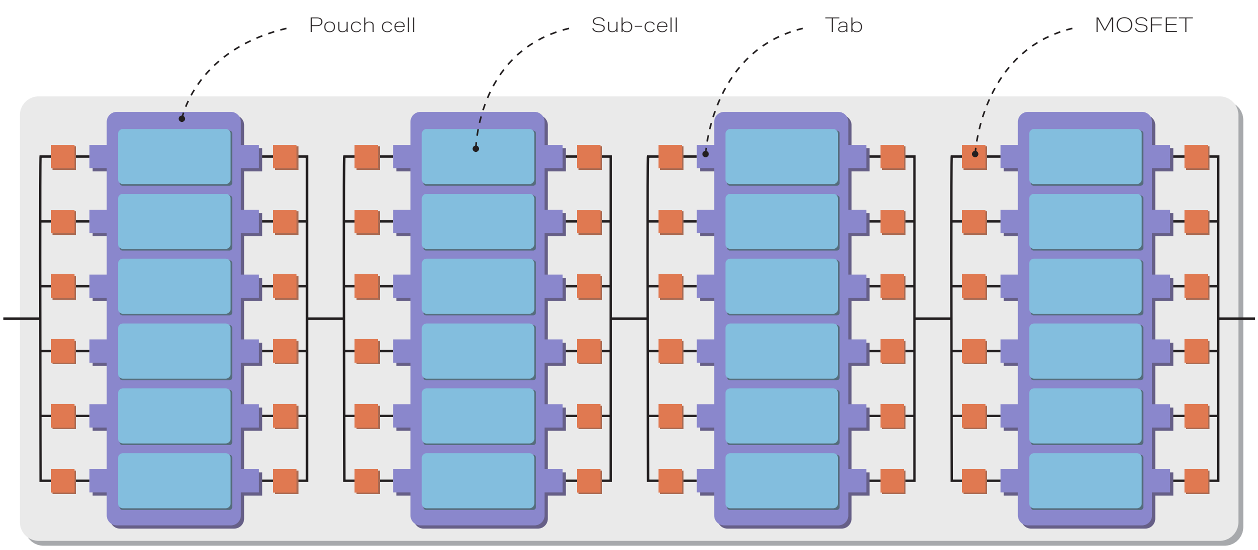
Correct

Figure 14a: modules must be connected in a balanced "rectangular" configuration. Each parallel row must match in module count (e.g. both rows contain three modules in series).



Incorrect

Figure 14b: a different amount of modules per parallel row (e.g. one in series vs three in series), causes imbalance, leading to uneven voltage, stress and damage.



Module lay-out

Figure 13: the cell layout within a 12V module, consisting of four pouch cells (which each contain six sub-cells). All sub-cell tabs are connected to their own MOSFET before being connected in parallel.

A direct parallel connection

It is advised to connect battery modules and cells directly in parallel rather than arranging them in separate series strings that are later connected in parallel. This design approach offers superior performance and reliability, especially when dealing with weak or damaged cells (Andrea, 2010).

In a direct parallel configuration, as shown in figure 15a, the total capacity of each row is the sum of the capacities of all the cells within it. For instance, if each cell in a row has a capacity of 2 Ah, the row's total capacity is 8 Ah. If one cell's capacity drops to 1 Ah, the other cells compensate, slightly reducing the row's capacity to 7 Ah. Crucially, this arrangement ensures that the entire pack maintains its capacity at 7 Ah, regardless of how many rows contain a low-capacity cell, since all rows are equally balanced and supported.

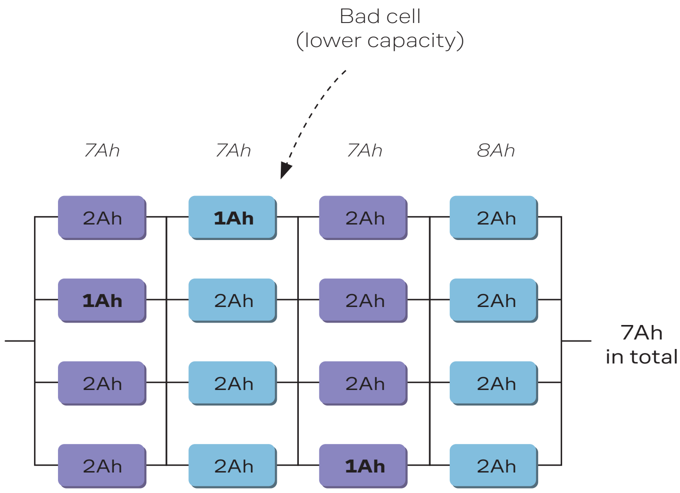
In contrast, if the pack is divided into separate series-connected strings that are later paralleled (figure 15b), the capacity of each string is limited by its weakest cell. For example, if one string contains a cell with a capacity of just 1 Ah alongside others with higher capacities, the entire string is constrained to 1 Ah. Consequently, the total pack capacity becomes the sum of these string capacities, which can drop significantly, in this case to 5 Ah. This happens because the strings cannot share the load across cells as effectively as a direct parallel configuration, making the system more vulnerable to the effects of weak or low-capacity cells.

It must also be considered that the actual usable capacity might be even lower in a setup with split series strings. In the previous example of figure 15b, the worst cell delivers only 1 Ah of capacity. Once this cell is fully depleted, its voltage drops, triggering the Battery Management System (BMS) to shut down the entire pack to avoid damage. This reduces the actual usable capacity to 4 Ah instead of previously mentioned 5 Ah, as each of the four strings has only discharged 1 Ah when the pack shuts down. While this reduction may be slightly offset by the weak cell's increased resistance as it nears depletion, the pack's overall performance is still significantly compromised.

For these reasons, connecting modules and cells directly in parallel is a more robust and reliable design for handling variations in cell capacity and performance.

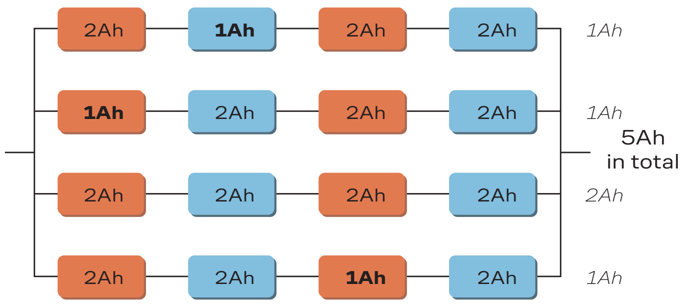
Additional wiring

Until now, the diagrams in this chapter focused solely on the power circuitry for the cells. Additional wiring is required for integrating the Battery Management System, managing the MOSFETs and connecting possible additional components.



Direct parallel configuration (preffered)

Figure 15a: connected in a direct parallel configuration, cells in a row compensate for each other. The capacity of the entire pack is equivalent to the row with the lowest capacity (7Ah in this example).



Seperate series strings

Figure 15b: connected in seperate series strings, the capacity of each string is equal to its worst cell (e.g. 1Ah). The capacity of the entire pack is the sum of the strings, which is only 5Ah in this example.

Main insights

- Pouch cell tabs must be connected to their dedicated MOSFET before they are connected in parallel.
- The modules must be connected in a "rectangular" configuration.
- Modules and cells are ideally connected directly in parallel to effectively deal with variations in cell capacity and performance.

3.4 Conclusions & design principles

Designing a battery architecture that allows for single-cell replacement is not a straightforward endeavour, especially when EAGLEBAT's newly developed pouch cell technology must be implemented as well.

Pouch cells offer notable advantages due to their lighter weight and higher energy density compared to the commonly used cylindrical cells, allowing for the creation of a more efficient battery pack. However, two primary challenges must be addressed concerning the cell itself. The first challenge stems from the softer structure of pouch cells, which makes them more susceptible to external impacts. Additionally, to align with EAGLEBAT's commitment to sustainability and ease of disassembly, the use of solder and adhesives must be avoided, further complicating the task of securing the pouch cells in place. The second challenge arises from EAGLEBAT's innovative technology, which divides each pouch cell into six sub-cells. Consequently, there are six anode and six cathode tabs instead of the usual single pair, significantly increasing the complexity of designing a reversible connector .

Given the scale and complexity of this project, initial decisions have been made to simplify the design space. First of all, the decision has been made to develop a system utilising 12V modules to accommodate for various battery specifications of electric bicycles. These modules can be connected in series and/or parallel to increase voltage or capacity of the pack. Consequently, the cell layout has also been defined, emphasizing the requirement for each individual tab to connect to its corresponding MOSFET before the six tabs are connected in parallel to create a pouch cell. The complete pouch cell has a nominal voltage of 3.2V and four of them can therefore be connected in series together to create a module of 12V.

Furthermore, a hierarchical Battery Management System (BMS) structure has been chosen. Unlike a fully centralised system, the hierarchical structure is compatible with a potential modular battery design and integrates well with the local controllers already in place to manage the MOSFETs for sub-cell control. A more complex, decentralised system is considered unnecessary due to the relatively small scale of a bicycle battery.

With the cell layout and BMS structure established, boundaries have been set for further development of the battery design. Findings from the research phase form the basis for a set of design principles that will be pursued (table 2). A more in-depth list of requirements can be found in appendix A.

DESIGN PRINCIPLES

Single-cell replacement	The main goal of the project. A reversible tab connection for the pouch cells of EAGLEBAT must be implemented into the design.
Battery safety	Safe operation of the battery must be guaranteed, both during use of the consumer and during repair by the producer. Safety includes proper heat dissipation, reliable electrical circuitry and being able to withstand cycling conditions such as shock, vibrations and weather.
Space optimisation	Space in the battery is limited. The volume of the pouch cells, in regards to the available space, must be maximised to get the highest capacity possible.
Durability	Single-cell replacement is only achievable when the housing structure, control hardware and other components have a longer lifespan than the cells itself.
Ease of disassembley	For feasible single-cell replacement and/ or repair, it is crucial that components are easy to reach and that replacement can be performed quickly.
Matching current bicycle batteries	To be viable, battery specifications of current bicycle batteries on the market must be met or improved on. The most important one is capacity, but it also includes weight, size and form.
Scalability	For applications across different bicycle types or perhaps even other vehicles in the future, a reconfigurable system is desired that can output different voltages and currents. Scalability also involves identifying the fixead boundaries of the design and clarifying areas where there is flexibility for design freedom.

Table 2: seven design principles derived from the research phase of the project.

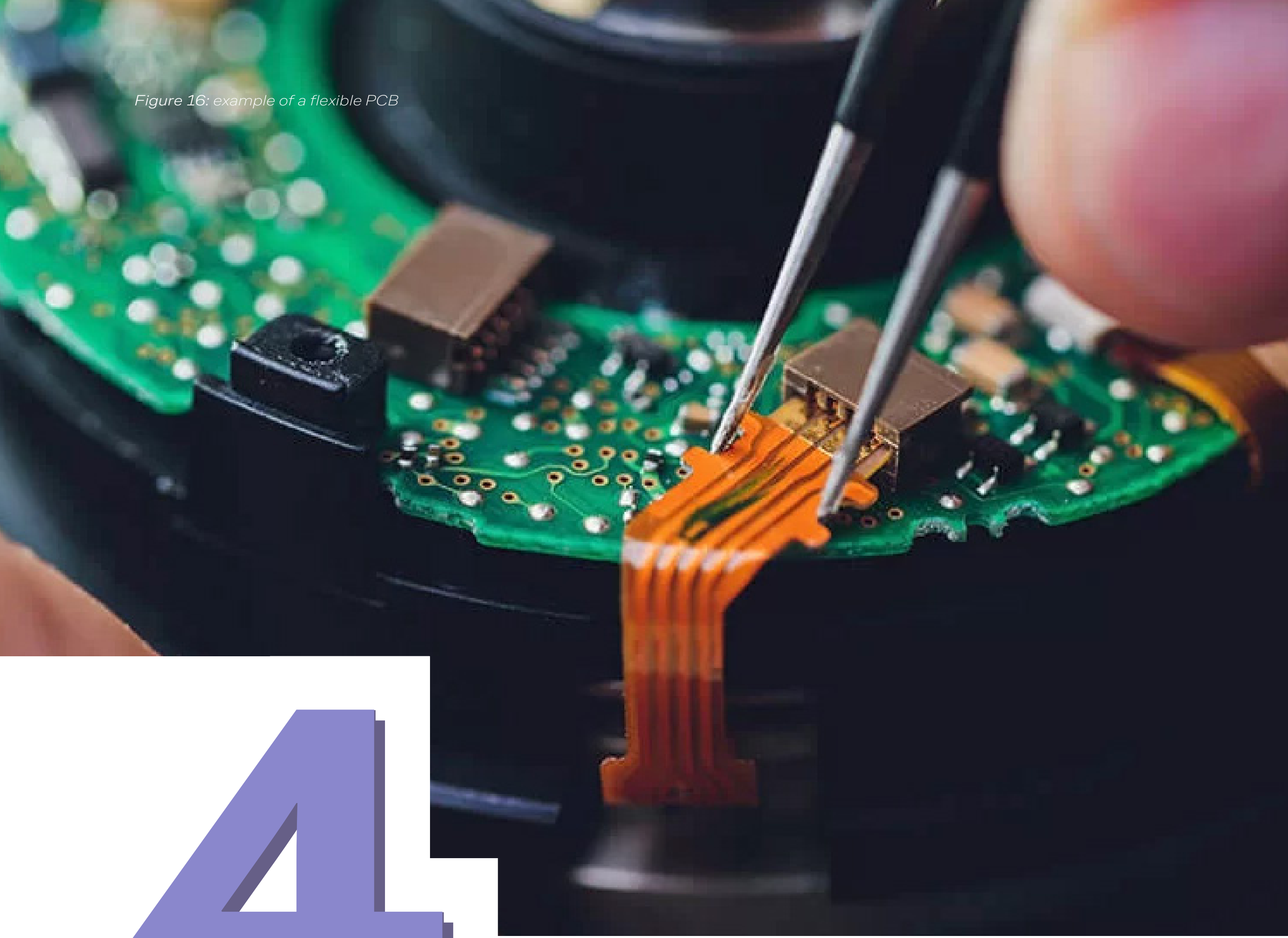


Figure 16: example of a flexible PCB

4

Concept development & selection

This chapter focuses on concept generation, ultimately leading to the selection of a reversible tab connector. It begins by breaking down the battery design into sub-problems, for which potential solutions are ideated and put into a morphological chart . This chart is used to systematically combine the solutions to sub-problems into possible concepts for the battery pack. These concepts lead to the discussion of design considerations for the concepts and a distinction is made between the most critical sub-problems at this stage of the design and those that should be addressed later. The reversible tab connector emerges as a central element for further development, as it has a significant impact on other design decisions. Finally, three reversible connector options are evaluated using the DATUM method, and a laser-welded flexible PCB connector is chosen as the focal point for the battery pack design, thanks to its compactness and vibration resistance.

4.1 Morphological chart

EAGLEBAT is a relatively young start-up, which comes with the advantage of fostering a dynamic environment full of creative and innovative ideas. However, this also means that few processes or guidelines are firmly established. The lack of defined boundaries can make it challenging to identify a clear starting point for ideation. To address this, a morphological chart has been developed to facilitate the creation of new concepts. This method was chosen because, during the early phases of the project, numerous sub-functions and potential solutions were already identified. The morphological chart (figure 17 on next page) effectively organizes these ideas, providing a comprehensive overview of the ideation that has already taken place. It also offers a structured approach for combining solutions to different sub-problems, making it easier to generate fresh, out-of-the-box ideas and avoid the pitfalls of tunnel vision (Van Boeijen et al. ,2014).

The sub-problems identified for the battery pack and included in the morphological chart are as follows:

1. Securing each pouch cell firmly within the battery structure to prevent movement.
2. Combining multiple pouch cells into a unified and coherent module structure.
3. Creating a reversible tab connection between the pouch cell tabs and the corresponding PCB.
4. Determining the configuration in which cells are arranged within a 12V module.
5. Deciding the placement of multiple MOSFETs for each pouch cell.
6. Preventing overheating of critical components to ensure safe operation.
7. Choosing the appropriate method for wiring components together.
8. Establishing connections between different 12V modules, both for power and data wiring.
9. Protecting the battery pack from damage caused by shocks or vibrations.

Then, for each sub-problem, solutions were ideated through How-To's. They were made with simplified descriptions of the sub-problems, which can be found in morphological chart. The How-To's for (1) holding cells firmly in place and (3) reversible tab connectors were performed in collaboration with two employees of EAGLEBAT. These two How-To's were selected to be performed together with EAGLEBAT as they seemed most influential in determining the future direction of the design. The employees provided input through their expertise of mechanical engineering and pouch cell creation respectively. The other How-To's were performed by myself. Consequently, the most promising ideated solutions for each sub-problem were organized into the morphological chart. This chart provides an overview of all the ideas and serves as the starting point for future concept generation.Advantages and disadvantages of each solution in the morphological chart can be found in appendix B.

Design steps

- With few components firmly established, designing a complete battery architecture is a complex task. To simplify and better understand the process, the battery pack design is broken down into sub-problems.
- Solutions for each sub-problem were ideated and organized into a morphological chart. This chart serves as a comprehensive overview of existing ideas and forms the foundation for generating future concepts.

