Politecnico di Torino

Politecnico di Torino

Master’s Degree in Automotive Engineering

SLIM: Second-Life Interchangeable battery Modules

Reefilla’s case study: Li-ion battery module evolution for circular urban mobility applications

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Abstract

This project introduces an innovative approach for reusing and extending the lifespan of second-life Li-ion batteries. It is developed in collaboration with Reefilla, a startup founded in Turin in 2021 and currently incubated in I3P at Politecnico di Torino.

Starting from the VDA3xx battery module a new architecture and packaging approach have been designed enhancing flexibility and supporting multiple applications. These characteristics can be achieved by leveraging a brand new swappability features and embedding a smart BMS to trace over the module lifetime important value such as SOH.

The concept design has been conceived to simplify the manufacturing process employing high pressure die casting that uses recycled aluminum. This job has been done with the collaboration of Endurance group and the participation in a European initiative aimed at environmental conservation (IPCEI). High pressure die casting production process improves cell's protection and enhance thermal performances without compromising the energy weight ratio. To achieve swappable attributes, a dedicated handling system has been specially designed for VDA3xx modules. The rotating handle and the locking system enables compliance with the specified constraints while preserving the product's ergonomics.

The project proceeded by conducting an in-depth analysis of the potential applications for the new module. Among the multiple usages enabled by this architecture, a small urban vehicle has been chosen as a demonstration of a real-life application of the module. Starting from a benchmarking analysis and progressing through the definition of functional objective, a performance evaluation was conducted. In accordance with the international WLTP regulation the final range of a quadricycle vehicle has been determined.

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Introduction

The following chapters represent a work done in collaboration with Reefilla, a startup founded and placed in Turin. Refilla's business is providing charging solutions for electric vehicles, among the others they offer the first mobile charging service in Italy. They develop the Fillee, a mobile charging station that contains second-life battery module coming from automotive traction battery. This device is an energy storage that contains up to 14 kWh, that is capable of partially recharge an electric vehicle and completely charge most plug-in hybrid electric vehicle. Fillee's energy is delivered by six battery modules of 3,2 kWh each, which were previously employed in the automotive industry for battery packs. The aim of the project is to convert the above mentioned modules from embedded batteries into swappable ones. In other words, enhance flexibility and increase the applications in order to create an ecosystem of devices that use one or more swappable modules. For instance, an electric scooter and a home energy storage system can effectively utilize these modules to deliver energy to the scooter and subsequently recharge it at home.

Evolving the module also means dealing with constraints. The first one is to maintain the original dimension of the module to be utilized for the first application (car battery pack) and then reutilized as a second life in the ecosystem already explained. Secondly, a battery management system (BMS) is required as the utilization of the module is stand alone. In fact, the original device did not incorporate the BMS within the module. Furthermore, the original frame does not allow handles, while swappable module need it to be enough ergonomics for customer usability. Finally, the weight reduction: while preserving structural integrity, enhances ergonomics and for this reason the material choice is fundamental. For instance, aluminum has been chosen for the case as the original version. However, the manufacturing technique (High Pressure Die Casting) has been modified to produce a frame with thinner walls. A different story for the BMS case, it is not a structural part, so aluminum is not required. The material is strictly related to the manufacturing technique. In fact, additive manufacturing has been chosen to reduce the production cost and enhance the sustainability of the project avoiding production scraps.

While the first part of the thesis is focused on designing part, the second part of the project analyze a possible application in automotive field. For that reason, a quadricycle L7 class is taken into considerations. The analysis has the aim of feasibility study demonstrating that a small car can be equipped by swappable battery pack. To achieve this target, a benchmarking activity has been done to understand if there are similar vehicle and the technology utilized. Moreover, benchmarking is useful to define the Functional Objectives (FO) of the product: the main characteristics that the hypothetical vehicle needs to have. The analysis concludes with the consumption evaluation (by WLTC application) and a proposal for battery pack with different final range.