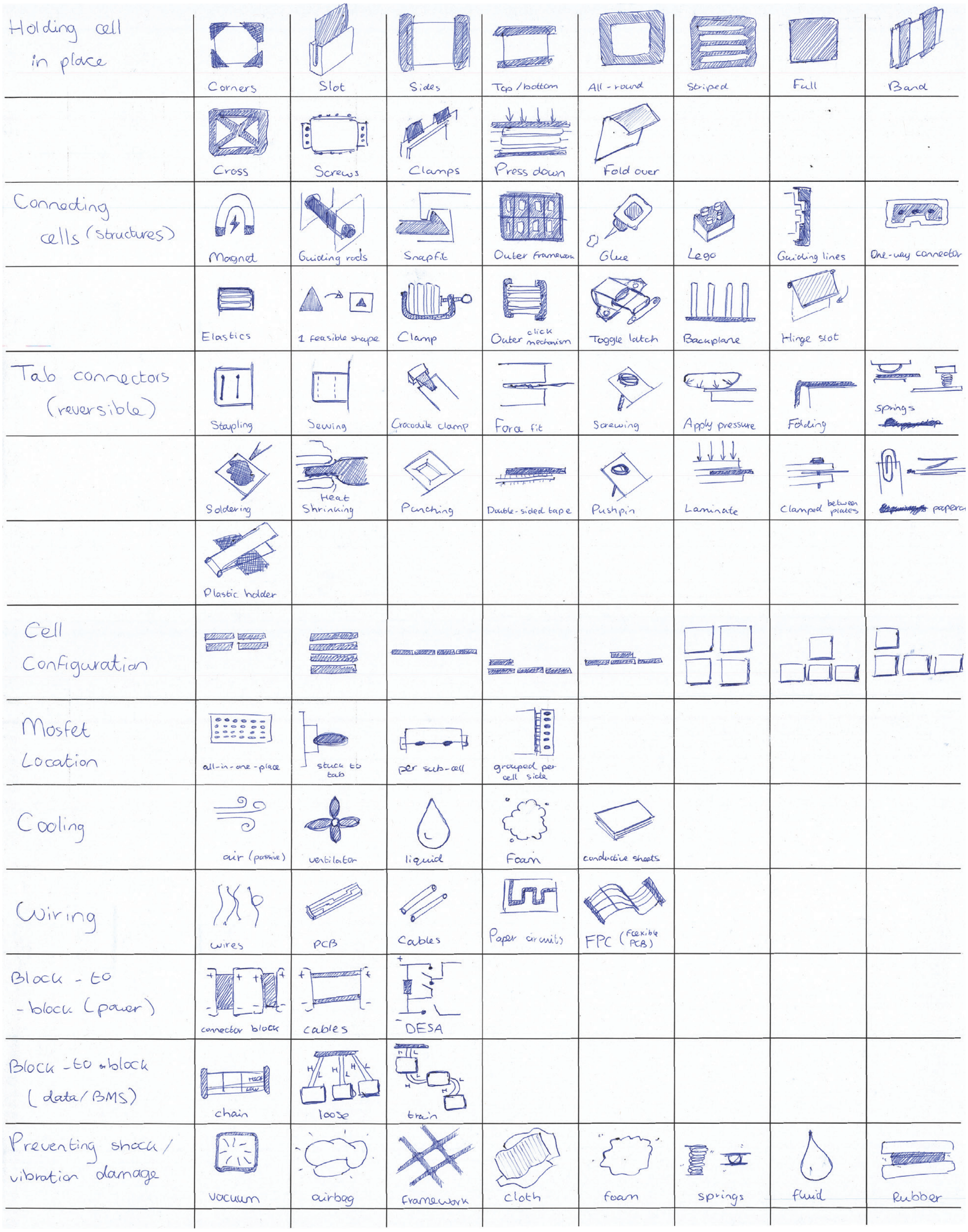


Figure 17: *the morphological chart displays all sub-problems along with their ideated solutions. Individual squares will be combined to form concepts.*

4.2 Concept generation

Combining solutions

To create concepts for the battery pack, solutions for each sub-problem in the morphological chart are systematically combined. Rather than combining ideas at random, combinations were developed based on the design principles. These combinations are found in appendix C.

Concept 1: as compact as possible

Design principle: space optimisation

For a compact design, all components must be positioned close together, leading to a stacked cell configuration. Four cells are secured together by the columns on the side. The cell tabs are connected per side in sets of six with a clamp connector, because an individual connector per tab would take up too much room. These clamps have integrated MOSFETs to save space as well. Other unnecessary components are avoided, leaving the tab connectors exposed. Passive cooling is chosen as it also eliminates the need for additional parts. The concept relies on the strength of the casing and framework to withstand shocks. Since connections must be made from multiple points, wires are used because they can navigate complex paths.

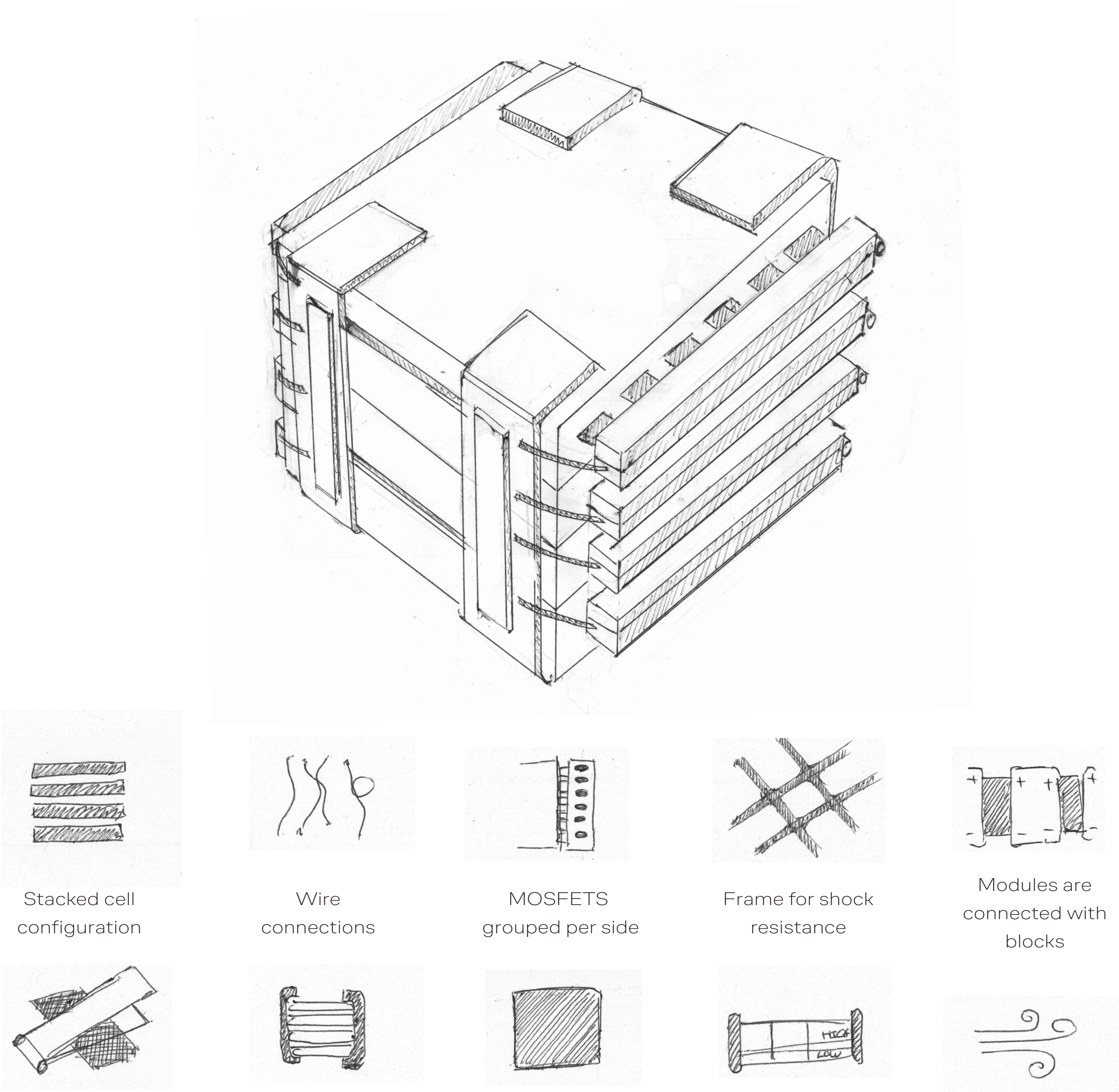
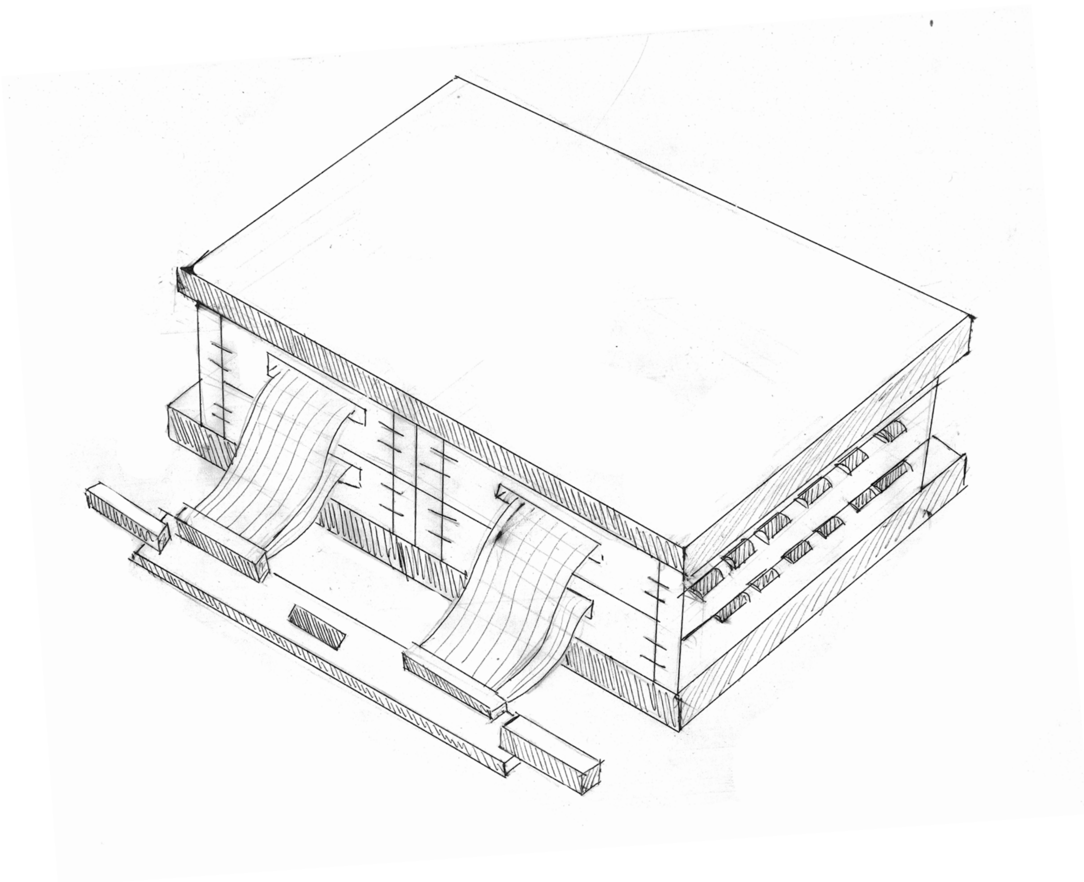


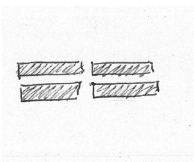
Figure 18: concept 1, as compact as possible, including the used sub-problem solutions from the morphological chart to create this concept drawing.

Concept 2: easy disassembly

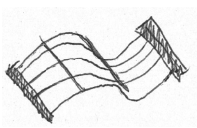
Design principle: ease of disassembly

For easy disassembly, all components must be accessible. The cells are placed in a tray, making their placement intuitive. They are arranged in a square configuration to ensure each cell is accessible from at least one side, preventing any from being trapped between others. MOSFETs are directly connected to the tabs to avoid misconnections during assembly, and springs are used in the tab connectors to ensure a reliable connection. Flexible PCBs connect the cells to other module components, offering flexibility and freedom of movement, which enhances accessibility as well. There are no active components for cooling.

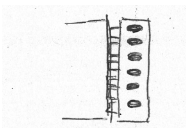




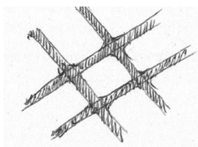
Square cell configuration



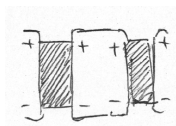
Flexible PCB as wiring



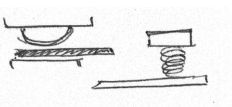
MOSFETS grouped per side



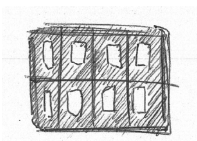
Frame for shock resistance



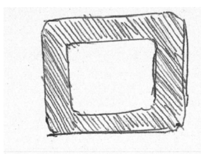
Modules are connected with blocks



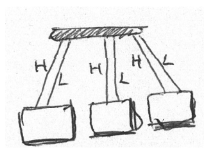
Springs to hold tabs



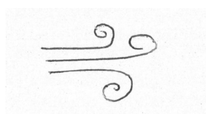
Outer tray to put cells in



Cells covered at the edges



Modules connect via loose wiring



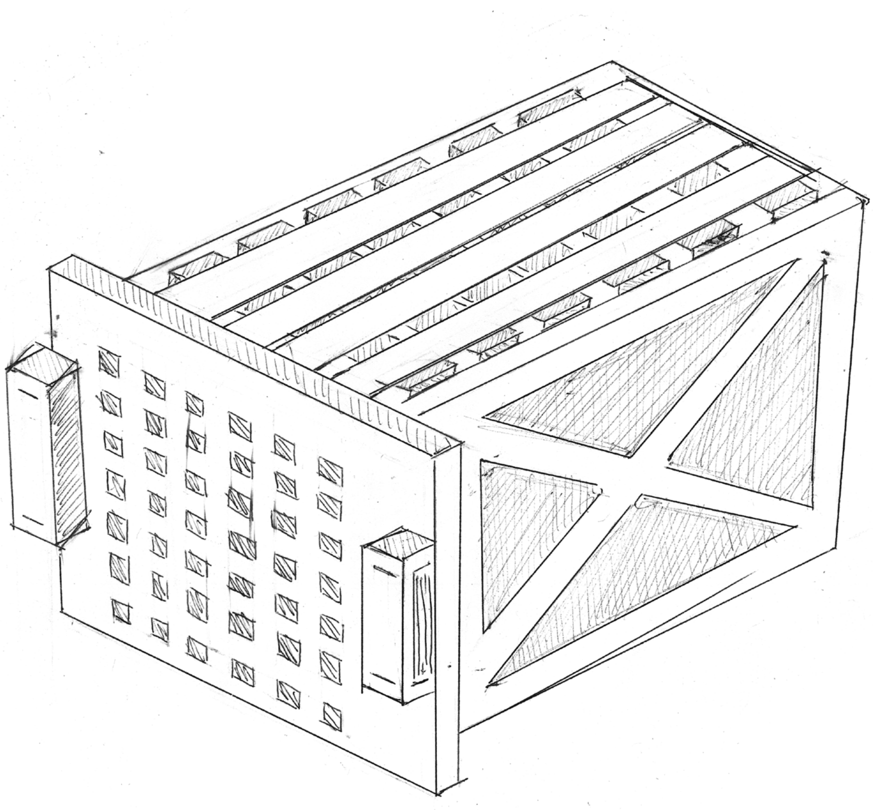
Passive (air) cooling

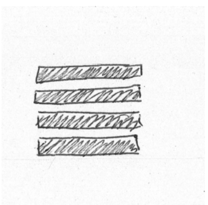
Figure 19: concept 2, easy disassembly, including the used sub-problem solutions from the morphological chart to create this concept drawing.

Concept 3: as durable as possible

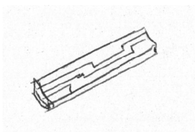
Design principle: durability

To maximize durability, each cell is encased in a casing with a cross pattern, which provides structural strength while still allowing heat dissipation. The cells are arranged in a stacked configuration and connected to the module board in a backplane pattern. This ensures that all components are securely fixed, creating a cohesive unit. The tabs are folded over and directly soldered or welded to PCB strips. This creates a permanent connection that ensures a robust and reliable tab connection, but reduces recyclability. All MOSFETs are mounted on a single board to minimise the risk of breaking component. Cooling is once again handled passively.

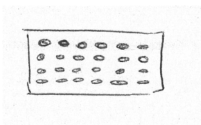




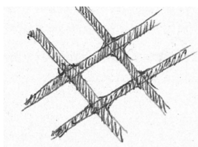
Stacked cell configuration



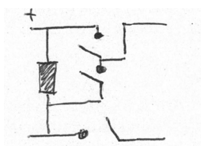
PCBs as wiring



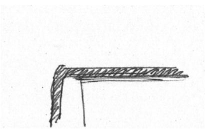
All MOSFETS on one board



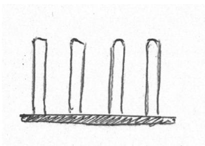
Frame for shock resistance



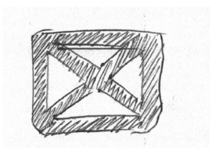
Modules are with DESA structure



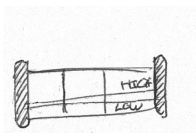
Tabs folded over



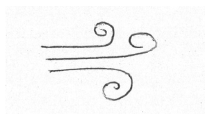
Cells connected to a backplane



Cells covered with a X-pattern



Modules connect in a chain



Passive (air) cooling

Figure 20: concept 3, as durable as possible, including the used sub-problem solutions from the morphological chart to create this concept drawing.

4.3 Design considerations

By combining solutions to sub-problems in the morphological chart, concepts were created. However, during this concept development, it became clear that designing the entire system was still too challenging. Some solutions were consistantly chosen across the design principles, but in many areas vastly different solutions were selected (appendix C). Many concept aspects and sub-problems are inherently interconnected and therefore the different design considerations for each aspect of the battery concept are discussed here. A distinction has also been made regarding the importance of each sub-problem, prioritizing those that must be addressed first. This process ultimately led to a focus on the tab connection for the continuation of the project.

Five detailed sub-problems

During the concept development, it became clear that some sub-problems are more critical at this stage of the design than others. Four key sub-problems significantly influence the overall shape of the module, while the remaining sub-problems pertain to finer details. These details are subject to change as they depend on the decisions made regarding the four main sub-problems. Therefore, they should be designed at a slightly later stage in the project, once the general shape has been determined. These more detailed sub-problems, including their design consideration, are:

1. Cooling: Current bicycle batteries are encased in a flame-retardant plastic, which provides sufficient heat dissipation. Given that the bike's power output remain unchanged, the heat generated by the pouch cells will be expected to be lower than that of cylindrical cells. Pouch cells namely have lower internal resistances and are therefore more efficient (Empower Greentech, 2024). Passive (air) cooling is therefore chosen for every concept as active cooling doesn't seem necessary.

2. Wiring: The choice of wiring depends on the available space and the components that need to be connected. Single wires are generally not ideal, as automating their connection to circuit boards is complex and requires handling each wire individually. Doing it manually would also be costly, time-consuming, and prone to errors. Ribbon cables offer a more efficient alternative, as their parallel structure simplifies automation and facilitates connections between multiple components. Whenever possible, PCBs should be used for wiring, as they allow for mass production with precise control over wiring parameters, ensuring consistency (Sedra et al., 2020). However, PCBs are only practical when the distances between components are short.

3. MOSFETs location: A module consists of four pouch cells, each with 12 tabs that require individual MOSFETs, totalling 48 MOSFETs per module. Placing all 48 MOSFETs on a single board could make repairs more challenging if a single MOSFET fails. An alternative approach is to distribute them across multiple boards, improving repairability. However, this would introduce additional components such as board connectors and screws to keep the board in place, increasing design complexity and cost. Moreover, extra electrical components also pollute the waste stream and make recycling harder. The MOSFETs location must thus be considered carefully.

4. Shock & vibration damage prevention: Structural reinforcement is essential, but its effectiveness on durability can only be assessed after building a prototype. The durability of the battery pack can be evaluated using the LV124 standard automotive testing procedures. As a start, ensure that structures are sufficiently thick and robust to withstand impact without breaking. Also assure that all components are securely mounted, minimizing movement and preventing loosening due to vibration. All three current concepts solely rely on an outer frame without features such as extra padding.

5. Connection between modules (data and power): A connector on the outer side of the module is required for interconnecting modules. Beyond this, the wire connections between modules have minimal impact on the module's design and can be addressed later.

Four main sub-problems

The remaining four sub-problems for the concepts have a significant impact on the outer shape of the individual module. These sub-problems are listed below, along with their design considerations:

1. Cell configuration: The cell configuration is primarily determined by the available space in the battery's outer case. The four cells in a module should be placed close together to minimize wiring distances. A rectangular configuration is preferred over an L-shape or T-shape. The cell configuration also influences the cell thickness. Thin cells with a large surface area are ideal, as they offer better heat dissipation and require fewer layers, reducing the risk of production errors.

2. Holding pouch cells in place: The cells must be securely held in place to prevent movement and avoid damage. However, the pouch cells cannot be mounted at the tabs, as these tabs should not bear any mechanical force. The soft nature of the pouch cell makes containment

more challenging as well, and screwing through them is naturally neither an option. The cells can most likely be secured by compressing them between a structure or by clamping/screwing them at the thin outer border of the pouch, where the aluminium foil is pressed together.

3. Module structure: The outer casing of the module houses all the components and is placed in the outer body provided by the bicycle company. The key question is how to attach the other components once the cells are encased. On one hand, everything must be easily accessible for disassembly; on the other hand, space needs to be optimized to ensure that as much room as possible is occupied by the cells, maximizing energy capacity. Additionally, the method of connecting the module structures to each other must be considered. It should allow for easy disassembly while providing sufficient protection against shocks and vibrations.

4. Reversible tab connector: An electrically and mechanically reliable connection is required for all 12 individual tabs. This connection links the cells to the rest of the module and its control components, making it crucial to the design. The main design considerations include reliability, reversibility, and ease of disassembly, especially given the large number of tab connections.

The tab connector as focus point

Whilst all four of these sub-problems are significantly important, it was found during concept creation that the first three functions are largely influenced by the design of the fourth sub-problem: the tab connector. As a result, a robust and reversible tab connector has been established as the cornerstone of the design, as it will have a significant impact on all other design decisions. The design will therefore be continued with a focus on this connector.

Design steps

- Designing an entire battery pack is still too challenging at this time because many aspects and sub-problems are inherently interconnected.
- A distinction has been made between more detail-oriented aspects of the design and the aspects that need to be adressed first.
- Among the sub-problems, the creation of a mechanically and electrically reliable reversible tab connector for the pouch cells was identified as the most critical challenge for the development of the battery pack.

4.4 Reversible tab connector

Tab connector requirements

The requirements for the connection between the 12 tabs tabs on the pouch cell and the corresponding PCBs are outlined in appendix D. In short, the most important ones are:

1. Ensure a reversible design.
2. Avoid carrying any mechanical load through the connector.
3. Withstand vibrations and shocks caused by cycling.
4. Minimize the steps required for cell replacement.

After reviewing all ideated reversible tab connector solutions from the morphological chart, three that will be outlined in some detail below, emerged as most promising. In addition to having the prospect of meeting many of the outlined requirements, their primary advantage over the other ideas lies in the ability to connect multiple tabs in a single action. This significantly reduces the time needed for cell replacement and might result in fewer components as well. Each solution employs a different method to ensure reliable electrical performance with low resistance. This is achieved through many micro-scale contact points (surface asperities), which can be established by either a large contact area and/or sufficient force to maintain constant surface contact (J. Koudijs, personal communication, October 3, 2024).

Connector 1 : tab-clamp

The first solution features a clamp designed to hold all six tabs securely (figure 21). A constant force is achieved through a snap-fit mechanism at the end of the clamp. The elastic properties of the plastic material ensure consistent surface contact for the connector as well. Copper traces are etched on the inside of the clamp, and multiple ribs, arranged in a W-shape, can be incorporated to provide additional protection against vibrations.

The advantages of this solution are its intuitive ease of use and sturdiness. However, its drawbacks include its relatively large size, difficulty in aligning with the tabs when closing the clamp, the need for enough space to open the clamp, and the fact that a new clamp design with copper traces for the tabs would have to be newly developed. Additionally, vibrations and material fatigue may still pose a significant risk to the connector's reliability.

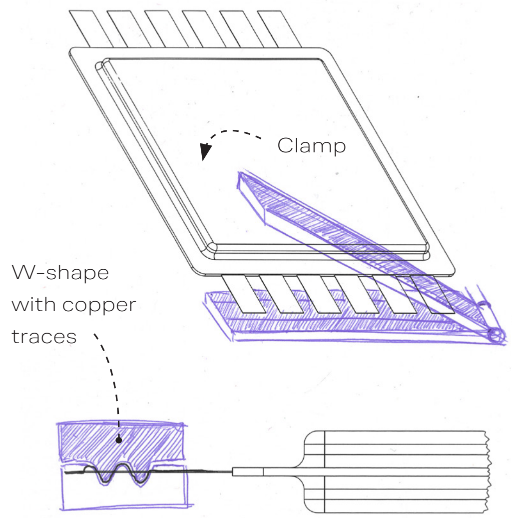


Figure 21: tab connector concept 1 - all tabs on one side of the cell are clamped between a plastic clamp with a W-shape. Copper traces are etched on the ribs of the W-shape to conduct electricity.

Connector 2 : plates with springs

The second idea involves securing the six tabs between two non-conductive plates, with the bottom plate featuring springs on which the tabs must be aligned (figure 22). These springs are equipped with copper traces to ensure good conductivity while also providing resistance to vibrations and shocks.

This design is relatively flat and ensures a reliable electrical connection, as the springs maintain surface contact points at all times. Aligning the tabs is easier since you can check the alignment before placing the top plate. However, screws are vulnerable to vibrations, so anti-loosening screws and screw adhesive must be used to prevent issues. This complicates the (re)assembly process.

Connector 3: laser-welded flexible PCB

The final idea involves laser-welding a flexible PCB directly to the 6 tabs, creating a mechanically strong connection while also ensuring electrical conductivity (figure 23). A standard connector can then be mounted at the end of the PCB, offering flexibility in the choice of connector as long as it can handle the required currents and voltages. The copper traces on the flexible PCB are only exposed at the points where they are welded to the tabs, with all other areas coated in resin. This coating helps prevent short circuits if multiple PCBs come into contact with each other or when the PCB folds onto itself. Furthermore, laser-welding is preferred over ultrasonic welding due to its non-contact nature, which makes it more suitable for flexible PCBs. Flexible PCBs are often delicate and can be damaged by the mechanical stress associated with ultrasonic welding, making laser-welding a better option for preserving their integrity (Andwin Circuits, 2024).

Upsides of this design include its thin profile, inexpensiveness, and the ability to withstand vibrations due to the flexible nature of the PCB, which allows the entire connection to absorb movement. Designing custom copper traces on the flexible PCB is also straightforward, and using a standard connector at the end is a convenient feature as well. A downside is that when the cell is at its end-of-life, the tabs are connected permanently to the tabs. This makes recycling harder as electronics contaminate the battery stream. Another thing to consider is that the flexible material of the PCB does not add mechanical strength to the connection. While the connector is not intended to bear any mechanical load, the other two solutions offer greater rigidity and strength, which is beneficial in case of mild mechanical loads. On the other hand, when unexpected mechanical loads occur, rigid connections might cause the connector or other parts of the pouch cell to break. For this reason, a flexible PCB is chosen over a rigid PCB. Whilst the flexible PCB allows vibration, it is important to make sure tabs from (different) cells do not touch each other or other electrical components, as this might cause an overload of the electrical system.

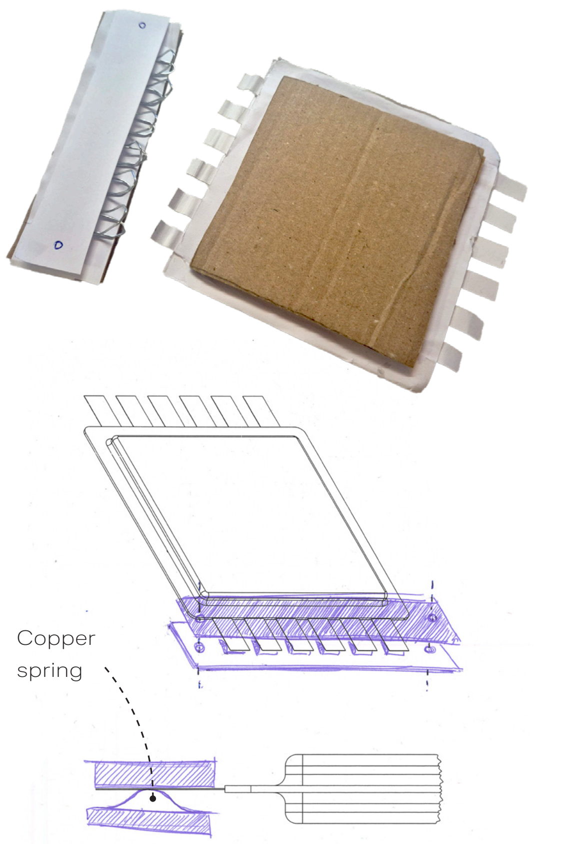


Figure 22: tab connector concept 2 - all tabs from one side of the cell are placed between two non-conductive sheets. Every tab touches an individual spring to ensure good conductivity while also providing resistance to vibrations and shocks.

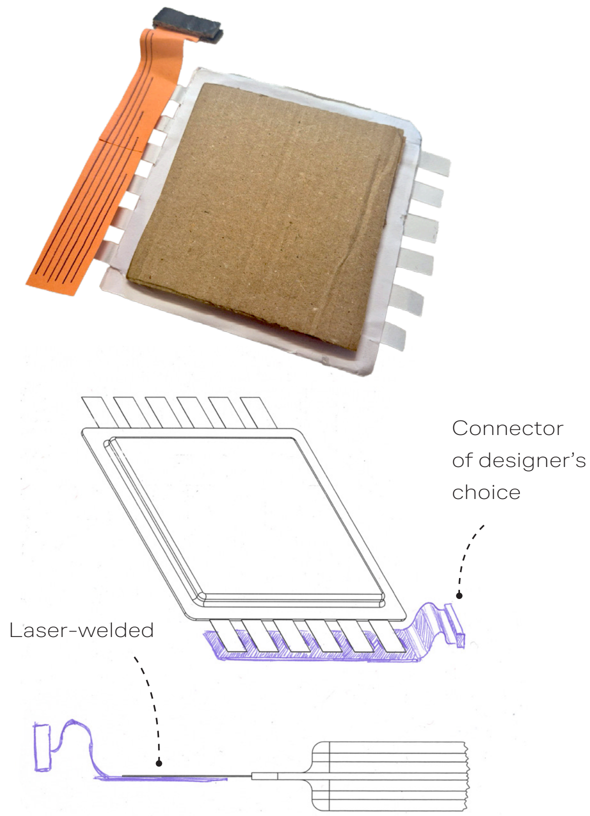


Figure 23: tab connector concept 3 - a flexible PCB is laser-welded directly to the tabs on one side of the cell to create a robust connection. The flexible PCB then ends with a standard connector of the designer's choice.

Choosing a reversible connector

The DATUM method was used to compare the three reversible connector options and identify the most suitable solution for the battery pack design (figure 24). In the DATUM method, one option is designated as the DATUM. Then, the remaining options are compared against it for each assessment criteria, being rated as better (+), worse (-), or the same (S). This process is conducted with a holistic approach. While the method does not provide definitive analytical justification for a single winner, it serves as a valuable decision-making aid (Van Boeijen et al. ,2014).

Initially, "Spring" was randomly selected as the DATUM (figure 24, first round). A comparison of the scores showed that "Clamp" performed similarly to "Spring," though slightly worse. In contrast, "Flex-PCB" demonstrated a clear advantage over the other two options, with numerous pluses and S, and fewer minuses.

For the second round, "Flex-PCB" was chosen as the DATUM to ensure all solutions were compared directly to each other and to validate the assumption that "Flex-PCB" was the best option (figure 24, second round). This comparison confirmed that "Flex-PCB" is the most suitable solution for the battery pack, as the other two options were consistently either equivalent or inferior across the assessment criteria.

While comparable in a few criteria, "Flex-PCB" mainly stood out due to its higher compactness, the use of fewer components and its ability to resist vibration and shock. All of these are great qualities for a battery design in which space is limited. For this reason, the laser-welded flexible PCB connector will be used for the final concept design.

Main insights

- While being similar in many of the assessment criteria to the other two connector concepts, the laser-welded flexible PCB connector excelled in compactness and vibration-resistance.
- The laser-welded flexible PCB connector has therefore been chosen as the connector for the remainder of the project.

CRITERIA	Clamp	Spring	Flex-PCB	Clamp	Spring	Flex-PCB
High compactness	-	•	+	-	-	•
Effective heat dissipation	S	D	S	S	S	D
Minimal steps required for replacement	S	A	S	S	S	A
Ease of production	-	T	S	-	S	T
Fewest possible components	+	U	+	-	-	U
Reliable reversibility of the pouch cell connection	S	M	S	S	S	M
Resistance to shock and vibration	S	•	+	-	-	•
∑ +	1	•	3	0	0	•
∑ -	2	•	0	4	3	•
∑ S	4	•	4	3	4	•
	FIRST ROUND			SECOND ROUND		

Figure 24: two rounds of the DATUM-method, comparing three reversible connector options against seven assessment criteria. Flex-PCB emerged as the most suitable solution for the battery pack.

Figure 25: *an electric bicycle*

5

Final design concept

This chapter presents the final design concept, which acts as a demonstrator for incorporating EAGLEBAT's pouch cells into reconfigurable a bicycle battery system designed for single-cell replacement. It elaborates design considerations across three levels: cell, module, and battery pack. The chapter concludes with an evaluation of the concept's overall performance.

Figure 26: impression of the battery on the rear of a bicycle

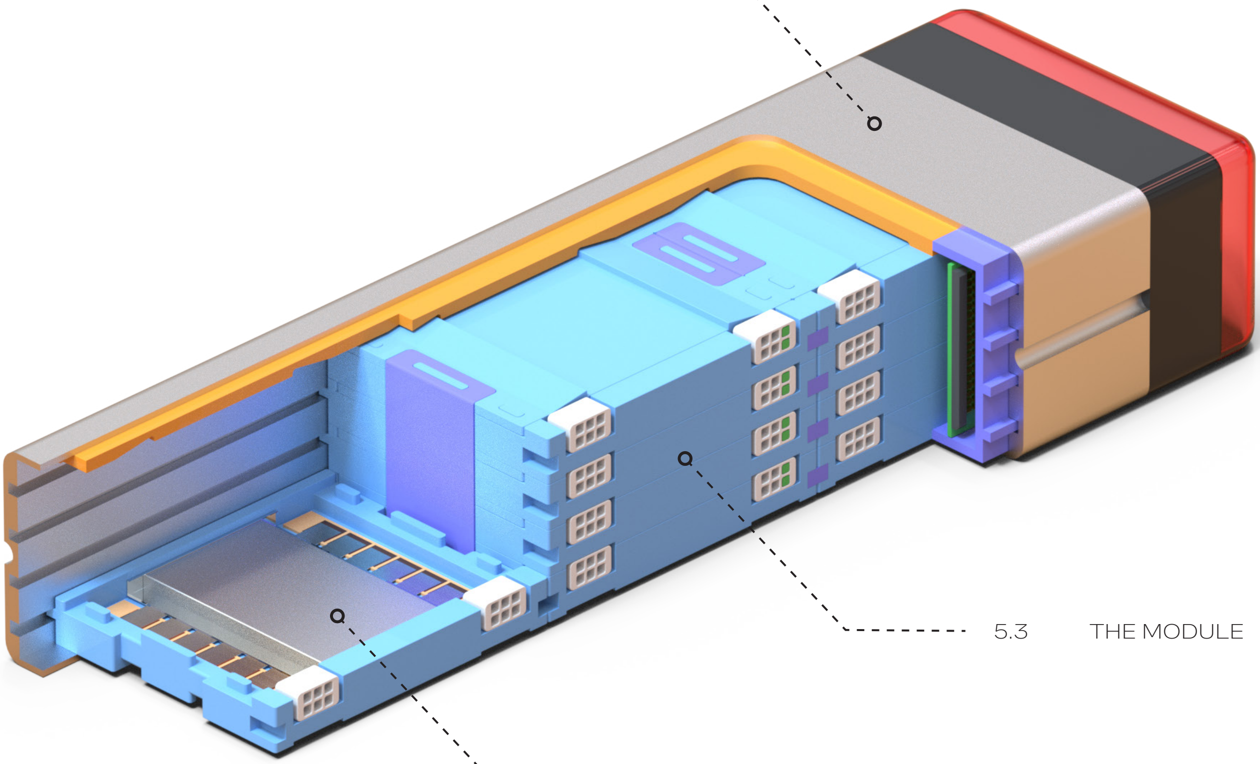


Figure 27: composition of the battery pack.

5.1 Final concept

Boundaries

A final design concept is proposed to show how EAGLEBAT's pouch cells can be integrated into a bicycle battery system that supports single-cell replacement (figure 27). This concept includes decisions made earlier in the project:

- A system with reconfigurable 12V modules is adopted for the design (chapter 3.1).
- A hierarchical Battery Management System structure is implemented (chapter 3.2).
- The cell layout has been determined (chapter 3.3).
- The laser-welded flexible PCB is used as the reversible tab connector (chapter 4.4).

To enable a direct comparison with the Gazelle Gold battery, the concept design uses the same specifications. This includes a rear-mounted configuration with a 36V output and identical outer dimensions.

Demonstrator

The design concept has been developed in accordance with the established design principles outlined in table 3. The primary focus of the design is the laser-welded flexible PCB as the reversible connector choice (figure 28). This concept design serves as a demonstrator for integrating this connector type into a reconfigurable battery pack. Relevant considerations for other design aspects are addressed in the coming sections.