1. Fundamentals of batteries

In order to design the brand-new module and introduce his applications, the basis of batteries should be understood. The evolution from Daniell cells to the latest chemistry of Li-ion batteries is analyzed, but also the EV architecture, their components and the battery pack configurations will be addressed.

Starting from last decades the electrification enhance battery development and production, in particular Li-ion based batteries. Contrary to popular belief the batteries and chemistry that is behind was discovered during nineteenth century by different scientist that as a relay race improve the idea of cell. To understand the modern cells and batteries used in Electric Vehicles (EV) is important to understand how work the elementary cells developed hundreds of years ago. The first one who studied electric phenomenon was Luigi Galvani (1780 – 1783) [1]. He focused on the relationship between muscular movement and electric input. His experiments involved experiments on frog legs that responded to electrical impulses with movements. Although opposite opinion Alessandro Volta [2] did a step up in this fields thanks to Galvani studies. In fact, in 1799, the Italian scientist create the first pile made up of metallic discs of Zn alternated with Cu, between them a thin layer of sulfuric acid in liquid form. This description corresponds to the voltaic pile that is represented in figure 1.

Figure 1 Voltaic Pile

The second improvement came from J.F. Daniell in 1836. He developed the voltaic pile focusing only on a single cell, not to an entire pile. The same elements (Zn and Cu) were utilized in order to focus on safety and max voltage. In this case Zn is immersed in a solution of Zinc Sulfate ($ZnSO_4$) and the metal Cu is immersed in Copper Sulfate ($CuSO_4$). A salt bridge connects the two solutions in order to balance them and the poles (zinc electrode and copper electrode) are linked by a wire in which the current can flow.

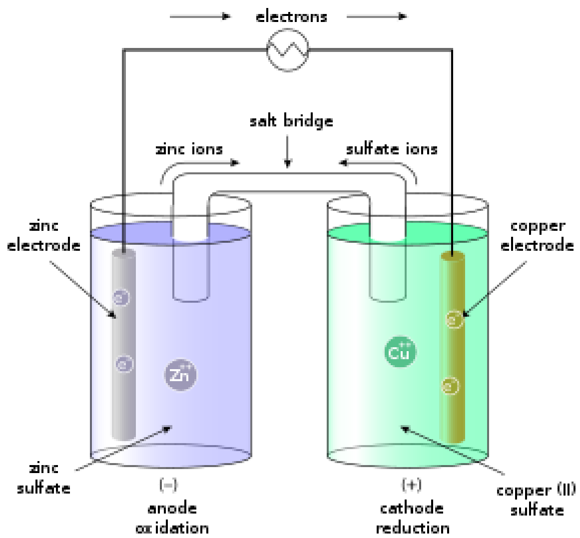

Figure 2 Daniel Cell

1.1 Voltaic Pile and Daniell cell working principles

The working principle of an electrochemical cell involves two important half-reactions that allow electrons to move between two electrodes (cathode and anode). These half-reactions are known as oxidation and reduction. The key players in redox reactions are the reducing agent, which facilitates the reduction half-reaction by donating electrons to another chemical species. The second agent is the oxidizing one which facilitates the oxidation half-reaction by accepting electrons from another chemical species. The reactions can be explained by the description of the Daniell cell. In fact, during the discharge phase, a redox reaction occurs between the two half-cells, namely the zinc electrode (anode) and the copper electrode (cathode). This reaction produces an electric current that can be used to power an external device. The following steps describe how it works:

Anode (Zinc Electrode):

At the anode, the oxidation process involves zinc (Zn), which is in the form of solid zinc metal and becomes a Zn^{2+} ion in solution. This reaction releases two electrons:

$$Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$$

Equation 1 half-reaction of oxidation

Zinc is oxidized and loses electrons. The released electrons are then available to flow through an external circuit to provide electrical energy. In this case the Zn is the reducer.