Figure 28: example of a flexible PCB

DESIGN PRINCIPLES	IMPLEMENTATION
Single-cell replacement	The implementation of the laser-welded flexible PCB as reversible tab connector.
Battery safety	A hierarchical Battery Management Structure is used. Cells are fully encased to protect them from external forces. Flame-retardant plastic is used for fire protection in case of internal failure. A DESA structure is recommended to connect modules. IP67 must be pursued.
Space optimisation	The volume of the pouch cells, in regards to the available space, is maximised to get the highest capacity possible.
Durability	The housing structure provides a durable enclosure for the pouch cells. The amount of wiring and connectors used are minimised to reduce system complexity and possible failure points. Components prone to early failure such as connectors are designed to be accessible for replacement.
Ease of disassembley	Care was taken to ensure that all components are easily accessible and require few steps to disassemble. The use of solder and glue is avoided in the design.
Matching current bicycle batteries	Within the same dimensions, the concept design outperforms the Gazelle Gold battery on capacity.
Scalability	A 12V module system has been implemented. The boundaries of the module have been identified as well as the areas where there is flexibility in dimensions.

Table 3: implementation of the seven design principles into the battery pack design

5.2 The pouch cell

Specifications

In this battery pack design, the final dimensions of the active part of the pouch cell (thus excluding the thin outer border where the aluminium is pressed against each other) are 73.4 x 45 mm. Each pouch cell consists of six sub-cells, with each sub-cell containing four anode-cathode pairings, resulting in a total thickness of 9.4 mm (appendix E).

The anode is made of SiFAB, while the cathode is composed of LFP. The cathode has the lowest capacity per cm^2 at 3.7mAh/ cm^2. By factoring in the number of layers, we can calculate the total capacity of a single cell, which amounts to 2.93 Ah per pouch cell. With three modules combining to form 12 cells needed for a 12V battery, the total capacity reaches 35.2 Ah (appendix F), significantly surpassing the previously seen Gazelle Gold battery, which had a capacity of only 11.25Ah.

Tabs

The cell uses 8mm nickel tabs (0.15mm) provided by EAGLEBAT, though future cell designs may incorporate tabs made from different materials. The choice of tab material is up to EAGLEBAT, ensuring compatibility with their cell composition while maintaining low electrical resistance. However, the chosen material must be compatible with the process of laser-welding the tab connector. Naturally, if EAGLEBAT decides to produce pouch cells with less sub-cells, the amount of tabs would decrease as well.

Regarding tab placement, they can theoretically be positioned anywhere along all the sides of the cell as long as there is space available. However, Lee et al. (2020) suggest that placing the anode and cathode tabs on opposite sides is most beneficial for minimizing internal resistance and optimising temperature distribution, ultimately extending the cell's lifespan. Figure 29 illustrates the tab placement in a pouch cell prototype. Aligning the tabs in a straight line also simplifies the tab connection process, enabling multiple tabs to be linked using a single, all-encompassing, straight connector, such as the laser-welded Flex-PCB. This would be much harder if the tabs were placed on all sides of the cell.

EAGLEBAT could experiment with alternating the anode and cathode for each sub-cell, potentially achieving a more uniform temperature distribution. However, this approach would result in alternating positive and negative tabs along the side of the cell, posing a risk of short circuits if the tabs were to come into contact. Given this concern, grouping all tabs of the same pole on one side remains the safer and more practical choice.

Figure 29: a prototype pouch cell highlighting the tab positioning

Laser welded flexible PCB connector

The laser-welded flexible PCB connector is used to connect the tabs to the rest of the battery pack (figure 30). This connector type was chosen for its thin profile and ability to quickly connect multiple tabs through the traces on the flexible PCB. Its flexibility also helps absorb shocks and vibrations from the bike, as the connection can move along with the vibrations. Since the connection area is enclosed, testing is necessary to ensure the connector's durability in its designated space. Apart from the laser-welded area, the flexible PCB is coated in a resin to protect the copper traces.

Another advantage of this tab connector solution is that both the positive and negative pole connectors are now located on the same side of the cell, simplifying future connections (figure 31).

Laser welding was chosen over ultrasonic welding because flexible PCBs can be damaged by the mechanical stress associated with ultrasonic welding, making laser welding a better option for preserving their integrity. Additionally, laser welding offers high precision, fast processing, and adaptability to various materials and complex geometries. It also improves production efficiency and is more environmentally friendly than traditional soldering (Andwin Circuits, 2024). However, challenges include ensuring proper alignment during welding and managing heat dissipation to prevent damage to sensitive components. Laser parameters such as pulse duration, repetition rate, and focal spot size must be tweaked for effective flex PCB laser welding, all impacting the strenght and precision of the weld.

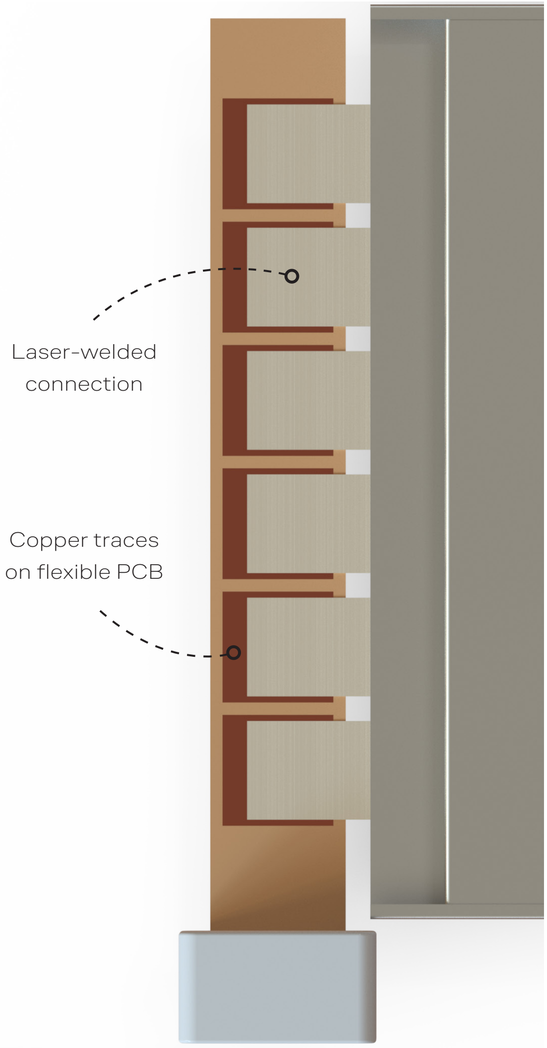


Figure 30: pouch cell tabs are laser-welded to square copper traces on a flexible PCB. This reduces the many required tab connections into one reversible connector.

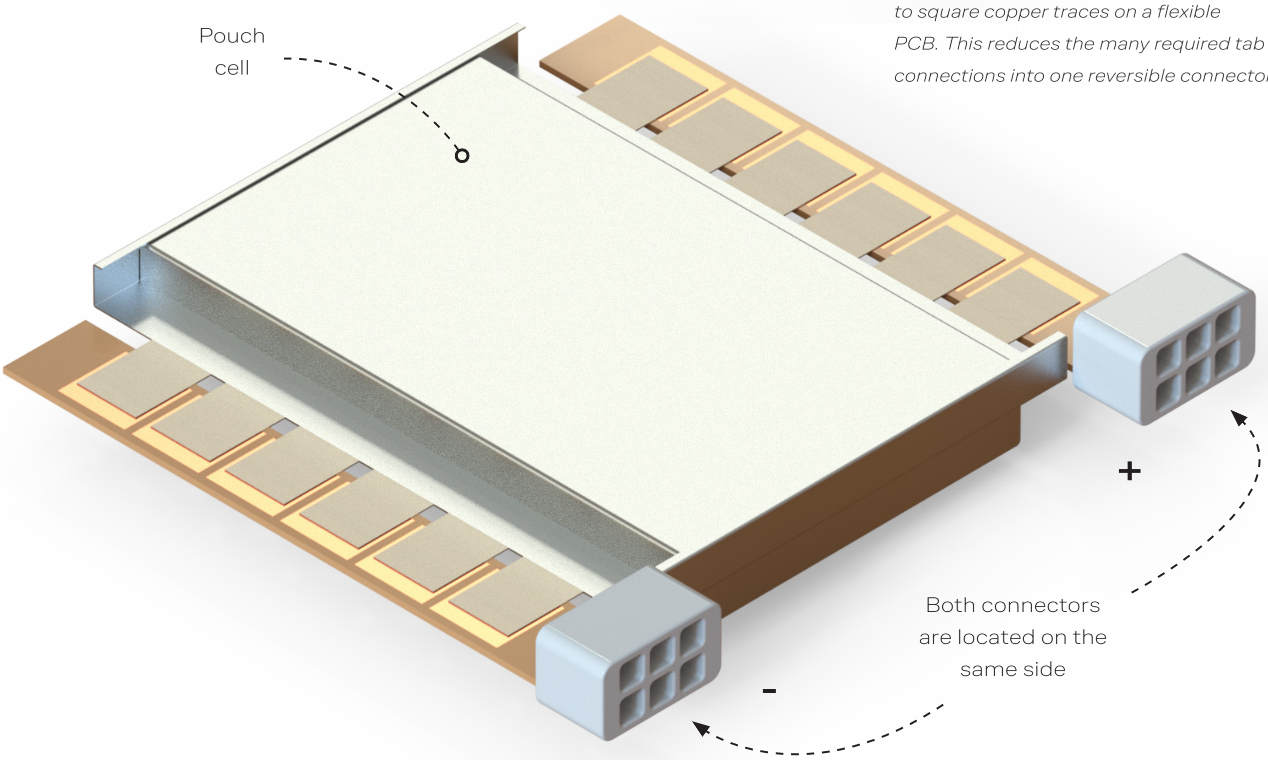


Figure 31: pouch cell with the laser-welded Flex PCB tab connector on each side.

Six-pin connectors

There was consideration of combining the two 6-pin Flex-PCB connectors from the pouch cells into a single 12-pin connector to be connected in the middle of the module PCB. Although two separate 6-pin connectors uses more connector components, they were ultimately chosen for several reasons:

- Combining the two connectors into one would require additional space, which felt wasteful since that space is now used by the pouch cell volume, ultimately increasing the overall capacity (figure 32). For the same reason, the pouch cell border is folded over in figure 33.
- A single connector would also necessitate a larger flexible PCB around the pouch cell, complicating alignment during the laser-welding process.
- In terms of disassembly steps, there is little difference between the two approaches. In both cases, the module PCB (inclusing all connectors) slide onto the pouch cells in one go (see chapter 5.3).
- Having a 6-pin connector on each side offers flexibility for potential future changes in connector type during further development. This could involve a longer flexible PCB or even a completely different connector type, such as one of the other reversible connector options that were previously considered.

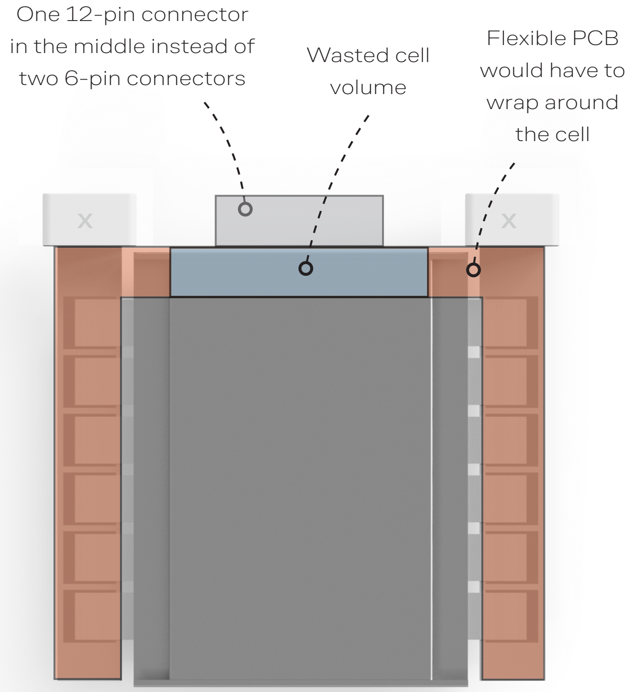


Figure 32: combining both six-pin connectors into one 12-pin connector would result in less cell volume and a more difficult flexible PCB connection.

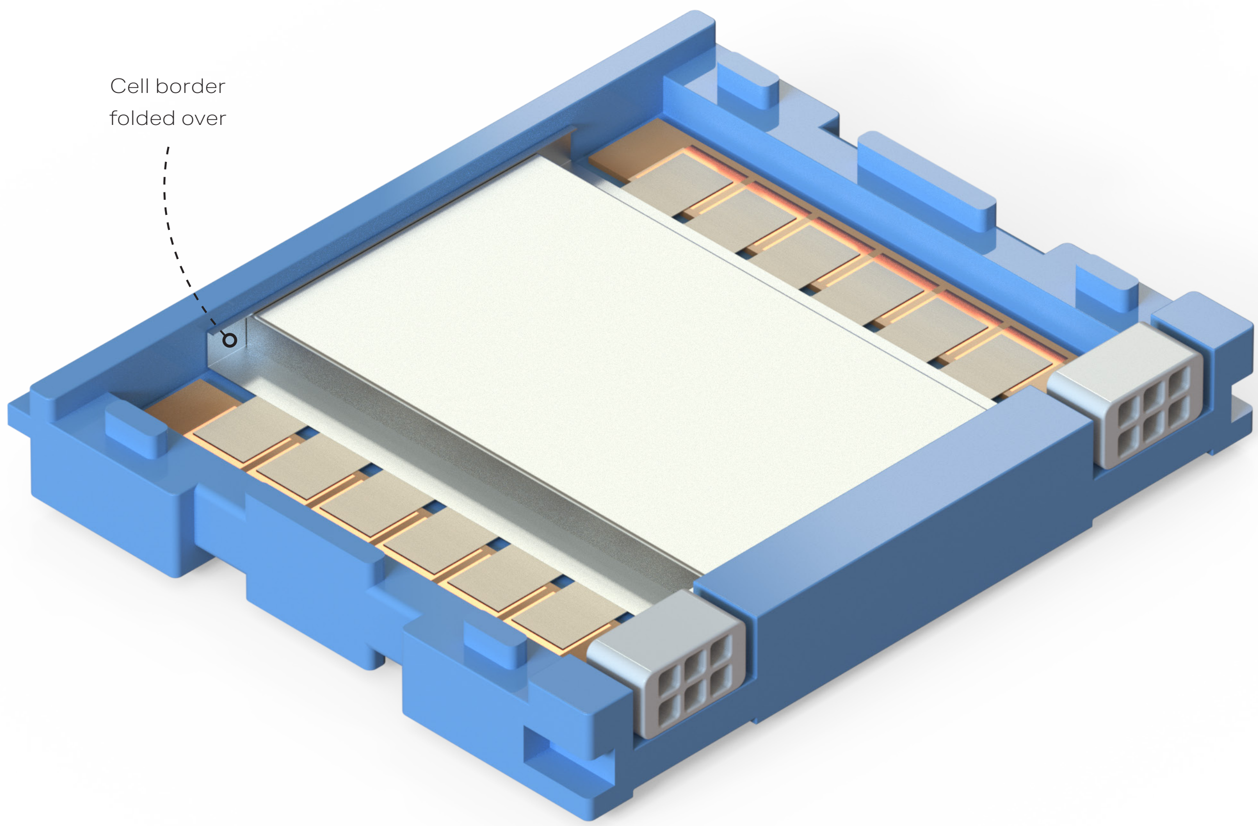


Figure 33: the pouch cell sits securely within its casing, with its edges folded over to maximise cell volume.

Cell enclosure

The goal of the enclosure is to protect the pouch cell from damage caused by external forces such as shocks or vibrations (figure 34). Therefore, the cell is firmly secured within the casing, with a small amount of space left for the vibration of the tabs (figure 35).

Once the pouch cell is placed inside the casing, it does not need to be removed until the end of its life. As a whole, it functions as a unit that can later be repurposed for other applications if the pouch cell is partially degraded. For example, in systems that require less capacity or in stationary systems that can be more easily recharged.

Since the bike's power output remains unchanged, the heat generated by the pouch cells is expected to be lower than that of the cylindrical cells currently in use. This is because pouch cells have lower internal resistance and are therefore more efficient (Empower Greentech, 2024).

No additional measures have been taken for heat dissipation, as existing bicycle batteries do not incorporate such features either. For added safety, a flame-retardant plastic can be used for the casing to help contain a fire in case of a cell failure

Figure 34: *the pouch cell is fully encased into a serviceable unit.*

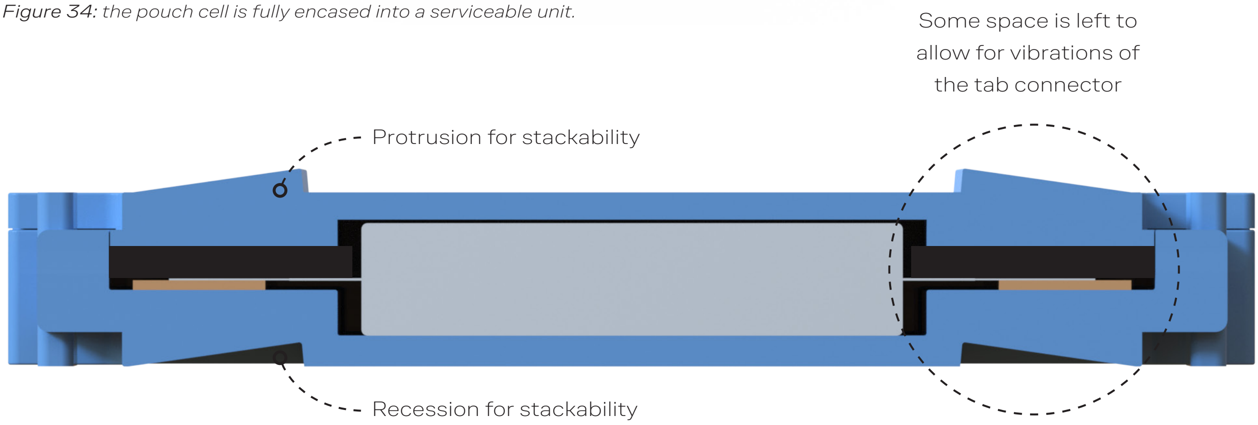


Figure 35: *cross section of the cell enclosure. For protection, the tab connection is covered by two beds.. Some space is left to accommodate vibrations of the tab connector. The cell itself fits securely to prevent any movement. A protrusion and recession in the enclosure are used for stackabilty of multiple cell casings.*

5.3 The module

Cell configuration

This cell orientation of the four cells maximises surface area while maintaining the thinnest possible cells to efficiently utilise the entire module space. Placing the cells sideways would have resulted in thicker cells with a smaller surface area (figure 36). Thinner cells are preferable because they require fewer layers, reducing manufacturing time and minimizing the risk of errors. Additionally, a larger surface area improves heat dissipation, enhancing overall performance.

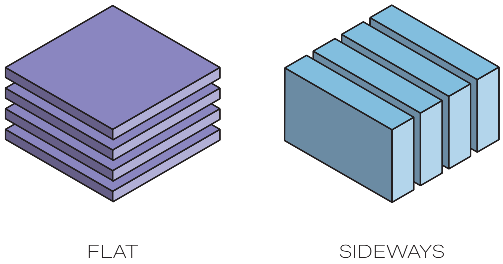
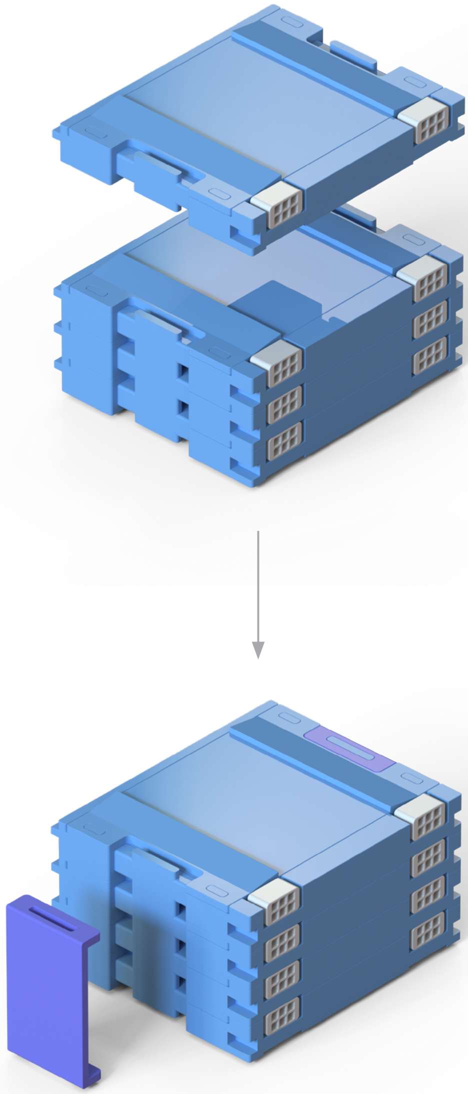


Figure 36: Within the same space, thin cells with a larger surface area are preferred. In this case, a flat configuration is favoured over a sideways arrangement with thicker cells..

Stacking cells

The four pouch cells are stacked on top of each other. To ensure proper alignment, indents are used (figure 37). The stacked cells are then secured together with an overarching clip. This method was chosen because it is the same approach used in Concept 1 that prioritised compactness.



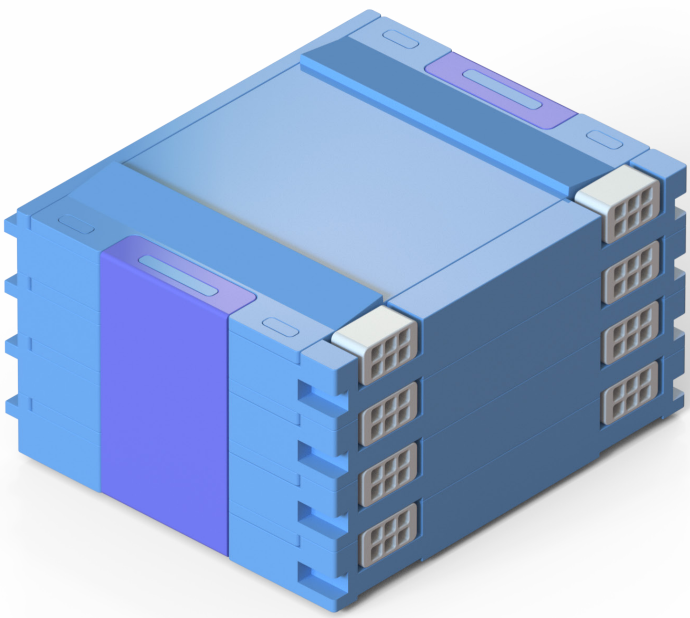


Figure 37: four cells are stacked on top of each other. Then they are secured together with an overarching clip.

Module controller

Each module contains its own local controller Printed Circuit Board (PCB), which handles sensing and communication with the Master Controller. The board includes a chip, sensing components, two connectors for inter-module connections, eight connectors for four pouch cells, and all MOSFETs required to control the sub-cells (figure 38, front).

A module requires 48 MOSFETs to manage the four connected pouch cells. To optimize board space, MOSFET arrays are recommended instead of individual MOSFETs. Due to space constraints, the PCB is elevated to allow the use of both sides for components. The MOSFET arrays are placed on the side facing away from the cells, as the opposite side is occupied by connectors. This placement also provides additional protection against accidental damage as they are not directly reachable (figure 38, back).

Since MOSFETs have a significantly longer lifespan than the pouch cells (W. Legerstee, personal communication, July 22, 2024), all MOSFET arrays will be mounted on a single large module PCB. Through-hole soldering is preferred, as it provides a stronger mount and simplifies replacement in case of failure, despite its slightly higher production cost (DigiSource, n.d.).

The possibility of using multiple boards to facilitate easier MOSFET replacement was considered. However, additional boards and connectors could negatively impact reliability and lifespan, as connectors are more prone to failure than the cells themselves (J. Koudijs, personal communication, October 3, 2024). More components would also increase production costs and assembly time. Given these factors, the use of multiple boards was discarded, especially since the MOSFETs outlast the pouch cells by a significant margin (W. Legerstee, personal communication, July 22, 2024).

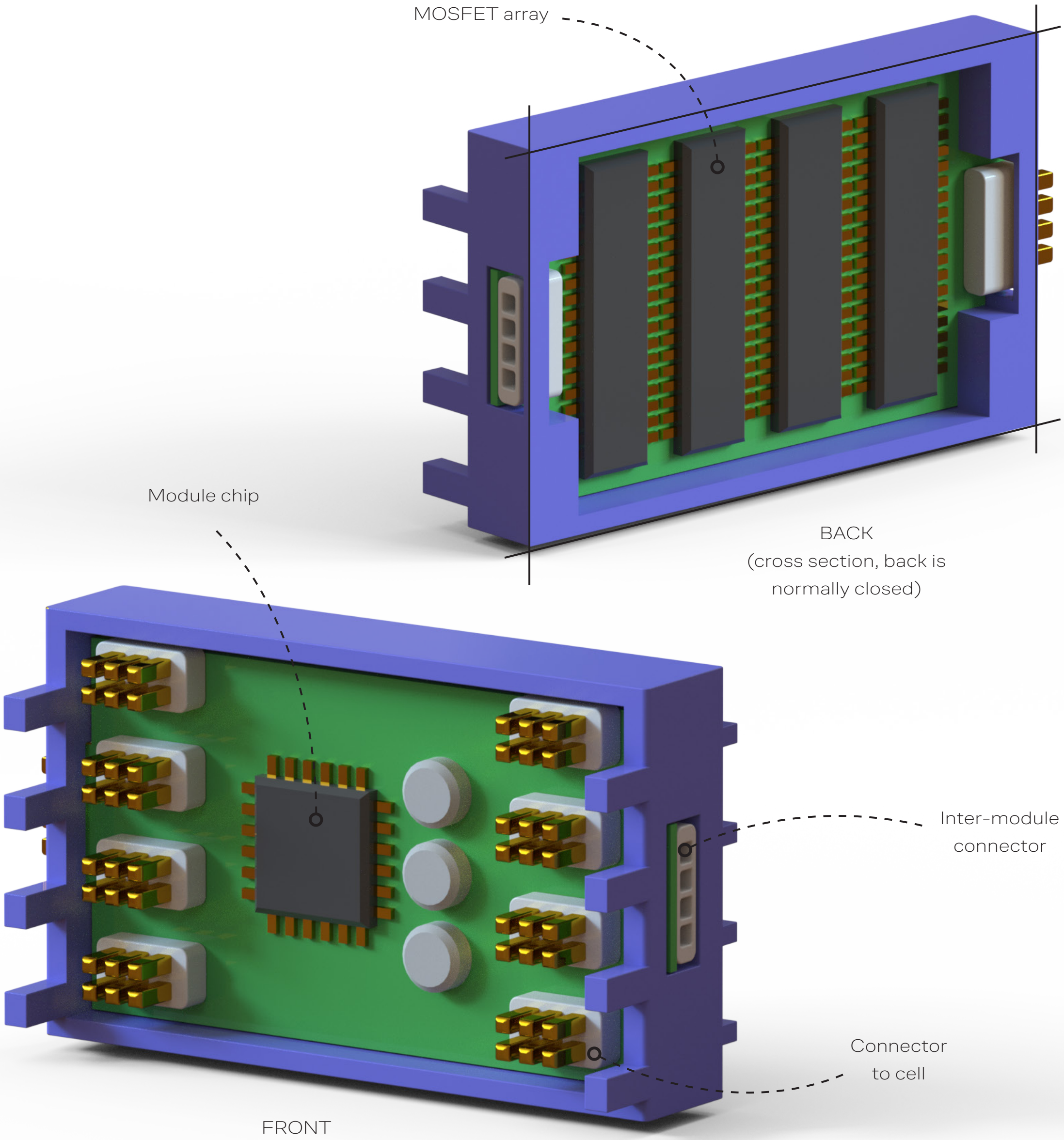


Figure 38: the module controller pcb in its designated part. On the front are connectors to connect to the cells. On the back are MOSFET arrays located.

Connecting cells to the module controller

The module consists of two main parts: one housing the module controller and the other containing the pouch cells (figure 39).

This two-part design allows the module controller to connect seamlessly to the cells in a single motion. Indents on the sides ensure proper alignment, preventing issues when the connectors (pins) engage. However, if alignment proves challenging, alternative connection methods should be explored. An alternative could be the use of ribbon cables between the two parts before sliding them onto each other. This would provide more space to manually attach connectors.

The single-motion concept was still pursued because it significantly reduces disassembly steps compared to connecting each of the eight connectors individually. Additionally, it eliminates the need to reach into tight spaces with fingers, which can be difficult given the limited space. The sensitive components, like the connectors, are positioned in less accessible areas to protect them from external forces. For this reason, the left and right sides must be separable to facilitate easier repair, as internal components would otherwise be inaccessible.

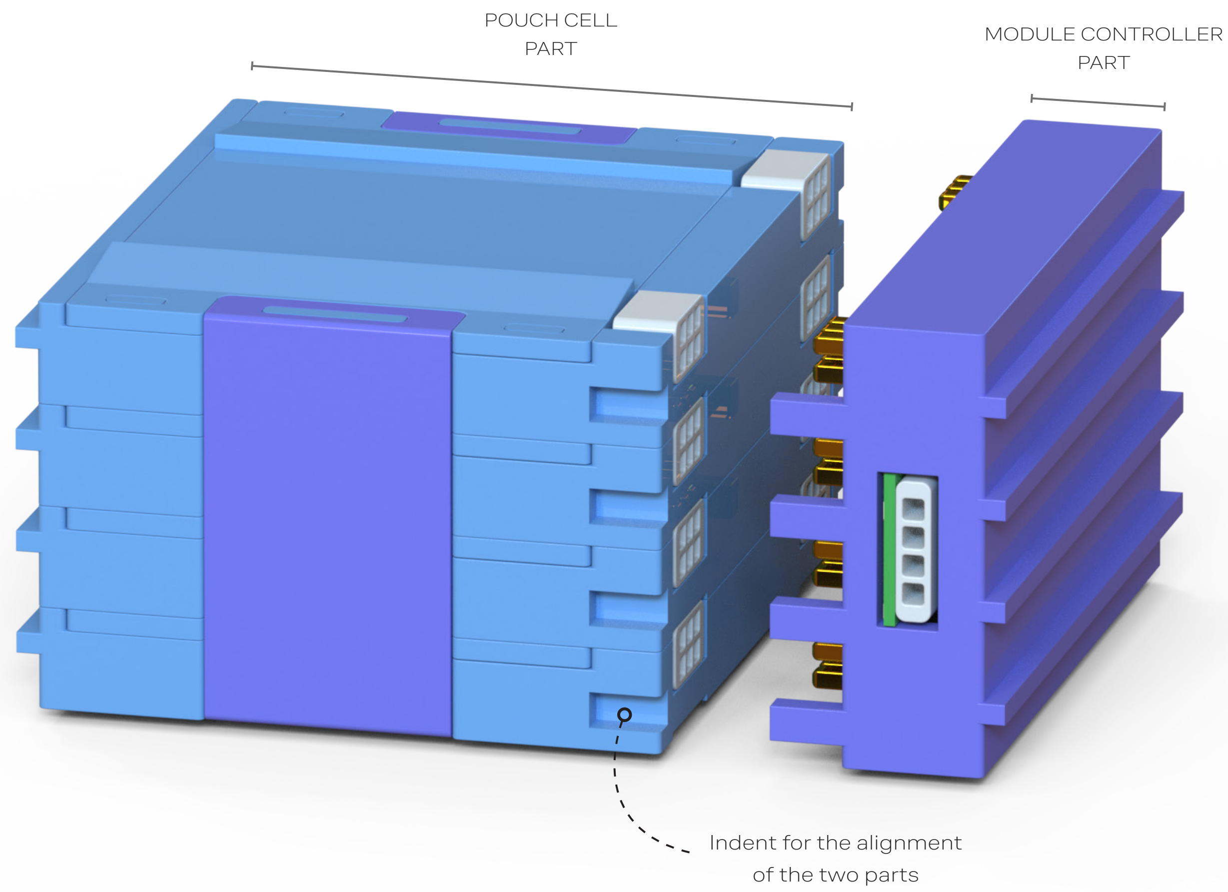


Figure 39: two parts can be joined together to form a module.

5.4 The battery pack

Reconfigurable modules

The battery architecture consists of 12V modules that can be arranged in series to increase voltage and/ or in parallel to increase current. To achieve the required 36V of an electric bicycle, this design incorporates three modules connected in series. Although perhaps not necessary for a bicycle, together with EAGLEBAT was decided to still pursue a reconfigurable system because of the strong potential for their pouch cell technology to be applied in markets beyond bicycles, where such a system would be advantageous.

Connecting modules

Multiple modules are placed behind each other inside the battery's outer casing (figure 40). Grooves on the sides ensure they remain securely in place. Before sliding the modules in, a top plate is added to align them, hold them together, and fill any remaining space to prevent movement.

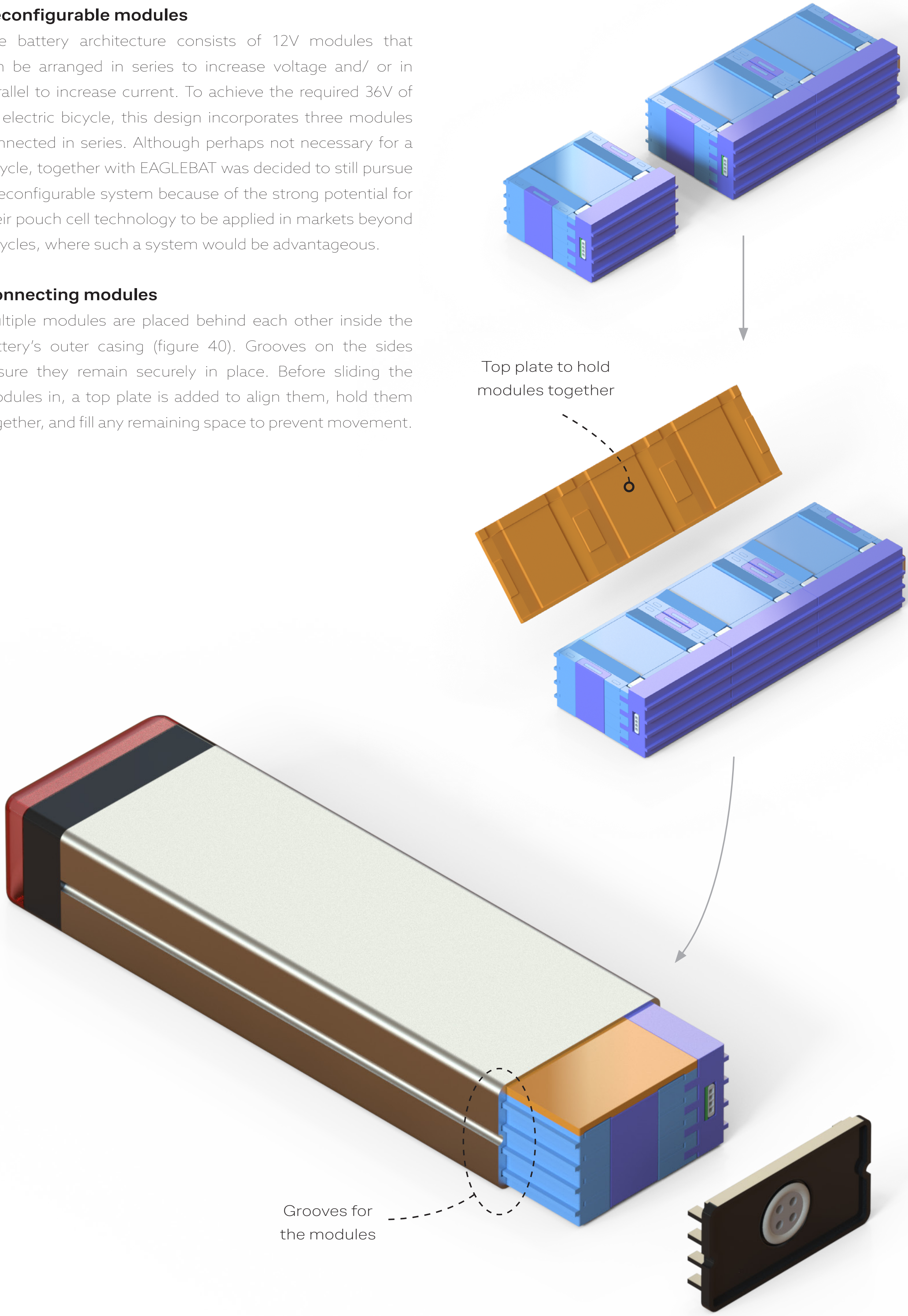


Figure 40: assembly of modules into a battery pack.

Master Controller

At the front of the module row is the main PCB, which houses the components for the Master Controller (figure 41). As part of the hierarchical Battery Management System (BMS), the Master Controller oversees the operations of the modules and performs primary computations, while local sensing is done within each module. The placement of the main PCB is flexible and can, for example, be mounted to the side of the first module.

Outer body

The internal battery architecture is housed within an external casing provided by the bicycle manufacturer. For the concept design, the design language of the Gazelle Gold battery has been used as a reference. As a result, the battery's outer dimensions are 365 x 120 x 60 mm. The casing is constructed from aluminium and the grooves along the sides have been replicated, which are used to secure the battery to the bicycle. An integrated bicycle light is located at the end of the casing. The charger plug is positioned at the beginning, where the battery also connects to the bicycle.