Cathode (Copper Electrode):

At the cathode, the copper ions (Cu^{2+}) present in the aqueous solution accept the electrons coming from the anode to form copper metal (Cu):

$$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$$

Equation 2 half-reaction of reduction

This is the reduction process in which copper ions gain electrons to become copper metal. The copper metal deposits on the copper electrode. In this case the Cu is the oxidizer.

Therefore, during the discharge phase of a Daniell cell, zinc is oxidized at the anode, losing electrons, while copper ions are reduced at the cathode, gaining electrons. Electric current flows through an external circuit from zinc to copper in fact electrons are transferred from one electrode to the other through a conductive wire. Meanwhile, the concentration of Zn^{2+} ions at the anode and Cu^{2+} ions at the cathode decreases as the reaction progresses, and the cell gradually discharges until Zn^{2+} or Cu^{2+} ions are depleted, stopping the flow of current. This point corresponds to a completely discharged cell.

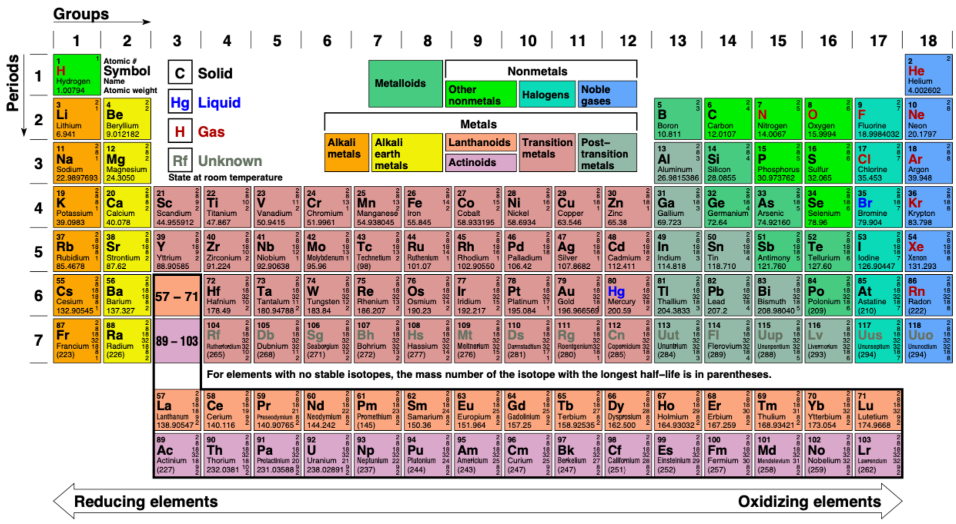

Figure 3 Periodic Table of chemical element

The elements of the cells are chosen by the potential energy difference. In other word the voltage of a cell is determined by the difference of potential energy of the two element that make the cell. This phenomenon can be easily explained by a periodic table (figure 3). Each column represents a group, and each row represents a period. Generally, the element on the left

of the table (lower group) is an element that reduces (give an electron) and the element on the right of the table oxidizes (receives an electron). This phenomenon is strictly related to the number of electrons in the last shell of the atoms.
Going back to the differential of potential is possible to understand the potential energy of each element of the table, based also on the number of electrons in the last shell. In the table 1 the potential energy is reported for the half reaction of each element. This means that if an element gives an electron (reduction) this reaction corresponds to an energy (in this case negative). The same can be done if the electron is accepted by an element (oxidation).
The difference between the potential energy gives the potential energy of the cell made up of these two specific elements.

Cathode (reduction) half-reaction	Standard potential E^0 (volts)
$Li^+ + e^- \Rightarrow Li_{(s)}$	−3.01
$K^+ + e^- \Rightarrow K_{(s)}$	−2.92
$Ca^{2+} + 2e^- \Rightarrow Ca_{(s)}$	−2.84
$Na^+ + e^- \Rightarrow Na_{(s)}$	−2.71
$Zn^{2+} + 2e^- \Rightarrow Zn_{(s)}$	−0.76
$2H^+ + 2e^- \Rightarrow H_{2(g)}$	0.00
$Cu^{2+} + 2e^- \Rightarrow Cu_{(s)}$	0.34
$O_{3(g)} + 2H^+ + 2e^- \Rightarrow O_{2(g)} + H_2O_{(l)}$	2.07
$F_{2(g)} + 2e^- \Rightarrow 2F^-$	2.87

Table 1 Potential energy of chemical elements

1.2 Li-ion batteries: chemistry and Intercalation principle

The increase of electric devices was followed by a rapid development of batteries, in fact during last decade the Li-ion batteries for automotive application are developed to fulfill the needs of the mobility revolution. A lithium-ion battery, however, can refer to a wide array of chemistries, ultimately consisting of charge and discharge reactions from a lithium metal oxide cathode and a graphite anode. The first milestone of Li-ion batteries was done due a petrol crisis in '70 [3]. M. Stanley Whittingham, John B. Goodenough and Akira Yoshino are the researcher that contributed to the evolution of Li-ion batteries. Starting from the beginning, between 1972 and 1976, the first of the three invent the cells made up of metallic lithium as a negative pole and titanium disulfide, a chemical compound made up of a crystal lattice able to host lithium ion. One of the most critical points occurs during the charging mode of the cells, in fact the Li- ion go back in the anode but occupying a different position with an increase of volume, as the image 4 suggest. Cycle by cycle this volume deforms the anode and generation of fire occurs. An important improvement was done by Goodenough that in 1980 improved the previous research changing the cathode with the cobalt oxide and avoiding the increasing of volume. Moreover, the material change enhances the voltage capacity from 2 V to 4V. The final steps were done by a Japanese researcher called Akira Yoshino that following the trend of electronic devices had to solve the problem of energy storage trying to develop a battery with higher energy density ratio. His solution was again a material change: from metallic Li-ion to carbon coke. This solution permit to reach the same performances of the cells without compromise the final voltage of the cells The working principle of Li-ion batteries is based on totally different criteria, in this case the two main characters are the lattice structure and ions. [4] In particular ions of Li move inside the lattice structure of both cathode and depending on the cells is in charging or discharging mode. As the figure 5 suggest the Li-ion move in the electrolyte and inserted themselves into a lattice structure, this phenomenon is strictly related to the flow of electron from cathode to anode and vice versa called current and measured in Ampere [A].

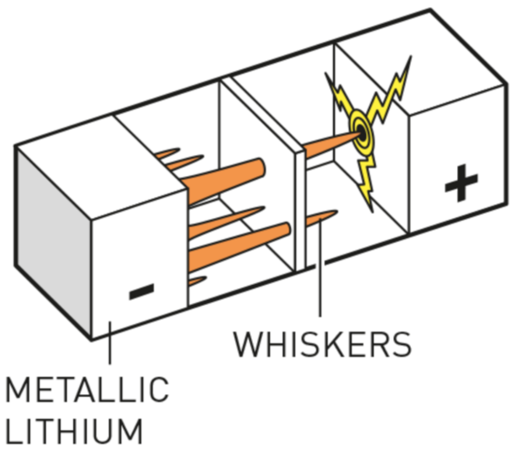

Figure 4 graphic representation of problems in Whittingham cell

The traction battery used for automotive applications must be designed to increase as much as possible the energy contained inside. For this purpose, the decision of positive electrode chemistry is fundamental. Now a day the challenge is study and develop the best cathode in order to fulfill the requirement of the battery. Currently the most used chemistries are:

- LCO: Lithium Cobalt Oxide.
- LMO: containing Manganese.
- LFP: Lithium Iron Phosphate.
- NMC: Nickel Manganese Cobalt.
- NCA: Nickel Cobalt Aluminum.
- LTO: Lithium Titanium Oxide.