Outdoor protection

Protecting the interior of the battery pack from dust and water is very important. For outdoor use, the battery must meet an IP67 rating to withstand the rain and dust it will inevitably encounter. IP67 ensures the battery is completely dust-tight, offering full protection against dust ingress, and capable of withstanding temporary immersion in water up to 1 meter deep for 30 minutes without water penetrating the enclosure (IEC 60529 standard). As the outer casing is provided by the bicycle manufacturer, it is important to arrange agreements with them to ensure the casing meets these IP ratings. To maintain this level of protection while allowing for maintenance, gaskets or O-rings made from silicone or EPDM could be used (AppleRubber, 2020). Unlike permanent sealants, which hinder disassembly, these alternatives provide a reliable barrier while enabling easy access for maintenance tasks.

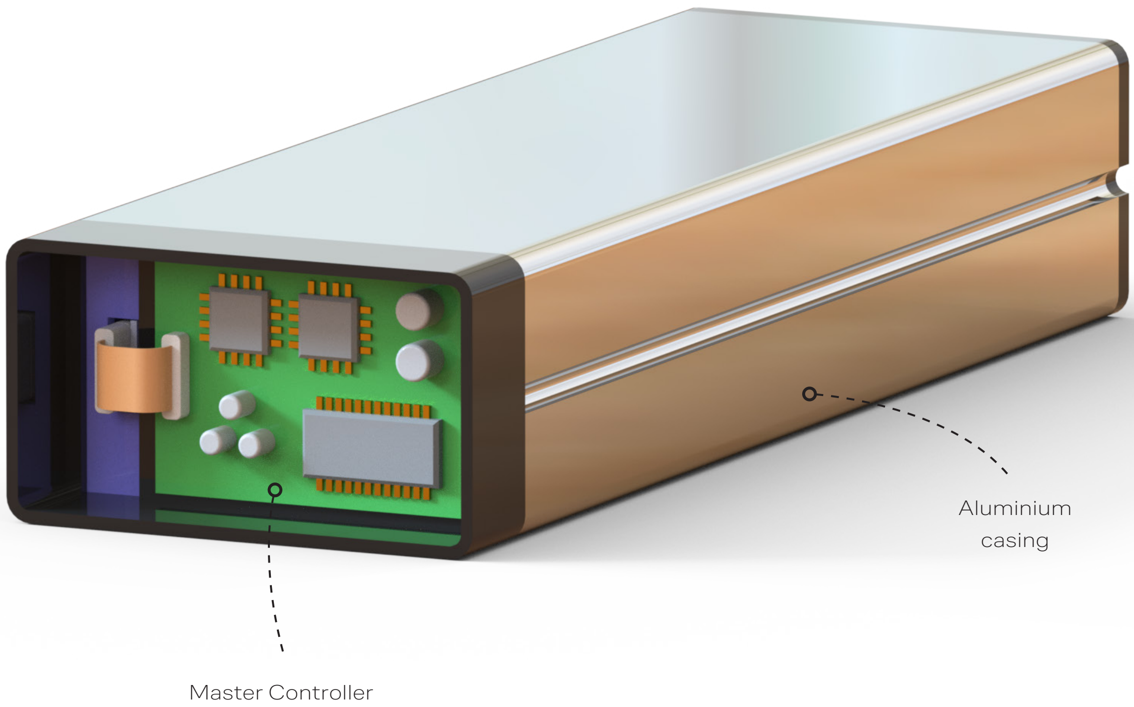


Figure 41: the Master Controller is located at the front of the battery pack. It oversees the operations of the modules and performs primary computations.

Communication protocol

The I2C protocol is recommended, as it is a two-wire serial communication method that enables communication between multiple devices using just two lines. In this case, it facilitates communication between the modules and the Master Controller (appendix G). This protocol is ideal for the battery pack due to the small number of components and short distances between them (M. Verwaal, personal communication, October 8, 2024).

Power transfer

Modules must be connected differently when wired in series compared to when connected in parallel. This presents a challenge when aiming for identical modules in a modular design. To address this, a solution is proposed that uses clever circuitry to ensure that modules can be connected in the same way each time, regardless of configuration.

The proposed setup is referred to as a DESA structure (see appendix H), which ensures consistent connections between the modules (positive-to-positive, negative-to-negative). By utilizing specific circuitry and switches (such as MOSFETs), the flow of electricity is controlled, allowing for both series and parallel connections with the same circuitry (Muhammad et al., 2019). As a result, all modules are connected in the same manner, and the configuration of the modules is determined digitally.

Altough the DESA structure requires three extra MOSFETs per module, incorporating this structure into the modules is worthwhile. Each module already includes a local controller chip, making implementation easier. The other benefits of this structure include:

- The setup is controlled digitally, improving safety by preventing incorrect power connections between modules and eliminating the possibility of manual errors.
- Incompatible, unbalanced series-parallel module configurations are no longer possible.
- Power between modules can be completely shut off, which is especially useful during maintenance, allowing for safe disconnection of modules.
- It can function as a fuse, protecting the system in case the currents exceed safe levels.

Four-Pin connector

A four-pin connector is required between modules, with two pins for the I2C connection and two additional pins for the positive and negative power connections. It is essential that the connector be designed so it can only be plugged in one way to prevent incorrect connections. Additionally, the connector must be lockable to ensure it does not come loose due to vibrations.

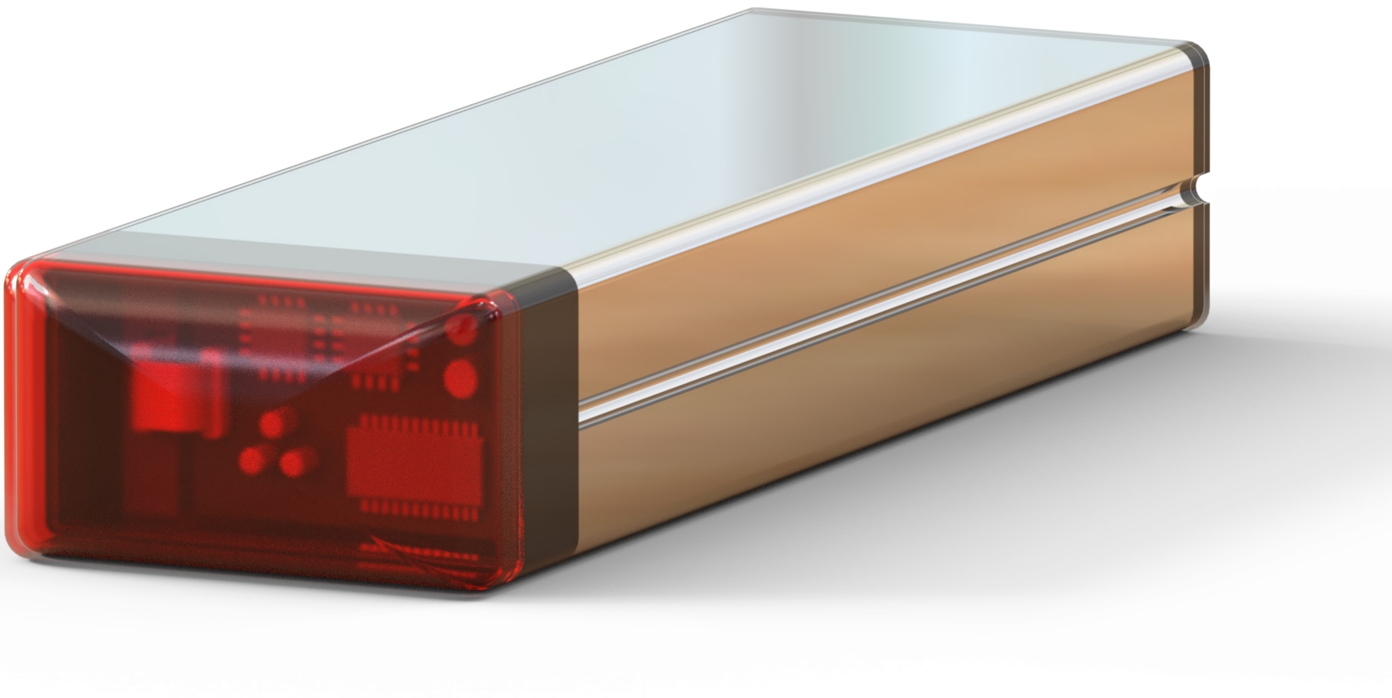


Figure 42: impression of the fully assembled battery pack.

5.5 Concept evaluation

Feasibility

The concept design is still in its early stages, but has been approached with a realistic perspective. The plastic casing and printed circuit boards are well-established technologies and can be manufactured once the design is further developed. For elements that are not yet fully detailed, relevant design considerations have been outlined.

The laser-welded flexible PCB tab connector is more experimental, yet promising. While laser welding to a flexible PCB is not a new technique, it remains relatively uncommon. Achieving a precise and strong weld will require finetuning of multiple variables.

Desirability

From a consumer perspective, the people who ride bicycles, batteries are seen as mostly a "black box." As long as they work and have sufficient capacity, the internal details don't really matter to them. Since a battery is included with a new electric bicycle, they will only seek a replacement when the original battery degrades or when they purchase a second-hand bicycle. In those cases, price and capacity are the primary factors to the consumer. Given that this design offers significantly higher capacity than current batteries, this design may be attractive to them.

For bicycle manufacturers, they already have proprietary battery systems designed to fit exclusively in their own bicycles, ensuring customer loyalty. Implementing a cell reuse system would require additional effort and resources, which they may be reluctant to invest in. However, the increased capacity of this design would certainly appeal to them. That said, they are more likely to only adopt the pouch cell technology without prioritising the ease of disassembly (no solder and excessive use of glue) that this concept provides.

For the client, EAGLEBAT, this concept illustrates how their pouch cell technology can be implemented into a reconfigurable bicycle battery system. It aligns with the design goal we originally set at the beginning of the project. While it demonstrates the potential for replacing pouch cells, it is also the first design developed with their technology, exposing many challenges as well. Therefore, the research conducted to develop this concept is just as valuable to them as the design itself.

Additionally, a solution was proposed for one of the main encountered challenges. The reversible tab connector, in the form of a laser-welded flexible PCB, solves their problem of connecting the many individual tab connections required for their technology with sub-cells.

Viability

Penetrating the already quite saturated bicycle market might be difficult. Therefore, it is not unthinkable that other markets or use cases will be explored. Specifically in areas where a reconfigurable system offers greater advantages than it does for bicycles or where the lower weight and higher energy density of pouch cells can be better utilised. During the project, doubts already emerged about whether a reconfigurable system is necessary for bicycles, especially since facilitating this system takes up a lot of space in the battery pack. However, in collaboration with EAGLEBAT, it was decided that this structure would still be pursued due to the battery's potential in other markets.

However, when the bike batteries are used in a system where they are returned once their capacity has degraded, this design will be effective. By minimising disassembly steps, it can be a significant step toward circular batteries.

If EAGLEBAT decides to explore different markets or discards the reconfigurable modules aspect, the laser-welded flexible PCB tab connector remains applicable. If flexible PCBs prove unsuitable for other use cases, rigid PCBs can be reconsidered.

6. Discussion

Design process

As a newly established start-up, EAGLEBAT has primarily focused on the development of their pouch cell technology, leaving many other aspects largely unexplored. As an industrial designer, I am the first to approach the product as a cohesive whole rather than as separate components. For this reason, the double diamond methodology is well-suited to guide the project. Initially, the goal was to achieve a detailed final design. However, as the project progressed, it became clear that establishing boundary conditions, such as the cell layout and Battery Management System structure, was necessary due to the overall complexity of the project. Consequently, more focus went towards research and exploration, resulting in perhaps a less detailed final design than initially anticipated.

The ideation process ultimately resulted in a connector choice. Identifying the importance of the connector earlier on might have led to a different project focus, likely emphasizing the connector's design and functionality. However, the preceding research was needed to establish the assessment criteria for the connector and other aspects of the product. Moreover, taking a broader, more holistic approach to the project also seemed more valuable for EAGLEBAT at this early stage of their journey. Part of this approach was the creation of the morphological chart. Not only does this chart provide an overview of initial ideation on many of their product aspects, it also functions as a starting point for future ideation by others.

The DATUM method was used to select the connector design. While this method is effective for comparing ideas, it does not evaluate the absolute quality of each idea against the assessment criteria. Consequently, the chosen outcomes might differ for different people due to different reasoning or understanding. It is the designer's responsibility to add nuance and interpret the results thoughtfully. Through clear reasoning, three ideas were narrowed down, and the Flex-PCB connector emerged as the best option among them with the support of the DATUM method. However, this does not mean this connector design is the best option in all scenarios. This project has taken the Flex-PCB as focus point and has formed the battery design around it. If the battery design changes , for example due to factors such as different space constraints or durability requirements, alternative solutions may prove to be more beneficial.

This stems from the approach to break down the design into sub-problems, which makes complex designs more manageable by focusing on smaller parts individually. While this can enhance comprehension, it may also lead to sub-optimisation. Solutions that work well for individual sub-problems might not integrate seamlessly with the overall design. Since a design is the result of multiple interconnected choices, designers must periodically step back, assess the bigger picture, and ensure the design remains on the right track. If necessary, previously discarded solutions should be reconsidered to achieve better overall synergy.

Validity of the design

The final proposed concept acts as an illustration of how single-cell replacement could be possible within a bicycle battery. The concept is a culmination of all insights gathered throughout the project resulting in a design that follows the established design principles. Although several concepts were shown during the ideation phase, the final concept seems to emerge somewhat unexpectedly. The final concept is built around the Flex-PCB connector, with a primary focus on space efficiency to maximize the battery pack's capacity. The Flex-PCB connector was selected using the DATUM method, but other aspects, such as the shape as the plastic module casing, were decided much more quickly for demonstration purposes. Further research into areas like heat management and mechanical strength could lead to alternative design choices.

Moreover, the final concept is designed for a rear-mounted battery, but many bicycles have batteries integrated in their frame as well. This changes the available dimensions drastically, ultimately leading to different design decisions. As an alternative, EAGLEBAT could shift their focus to production processes that accommodate different pouch cell sizes and component placements. This scalability would better suit the needs of various bicycle manufacturers and allow for the production of both rear-mounted and in-frame batteries. On the contrary, this would negatively impact the ability to repair bicycle batteries, which benefit more from standard size modules. For this reason, EAGLEBAT must be very careful with their choice for module size, where the location of application, recyclability and durability must all be balanced. Possible options could be two product types (one for in-frame and one for rear-end), or more flexibility through a seperation into "energy" modules with only pouch cells and "control" modules which would house the other electronics.

It could also be argued that the necessity of a reconfigurable system with 12V modules for a bicycle battery is debatable and likely unnecessary. Such systems are more desirable for larger setups with greater variations in voltage and capacity requirements. This could mean that the tab connector design must be adjusted as well, because the pouch cells would be placed differently within a bicycle battery without modules. On the other hand, the Flex-PCB connector does provide a thin and vibration-resistant connection to multiple tabs at once, which will be useful in systems without modules as well.

That said, the project has stayed true to its initial design goal of: "*to design and build prototypes that explore ways for a reconfigurable battery system that enables the possibility of replacing individual battery cells during repair*". Although not many functional prototypes were build, the final concept does encapsulate a concept design for this statement. This design, in combination with all the insights gained during the project, provides a solid foundation for future development of EAGLEBAT's product.

Limitations

Even though reuse of cells and ease of disassembly have been a major aspect of design choices, the extent to which these can actually be performed stays ambiguous due to the conceptual nature of the end product. Easy of disassembly could have been reviewed with a disassembly map, but this has not yet been done because of the lack of detail concerning the components in the design. Furthermore, while the design seems to be durable, no quantitative indications can yet be given concerning its life-cycle or end-of-life as this requires specific testing. The concept design's casing has been modelled with a similar outer aluminium structure as the Gazelle Gold battery and with similar inner thicknesses regarding the plastic casings of the cells. However, this does not guarantee that the level of durability will be the same. Recyclability has also not been thoroughly addressed either other than the prevention of glue. Both for durability and recyclability, the amount of electrical components such as PCB connectors has been minimised. On the other hand, laser-welding the flexible PCB directly to the tabs does contaminate the waste stream at the end-of-life of the pouch cells.

Also the structural design remains conceptual at this stage. Earlier implementation of prototyping steps could have significantly enhanced the structural details of the design. However, due to external constraints, these steps could not be undertaken as planned. Investing more time in physical prototyping would likely have produced a more detailed and robust structural concept.

Lastly, the absence of an actual EAGLEBAT pouch cell posed challenges in designing the battery pack. A physical sample would have provided a better understanding of the cell's characteristics. Additionally, the slow progress in battery development left many questions about the cell unanswered by EAGLEBAT until later in the project. As an alternative, a non-functioning cell was prototyped.

Alternative markets

EAGLEBAT needs to carefully assess their business model for the bicycle battery. They currently propose a leasing system to ensure batteries are returned for reuse and repair when their capacity degrades. However, it is unclear how this would fit into their business-to-business strategy, in which they supply the internal battery architecture while the bicycle manufacturer provides the outer casing. Entering the market directly would also be challenging due to the wide range of existing battery options. Although a significantly higher capacity will certainly appeal to consumers, it's worth noting that batteries are often included with the purchase of a bicycle, reducing the demand for standalone battery purchases.

Alternative markets could therefore be explored that also benefit from the advantages offered by their pouch cell technology. This approach also presents an opportunity to optimize the ratio between cell volume and control components, as the current design allocates a relatively large amount of space to control components, which are not yet being utilized to their full potential.

The first proposed market is the mobile phone industry, which already utilizes pouch cells and could significantly benefit from the extended lifespan offered by EAGLEBAT's technology. Given the smaller scale and the presence of a single battery per phone, this market would allow EAGLEBAT to concentrate solely on their pouch cell technology of controlling the individual sub-cells, sidestepping their current objective of developing a reconfigurable system as well. However, they would have to transfer to a design with lower peak currents, which might make a market switch harder to realise. Additionally, this market may align less with their sustainability goals, as many phones, and thus their batteries, are typically discarded after only a few years.

In contrast to the phone market, another option is to scale up significantly beyond bicycles. Industries such as automotive and aviation could greatly benefit from the advantages that pouch cells offer. Higher energy density and lower weight compared to cylindrical cells are critical factors in these markets. While the control components would need to handle much higher voltages and capacities, the core principles of the concept design are scalable. Notably, the laser-welded flexible PCB connection becomes even more important in a system with a large number of cells and tabs, providing an efficient method for connecting multiple MOSFETs to their respective sub-cells. Additionally, pouch cells for applications like cars would likely consist of more sub-cells than the current design used for bicycle batteries. For larger, more complex systems such as cars, a partially distributed BMS is recommended over the current hierarchical structure to effectively handle the increased complexity.