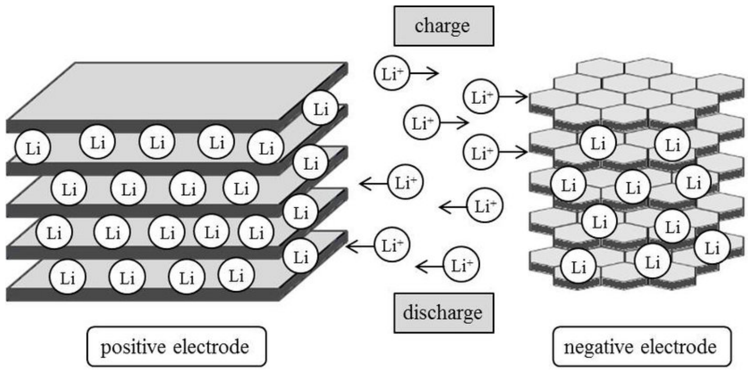

Figure 5 graphical representation of Li-ion moving between anode and cathode.

LCO

LCO stands for Lithium Cobalt Oxide, known for its remarkable energy storage capacity, which is why it finds extensive use in smartphones, laptops, and electric vehicles (EVs). However, there are several significant drawbacks associated with LCO chemistry. Firstly, the high cost of cobalt directly inflates the overall production cost of devices employing this technology. Moreover, LCO batteries are susceptible to thermal effects and can be damaged when exposed to elevated operating temperatures.

Furthermore, an ethical concern arises due to the extraction of cobalt, as it is a challenging element to source naturally. This ethical issue is compounded by the fact that cobalt mining often raises environmental and human rights concerns in certain regions where these resources are prevalent.

LMO

[5] Lithium-ion batteries with LMO cathodes, or Manganese Oxide, represent an innovative solution aimed at addressing the challenges associated with cobalt usage in cathodes. The adoption of manganese as a cobalt substitute significantly reduces production costs but results in a decrease in energy density compared to batteries using LCO.

What distinguishes LMO batteries is their operational safety, particularly in situations involving thermal fluctuations. This is due to the absence of cobalt, which is sensitive to temperature variations. The choice of manganese enhances the thermal stability of LMO batteries, even though their discharge cycles are reduced compared to LCO chemistry.

LFP

[5] LFP that stand for Lithium Iron Phosphate present important thermal stability and safety with a long life in term of cycles. Phosphate and Iron are abundant element, and this means low production cost and low risk of fire/explosion due to intrinsic characteristic of this elements. One of the most drawbacks is the weight of iron that is higher than Cobalt or Manganese and this means that LFP batteries has lower energy density compared to others.

NMC

[5] Nickel Manganese Cobalt cells are the most used in automotive field due to great energy density, a good number of life cycle (around 2000), and the voltage of the cell is 3.6 V. the percentage of elements inside the cell can vary influencing the final characteristic of the cell. NCM111 correspond to an equally distribution of elements, NCM622 consider 60% of nickel and 20 of the other two, and finally NCM811 follow the same criteria whit 80% of nickel. As possible understand the trend is to has higher percentage of nickel and reduce Cobalt due to the reason already explained previously. Increasing nickel. Furthermore, the last research are focused on NMX in which the presence of cobalt is reduced to 0%.

NCA

[5] Nickel Cobalt Aluminum cell is very similar to NMC, but an increase of energy density is followed to a decrease of safety. This technology is used also in automotive field whit a compromise, in fact a blend of chemistry between NCM and NCA is inserted into battery pack.

LTO

[5] Finally, Titanium is one of the latest chemistries introduced with a very high potential. In fact, the life cycle of this kind of cells permits from 15,000 to 20,000 cycle. On the other hand, the drawbacks are relevant: low energy density and high production cost are very limiting for large-scale usage.