7. Recommendations

Design detailing

The final design is still far from being developed into a finished product. Instead, it represents a broader conceptual design demonstrating how EAGLEBAT's pouch cell technology could be integrated into a more sustainable bicycle battery. A potential solution for a reversible connector has been identified and shows promise for future battery development. However, a couple of areas that require further in-depth research are discussed here.

The laser-welded flexible connector appears to be promising solution for creating a reversible connector capable of making multiple separate connections simultaneously. Laser welding flexible PCBs is an emerging technology, but involves tweaking numerous parameters to achieve optimal results (Andwin Circuits, 2024). Extensive experimentation is therefore required to ensure that nickel tabs can precisely and reliably be bonded to the flexible PCB. After that the durability and strength for the connector as a whole can be tested.

Securing the soft aluminium pouch cell within the module remains an important challenge in further development. Along with the connector selection, the structural design will have the greatest impact on the overall design. It is recommended to prioritize the development of this structure before proceeding with other components.

It is currently anticipated that active cooling will not be necessary, as the Gazelle example battery operated without it. Given that the bike's power output remain unchanged, the heat generated by the pouch cells will be expected to be lower than that of cylindrical cells. Pouch cells namely have lower internal resistances and are therefore more efficient. However, this assumption can only be validated once an actual EAGLEBAT cell has been produced and tested. If necessary, aluminium casings or heat plates can be investigated.

Lastly, a Battery Management System structure (BMS) has been chosen, but the actual electrical design of the BMS must be performed by an expert.

Durability testing

While durability and resistance to conditions such as heat, vibration, and shock have been considered throughout the project, the true performance of a product can only be determined through actual testing. These conditions must not be underestimated and the battery must comply with the UL2271 standard for batteries for use in light electric vehicle applications. It is also recommended to consult the VW8000 document when more advanced battery prototypes are developed (Volkswagen, 2017). This document not only outlines the LV124 standard automotive testing procedures, but also provides examples of tests conducted by Volkswagen.

End-of-life

The use of modules simplifies the replacement of entire units and provides easier access to individual cells when needed, improving both disassembly and recyclability because components can be pre-separated. However, as the design evolves, a comprehensive disassembly map should be created to critically evaluate the disassembly process. This should include user testing with EAGLEBAT employees, who will be responsible for cell replacements. Additionally, recyclability should be further assessed and enhanced where possible, primarily by minimizing the variety of (electrical) components in the waste stream and avoiding the use of critical materials. Consulting an expert in this field is advised.

8. Conclusions

This report has presented the design process and results of a reconfigurable bicycle battery pack with replaceable pouch cells.

Research was performed in several areas, including the challenges of disassembling existing batteries and battery safety features. Different cell types, EAGLEBAT's pouch cell technology, and a variety of joining techniques are discussed as well. This research has provided a solid understanding of the context at hand.

Then, several boundaries were defined. A reconfigurable system consisting of 12V modules was introduced, a Battery Management System was selected, and a cell layout was determined. In the end, several design principles are formulated..

Next, development started with dividing the problem into sub-problems. Solutions for these sub-problems were ideated and collected in a morphological chart. This chart was used to create three concepts based on the previously established design principles. After evaluating these concepts, design considerations were laid out, and a focus on a durable reversible tab connector emerged. Three tab connectors were elaborated, and through the DATUM method, the laser-welded flexible PCB tab connector was selected as the most suitable.

All insight were then combined into a final design concept that serves as a demonstrator for how the laser-welded flexible PCB tab connector can be integrated into reconfigurable battery pack with replaceable pouch cells.

The main question that this project aimed to answer is:

"Can we create a reconfigurable bicycle battery pack that enables the possibility of replacing individual pouch cells during repair?"

The proposed concept for a rear-mounted bicycle battery consists of three 12V modules connected in series. Each module is composed of four pouch cells, which are further divided into six sub-cells. To extend the overall lifespan of the pouch cells, each sub-cell is individually controlled using MOSFETs.

To facilitate durable and reversible connections to the numerous cell tabs, a thin, laser-welded flexible PCB connector is proposed. Its flexibility allows it to absorb shocks and vibrations while efficiently managing the many individual connections required between cell tabs and MOSFETs.

The battery design prioritises maximising cell volume within the available space in order to achieve the highest possible battery capacity. Additionally, considerations have been made for durability and ease of disassembly. Proposals have also been provided for aspects such as the Battery Management System, heat dissipation, and inter-module connections. Various steps for further development are listed in the recommendations.

Although EAGLEBAT's pouch cell technology is still in its early stages, and its suitability for the bicycle market may be questioned, the answer to the main question is that developing a reconfigurable bicycle battery pack with replaceable pouch cells is in fact possible.

Terminology list

TERM	EXPLANATION
Ampere	Often referred to as amp, this is a unit of measurement of the battery current represented by unit I.
Anode	The anode is the negative (e) electrode inside the battery cell. It is the opposite of the cathode.
Battery Management System (BMS)	The BMS is the control system within the battery pack that consists of one or more electronic controllers that manage charging and discharging, monitor the temperature and voltage, communicate with the vehicle system, balance the cells, and manage the safety functionality of the battery pack.
Battery pack	The battery pack is a term designating an assembly of mechanically and electrically connected cells, modules, control electronics, thermal management systems, battery management systems, mechanical structures, and enclosures. In essence it is everything that is in the battery box. The battery pack is often the final form the product takes before it is assembled into the end applica-tion.
Capacity	Capacity is measured in ampere hours (Ah) and is a measure of the amount of energy in a system. Think of capacity as being analogous to the size of the hose through which water may flow. Larger capacity is equal to a larger hose.
Cathode	The cathode is the positive (þ) electrode inside the battery cell. It is the opposite of the anode.
Cell	Cells are the foundational elements in constructing a battery pack and are the components in which power is stored. Cells comprise of three key components: the cathode (positive electrode), the anode (negative electrode), and the separator.
Current	Current is the measurement of the flow of electrical charge, which may be carried by electrons moving through a wire or circuit board and by ions moving through an electrolyte between the anode and cathode.
Cycle	Current is the measurement of the flow of electrical charge, which may be carried by electrons moving through a wire or circuit board and by ions moving through an electrolyte between the anode and cathode.
Electrodes	The term electrodes refers to the pair of the anode and cathode when it is assembled in a battery cell. The anode uses an aluminium film with graphite or another anodic material coated on the film whereas the cathode uses a copper film with a cathode material coated on the film.
Electrolyte	The electrolyte is liquid, gel, or other material used as the medium to transfer lithium-ions back and forth between the anode and cathode inside the cell.
End-of-life (EOL)	The end of life (EOL) of a battery is reached when the battery's maximum power and energy have been reduced to about 80% of their measurements at their Beginning-of-life. The general rule of 80% is based on when power or energy has dropped to a point at which acceleration (power) or range (energy) is no longer satisfactory to the consumer. However, depending on the application, a lower EOL may be used.

Energy	The term energy, which is measured in watt hours or kilowatt hours, refers to the amount of energy that a battery will store. It is analogous to the size of the gas tank.
Energy density	Energy density is the measurement of how much energy a cell or pack contains in relation to its mass or volume. Energy density is measured in watt hours per kilogram or as watt hours per litre.
Module	A couple of cells connected in series or parallel (or both). Their aggregation is needed to increase the total power output. Modules are created to get manageable and serviceable units.
Parallel	Parallel refers to a type of electrical battery connection in which positive terminals are connected and negative terminals are connected (e.g., positive to positive, negative to negative). In a paral-lel connection you feed current into all cells at the same time and pull current out of them at the same time. When connecting cells in parallel, the system capacity and energy are increased.
Printed Circuit Board (PCB)	A flat board made of insulating material, typically fiberglass, that electrically connects and me-chanically supports electronic components using conductive pathways, pads, and traces etched from copper sheets.
Series	Series refers to a type of electrical battery connection in which the positive terminals of one cell are connected to the negative terminals of the next cell, and the negative terminals of the first cell are connected to the positive terminals of the cell. A series configuration refers to a grouping of cells connected in series (e.g., negative to positive). Connecting cells in series increases the voltage of the overall system but does not increase the current.
Short circuit	A short circuit occurs when the positive and the negative poles or electrodes of a battery are connected. In essence, a short circuit creates a circular connection within a cell, driving all of the current back into the cell or pack, which will eventually, and usually quickly, lead to catastrophic failure. If it happens inside the cell, it is an internal short, but if the electrical connection is made between the poles outside the cell, it is referred to as an external short (e.g., outside the cell).
State-of-health (SOH)	SOH measures how much the battery has degraded and how much capacity is remaining. It tells you how long until the battery reaches its EOL. SOH measures internal resistance, capacity, volt-age, self-discharge, the battery's ability to accept charge, and the total number of charge-discharge cycles that the battery has completed at that point in time. The SOH calculation is an algorithm programmed into the battery management system main controller.
Sub-cell	EAGLEBAT's pouch cell is divided into smaller sub-cells, which are each controlled seperately. This way not all parts of the pouch cell have to be used at all times. This provides greater control over the pouch cell and increases the lifespan of the cell overall.
Voltage	Voltage is the potential of the charge in a battery, but for clarity it can be thought of as being analogous to the pressure in a hose.

Table 4: terminology list of common words within this report. Many definitions were found in Warner (2024)

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Appendix A: list of requirements

BATTERY LEVEL	REQUIREMENT	STEMMING FROM
Cell	Each pouch cell is divided into 6 sub-cells, each with its own positive and negative tab, resulting in a total of 12 tabs per cell.	EAGLEBAT
Cell	Each tab must be connected to its own MOSFET.	EAGLEBAT
Cell	The tab connection must be reversible.	EAGLEBAT
Cell	Each pouch cell/ tab connection must be easily accessible, without interference from other components, to facilitate time efficient pouch cell replacements.	Own reasoning
Cell	The steps required to replace a cell should be minimised.	Own reasoning
Cell	The soft aluminium casing must be protected from external forces.	EAGLEBAT
Cell	The cell must be able to be replaced every 2 years (warranty period).	Own reasoning
Cell	Cell volume must be maximised for highest capacity possible.	Own reasoning
Module	A module must contain a local controller to facilitate the MOSFETs.	EAGLEBAT
Module	A module must contain four cells in series to create a 12V module.	EAGLEBAT
Module	Modules must be able to be connected in series, parallel or both.	EAGLEBAT
Module	A module must contain 48 MOSFETs (required for sub-cell control).	EAGLEBAT
Module	The number of sensitive components, such as connectors, must be minimised.	Own reasoning
Battery pack	A Battery Management System must be included.	EAGLEBAT
Battery pack	The battery will be rear-mounted on the bicycle.	Own reasoning
Battery pack	The outer dimensions must be close to 365 x 120 x mm to match the Gazelle Gold battery.	Own reasoning
Battery pack	The use of glue or solder is prohibited.	Own reasoning

Table 5: list of requirements for the battery pack.

Appendix B: morphological chart's solutions evaluated

HOLDING CELLS IN PLACE

Corners	+ +	Corners are the most vulnerable places of cell Few material needed	– – –	Four pieces are loose of each other Doesn't protect sides Alignment with other cells is hard
Slot	+	Access to cell in one move	–	Only one side protected
Sides	+	Tabs are protected	–	Sides are not connected
Top/ bottom			–	Tabs are not protected
All-round	+ + +	All sides protected Gap for heat dissipation Good heat dissipation	–	Quite some material needed
Striped	+ +	Very rigid Some gaps for heat dissipation	–	Quite some material needed
Full	+ –	Good protection No indication for cell alignment	– –	Lots of material Poor heat dissipation
Band	+ +	Few material needed Good heat dissipation	– – –	Tight fit around cell needed Should cover the tabs to be viable Poor cell alignment
Cross	+ +	Very rigid Some gaps for heat dissipation	–	Quite some material needed
Screws	+	Strong connection	– –	Takes some time to unscrew Material on cell needed to screw into
Clamps	+ +	Few materials Strong connection to cell	– –	Doesn't protect tabs Hard alignment between cells
Press down			– – –	External pressure needed No air between cells for heat dissipation Pressure might harm cells
Folder over	+	Compact	– –	No protection Unclear how cells are properly held in place

CONNECTING CELLS (STRUCTURES)

Magnet	+ +	Flexible Easy to separate cells	– –	Strong magnet needed Connection might shift after shock
Guiding rods	+ +	Very clear where cells need to go Sturdy	– –	Only possible for four cells in one straight line Makes it harder to access cells in the middle of the line
Snap fit	+ +	Easy to produce Small	–	Hard to loosen connection again
Outer framework	+ +	Good protection for cells Predefined places for cells	–	Quite spacious
Glue	+	Cheap	– –	Permanent Hard to recycle
Lego	+ +	Semi-flexible All cells are placed on grid	– –	Connection only defines location Connection hasn't any strength itself

Guiding lines	+	Ensures cells are connected in right orientation	– –	Connection only defines location Connection hasn't any strength itself
One-way connector	+ +	Ensures cells are connected in the right orientation Reversible	– –	Expensive Might be hard to get loose
Elastics	+	Flexible	– –	Fragile Elastics loos elasticity over time
One feasible shape	+	Ensures cells are connected in the right orientation	– –	Connection only defines location Connection hasn't any strength itself
Clamp	+	Tightly packed together	– – –	Only possible with stacked configuration No heat dissipation Might damage cells
Outer click mechanism	+ +	Holds everything tightly in place in the right location Reversible	–	Only possible for stacked configuration
Toggle latch	+ + +	Reversible Can be bought Strong	– –	Expensive Requires quite some spaces
Backplane	+ +	Integrated PCB Compact	–	Possibly too much force on connections
Hinge slot	+ +	Viable for thin outer edge of cell Space efficient	–	Only grabs one cell, doesn't really connect cells

TAB CONNECTORS (REVERSIBLE)

Stapling			–	Non-reversible
Sewing			–	Non-reversible
Crocodile clamp	+ +	Made for electric connections Can be bought	– –	Expensive Spacious
Force fit	+	Semi-permanent	– –	Hard to align Might come loose
Screwing	+	Strong connection	– –	Takes quite some time to unscrew Tiny screws required
Apply pressure	+	Ensures good electrical contact	–	How is the pressure applied?
Folding	+	Cheap	– –	Deforms the tabs Still needs to be clamped
Springs	+ +	Good electrical contact Small	–	Alignment might be hard
Soldering	+ + +	Strong connection Cheap Easy to automate	–	Permanent
Heat shrinking			– –	Heat might damage cell Hard to align
Punching			–	Connection probably comes loose
Double-sided tape			–	Weak connection

Pushpin	+	Ensures good electrical contact	–	Prone to vibrations
Laminate	+	Some freedom in alignment	–	Heat might damage cell
Clamped between plates	+ +	Good electrical contact Mechanically strong and reversible	– –	Many components Many steps to reverse connection
Paperclip	+ + +	Thin Cheap Ensures electrical contact	– –	Prone to vibration Tab might fold onto itself
Plastic holder	+ +	Can grab multiple tabs at once Cheap	–	Plastic can fatigue

CELL CONFIGURATION

Square	+	Well-balanced		
Stacked	+	Compact		
Flat	+	Thin		
L-shape (side)			–	Unpractical shape
T-shape (side)			–	Unpractical shape
2x2	+	Well-balanced		
T-shape (top)			–	Unpractical shape
L-shape (top)			–	Unpractical shape

COOLING

Air (passive)	+	No costs	–	Might not be enough cooling
Ventilator	+	Active cooling dependent on current temperature	– –	Extra components needed in a limited space A ventilator only works if the air can go somewhere
Liquid			– –	Prone to vibrations Heavy
Foam			– –	Not all foam is sustainable Makes it hard to access cells
Conductive sheet	+	Very flat	–	Must be directly placed on cell

MOSFET LOCATION

All-in-one	+ Easy to produce in factory	– Hard to replace individual MOSFETs when broken
Stuck to tabs	+ Reliable connection	– MOSFETs are thrown out when cell is discarded
Per sub-cell	+ Good overview of which MOSFETs belong to which sub-cell	– Difficult to wire everything up
Grouped per side	+ Grouped per Anode/ cathode + Easier to replace broken MOSFET's	– More PCBs needed

WIRING

Wires	+ Conventional + Freedom in movement	– Gets messy – Hard to solder automatically
PCB	+ Conventional + Can contain build-in components + Rigid	– Needs to be planned out well – Only short distances
Flexible PCB	+ Flexible + Structured	– Fragile

MODULE-TO-MODULE (POWER)

Connector blocks	+ Simplifies a series or parallel connection + Adds to the strength of the battery structure	– Bulky – Extra weight and material
Cables	+ Flexible	– User needs to be careful what to connect where
DESA	+ Only one and the same connection between each module + Required computing power (PCB) already present + Provides extra safety features	– 3 extra MOSFET's per module

MODULE-TO-MODULE (DATA/ BMS)

Chain	+ Compact	
Loose	+ Fits in more unconventional spaces	– Longer data lines
Train	+ Combination of Chain and Loose	– Longer data lines – Requires many extra electrical components

MOSFET LOCATION

Vacuum	+ Everything pressed together firmly	– Hard to reopen – Limited control during production
Airbag		– One-time use
Framework	+ Rigid structure + Shapes can be used as shock-absorption	

Cloth	+	Good protection	–	Fire-hazard
	+	Cheap		
	+	Non-conductive		
Foam	+	Good shock protection	–	Not all foam is sustainable
			–	Makes it hard to access cells
			–	Bad heat transfer
Springs	+	Flexible	–	Mostly one-directional
			–	Loose strength over time
Fluid			–	Impractical
Rubber	+	Good against vibrations	–	Less good for shocks
	+	Cheap	–	Bad heat transfer
	+	Non-conductive		

Table 6: advantages and disadvantages of all solutions to the sub-problems mentioned in the morphological chart.