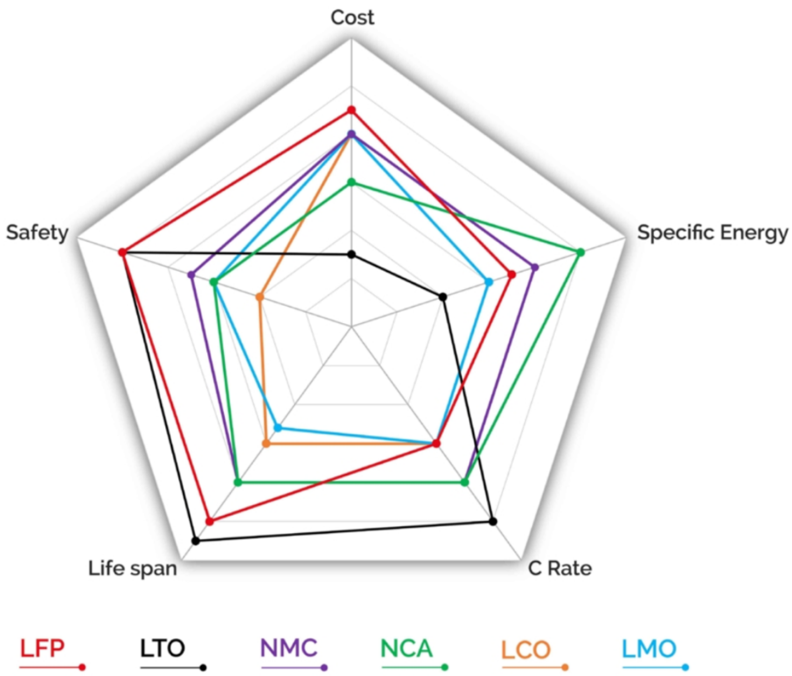

Figure 6 graphical representation of chemistry cell and their characteristics [5]

Anode

For what concern the negative electrode usually it is carbon based, in fact graphite is the most used Anode due to important capacity of intercalation of ions and relatively low cost. An alternative could by silicon (Si) that has incredible higher capacity of ion storage, up to 10 time compared to graphite. Unfortunately, the lattice structure deform itself increasing his final volume of the cell influencing the safety of cells: explosion and permanent damage can occur.

1.3 Cell packaging format

Previously an overview of the cells explains the chemistry working principle of these devices, but no mention of the packaging has been done. Clearly the actual cells are not like Voltaic pile or Daniel cell but can be subdivided into four main shapes with different purpose and characteristics: cylindrical, prismatic, button and pouch.