Appendix C: combinations made for concept generation

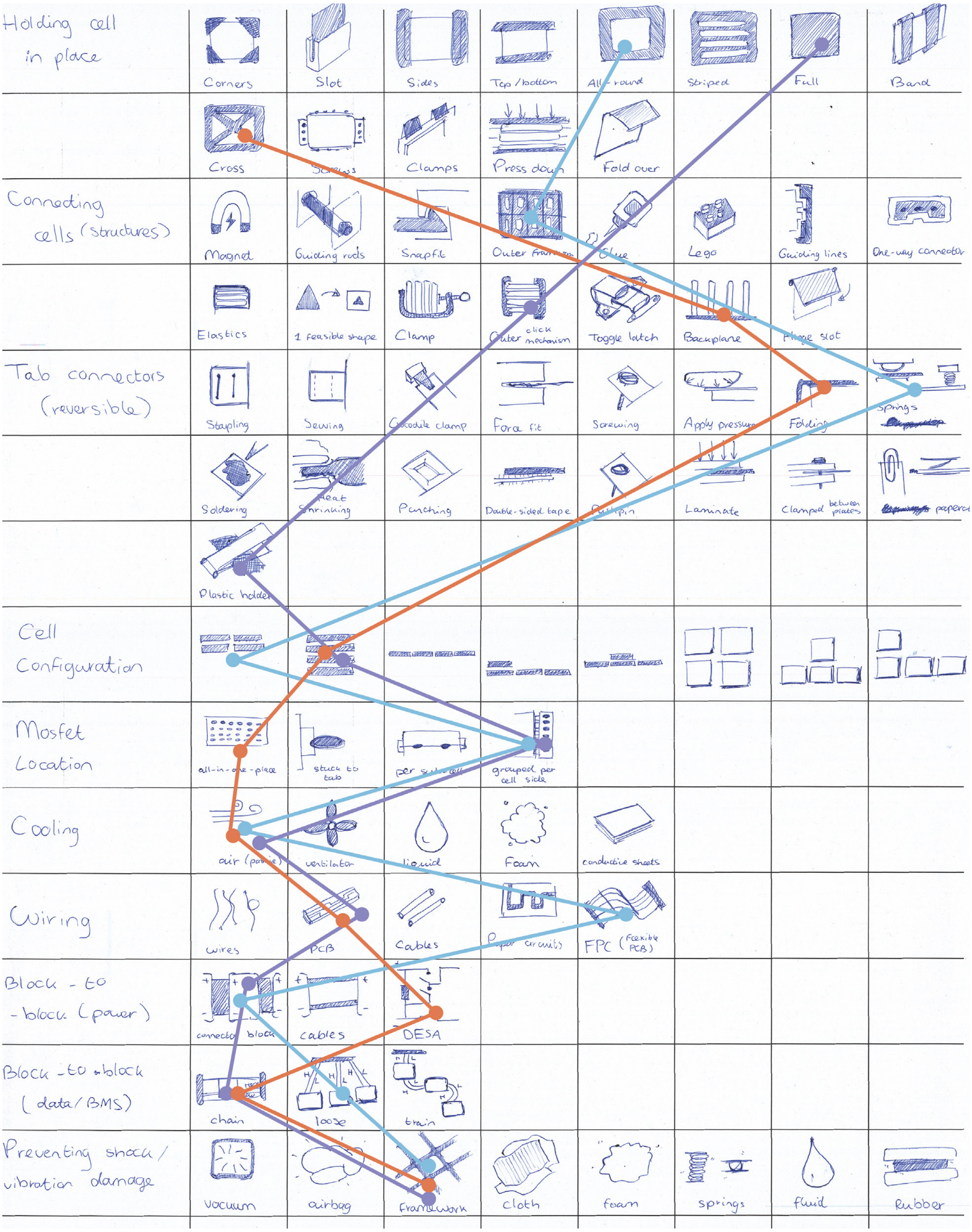


Figure 43: *squares are combined into concepts. Concept 1 (orange) aims to be as compacts as possible. Concept 2 (purple) aims to be easy to disassemble. Concept 3 (blue) aims to be as durable as possible.*

Appendix D: quality criteria for tab connector

Reversibility requirements imposed by EAGLEBAT

- The tab connection must be reversible. The tab connection must allow the cell to be replaced every 2 years, as this is the warranty period for most e-bike batteries.
- The tab connection is directly accessible without interference from other parts
- Every tab must be individually connected to its corresponding MOSFET
- Every connection must withstand shocks and vibrations that occur during cycling.

Electrical and thermal requirements

- Resulting joints should have low electrical resistance with a narrow scattering range
- Thermal input during manufacturing should be as small as possible
- High thermal fatigue resistance of created joints

Material and metallurgical requirements

- Low corrosion risk
- Joining of dissimilar materials
- Adaptability to a variety of surface conditions and materials

Mechanical requirements

- Strong interconnections
- Good fatigue and creep resistance
- Low pre-stress level
- Avoid mechanical or vibrational damage during joining

Economic requirements

- Suitability for mass production
- Low acquisition costs
- Good possibility to be stabilised and standardised

Figure 44: quality criteria for suitable tab connector joining techniques (Zwicker et al, 2020)

Appendix E: cell thickness calculation

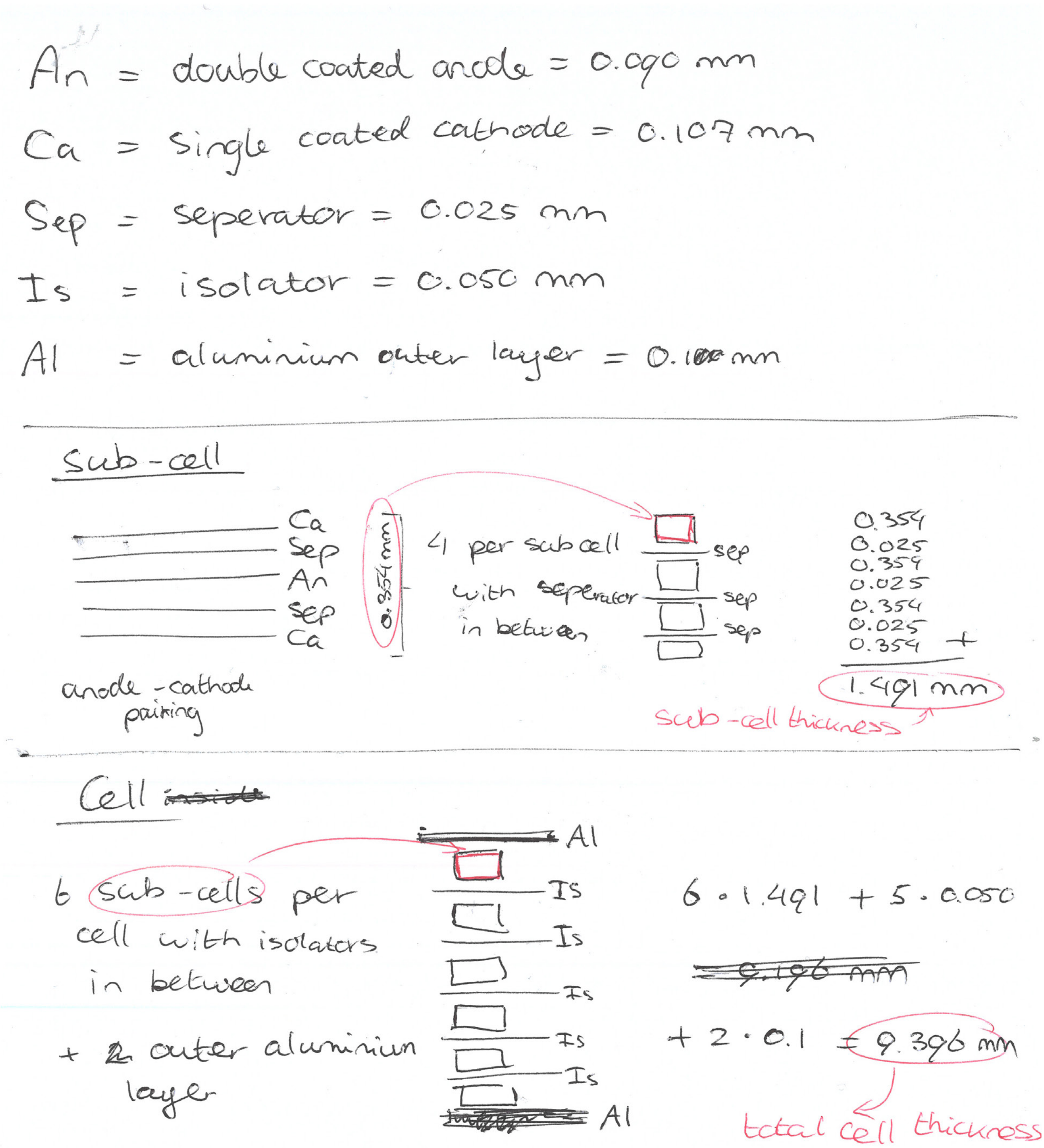


Figure 45: *calculation for the thickness of a pouch cell. Each pouch cell consists of six sub-cells, with each sub-cell containing four anode-cathode pairings.*

Appendix F: battery pack capacity calculation

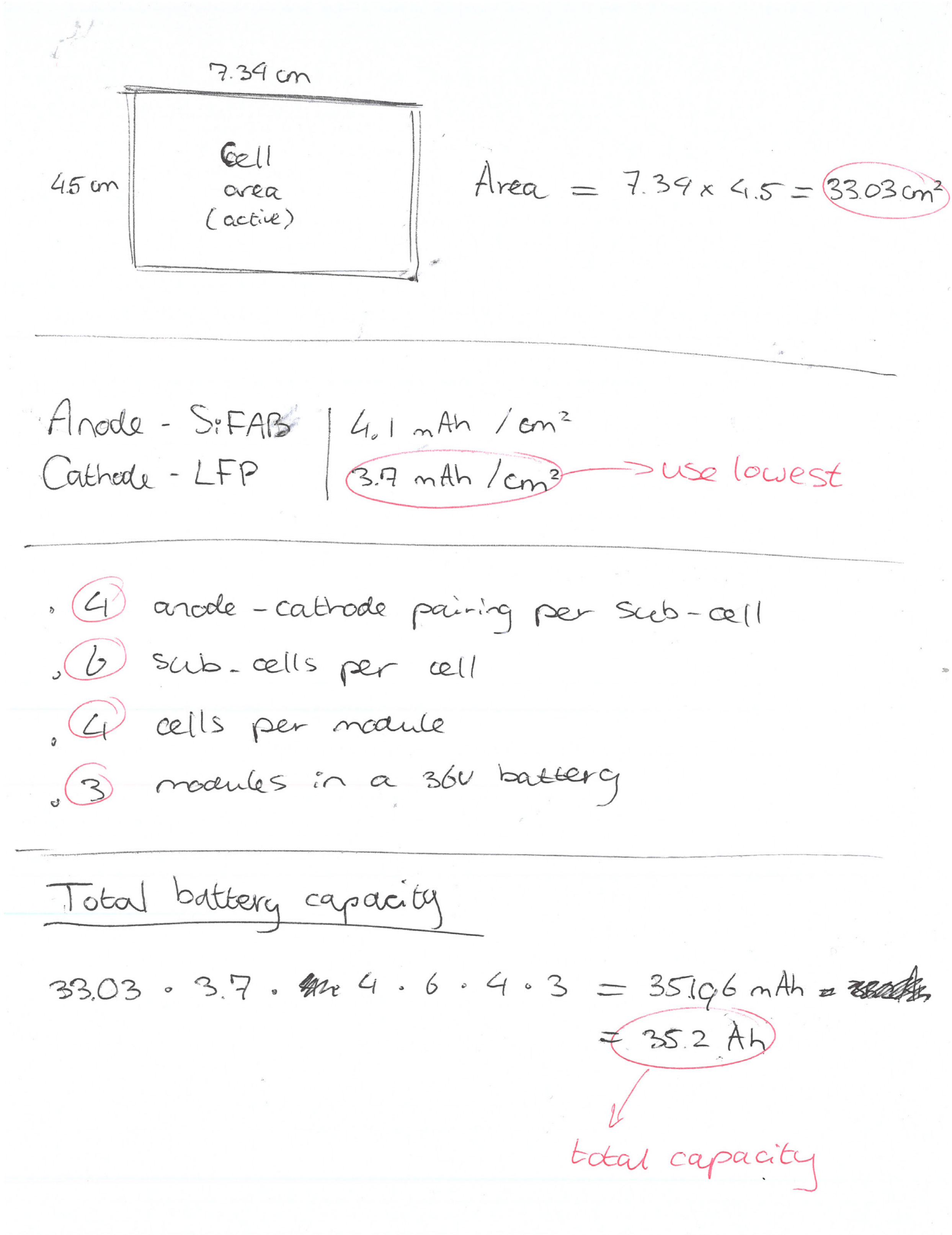


Figure 46: *capacity calculation for a battery pack with 3 modules (in total 36V).*

Appendix G: I2C structure

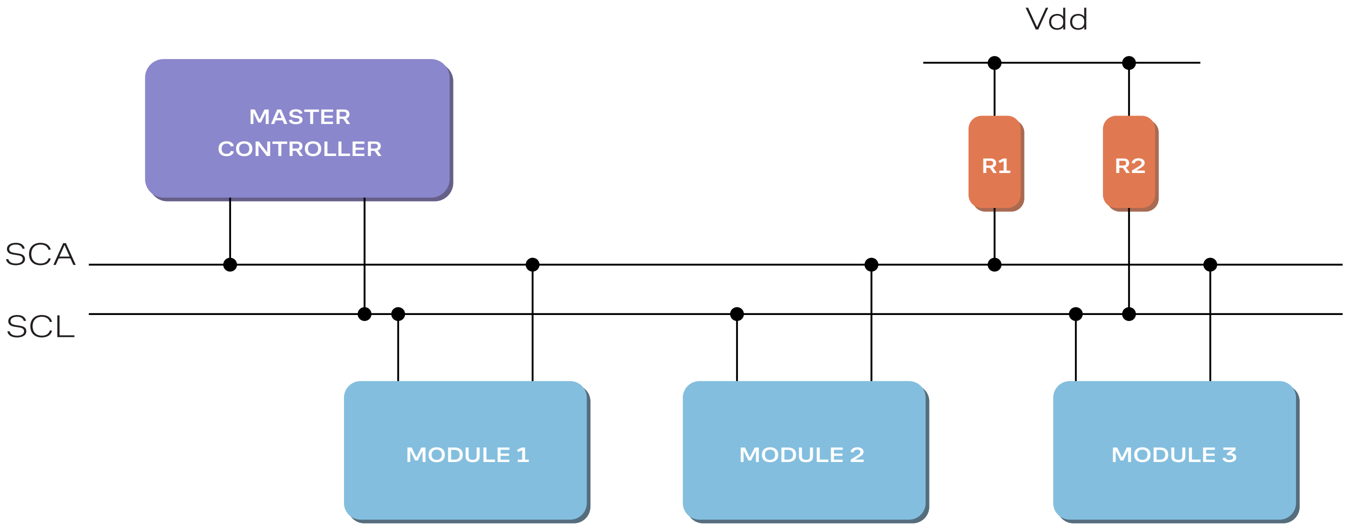
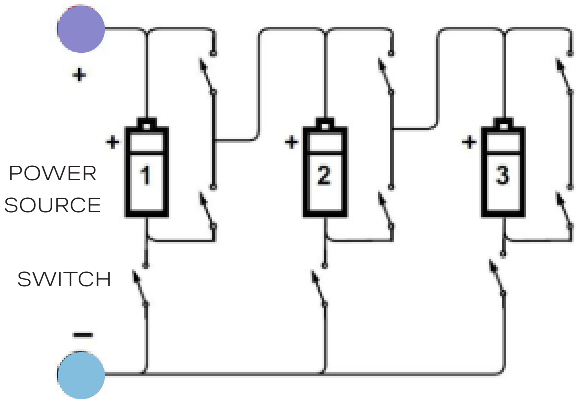


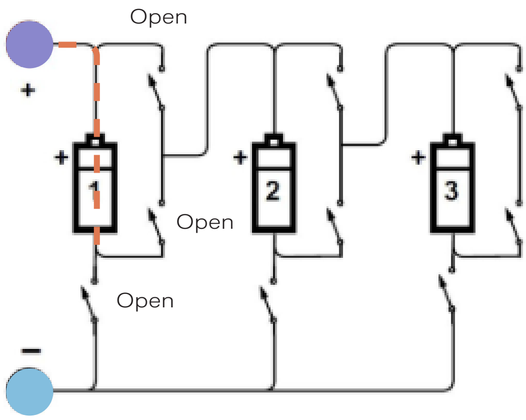
Figure 47: wiring for a I2C data connection to three modules.

I^2C (Inter-Integrated Circuit) is a two-wire serial communication protocol used to connect multiple devices using only two lines: SDA (Serial Data) and SCL (Serial Clock). SDA carries data between devices, while SCL synchronizes communication with a clock signal. Both lines are open-drain, meaning devices can pull them low but need external pull-up resistors (R) to bring them high when inactive. These resistors (typically 4.7kΩ–10kΩ) connect SDA and SCL to VDD (the supply voltage, e.g., 3.3V or 5V), ensuring proper signal levels. I^2C allows multiple devices to share the same bus, with each device assigned a unique address, making it ideal for sensors, memory chips, and display modules. Figure 47 shows how components must be wired up.

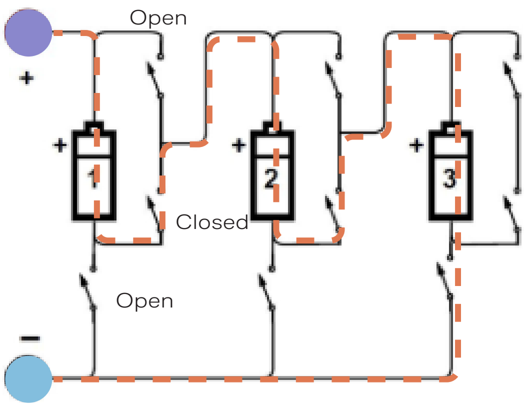
Appendix H: DESA structure



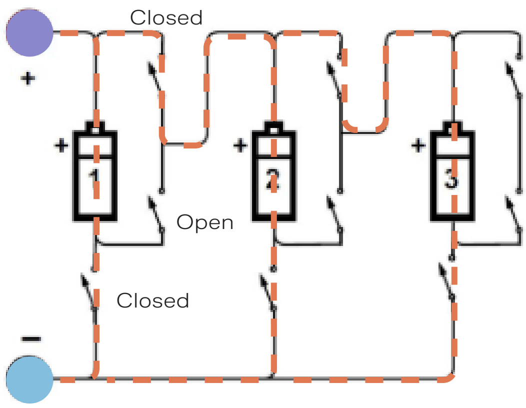
A DESA structure with three power sources. In the battery design, the power source can for example be all the power one module outputs (which is 4 pouch cells in series). In that case you apply the DESA structure between modules. This structure allows them to be connected in both series and/ or parallel within the same circuitry. As a result, you can connect them always in the same manner to each other, and determine digitally if the connection is series or parallel. The switches used in the battery pack are MOSFETs.



With all three switches open, power cannot continue to go through



With this configuration of switches, the power sources are connected in **Series**



With this configuration of switches, the power sources are connected in **Parallel**

Figure 48: *a DESA structure allows components to be connected in seriesas well as in parallel within the same circuitry.*

Appendix I: design brief