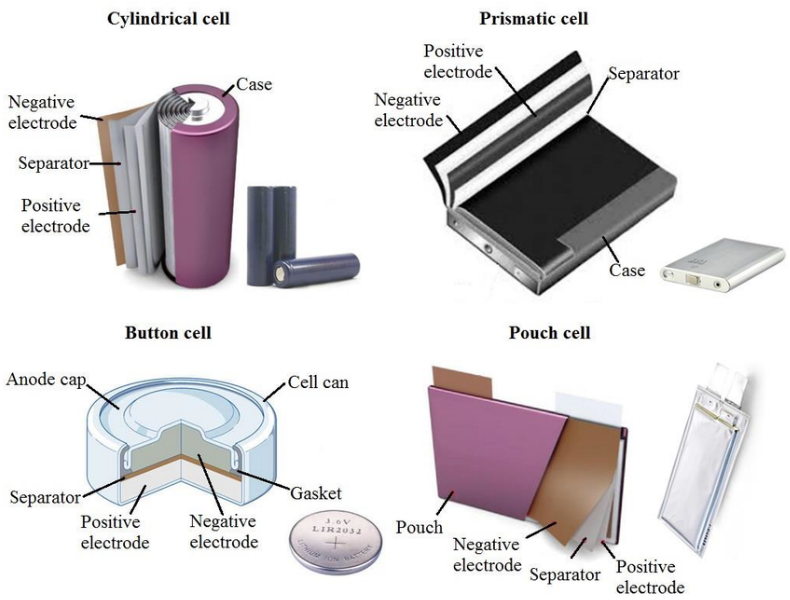

Figure 7 graphical representation of types of cells packaging

The first two are very similar contrary to what can be seen in the figure 7, in fact, cathode and anode are divided by a layer of separator (electrolyte) and then rolled up. In prismatic cells the layers are rolled up around a prismatic support, this gives the specific shape to the cells. Moreover, both the shape presents an external case that has two functions: maintain in position the layers and protect from external damages. Finally, on the top a gas valve preserves the correct pressure inside the calls avoiding explosion or not safe working condition. For what concern the button cells the wrapping principle is no longer used and only two layers are present. Is important to highlight that this kind of cells are not used in automotive fields but generally for small electronic devices. The last type of cell is largely used in traction batteries and present again the layer principle but in this case no rolling is expected. The cell doesn’t present external protection like the previous cases but only a containing layer that wrap the cells.

Cylindrical cells

These kinds of cells are used for small devices like laptop, screwdriver, or remote control. Also, in some automotive applications are present like some model of Tesla (Model S and Roadster).

One of the advantages is the higher power compared to a prismatic cell and this is perfect for high performance vehicles (Formula E competition cars). Moreover, another pro is the compact size that permit their use in portable devices, but it is also a drawback because the energy that can be stored is much lower than a prismatic or pouch one. Tesla could be an example: to fulfill the energy request of a Model S, are necessary from 6,000 to 9,000 cells, this means also that the internal connection and the final weight increase. [6]

Prismatic cells

In 2020 the market share of this shape was around 40% of automotive batteries against 35% of pouch and 10% of cylindrical. For that reason, is possible to say that the prismatic cells are one of the most used cells for automotive battery pack [7]. As said in the previous paragraph, the dimensions and the energy contained are directly related obtaining a final device with higher energy compared with cylindrical models. Prismatic shape permit to avoid a huge number of cells decreasing the weight of the wires, on the other hand the cylindrical one can perfectly fit every corner of the battery pack chassis increasing the energy ration.

Finally, talking about chemistry, LFP is particularly suitable for this shape. [6]

Pouch cells

These light and versatile cells are often used in cars due to the high production speed but also incredible flexibility in size: fundamental aspect in automotive industry. Moreover, due to the absence of case, the lightweight is one of the stronger points, but also a con due to low protection. In fact, they need to be compressed each other in order to be packed and because after hundreds of cycles could increase their volume. This theme of pre-compression is fundamental for pouch cells, but up to now the manufacturer don't know yet the amount of force is needed. In other word it isn't yet discover the correlation between pressure and performance, the only known aspect is that a pressure is needed.

1.4 Battery implementation in Automotive field

Before the description of batteries for BEV is necessary a clarification of terms. Up to now there was no distinction between service batteries and traction batteries. The first one is batteries that are used for secondary implementation like lights, heat and cooling system and everything don't strictly relate to traction. This kind of batteries was introduced with the first cars and are currently used in both BEV and internal combustion engine cars (ICE). Usually use Pb–acid is the common chemistry, and 12 V is a standard (consider that a Pb-service batteries is a module of 6 cells of 2 V each). On the contrary the traction battery presents a different chemistry already explained in the previous chapter and a consequently different module voltage. From now on when is write the term "battery" it is intended "traction battery".

Another important distinction is between primary cells and secondary cells. The first kind of batteries cannot be rechargeable, this means that when the State of Charge (SOC) is equal to 0% or the Voltage is at minimum cannot be reusable. On the contrary the secondary cells can be recharged: in fact, both service batteries and traction one can be recharged. [8]

1.4.1 EV architecture and components

Considering a BEV, the typology of vehicle considered are full electric vehicle and hybrid vehicle (plug-in, full, mild, and micro). The first one is cars with a single propulsion system: only Electric motor/s. In the second case the cars present both the ICE and EM and the main differences between all the typologies are the size of battery and consequently the electric support that can be done by the car. More in detail Plug-in cars can be recharged by the grid, on the contrary the other models recharge their batteries by ICE passing through an alternator. Focusing only on EV their propulsion system is by an electric motor mounted on one of the two axis or two of them placed on both axes. Rarer is a vehicle with EM on wheels but is possible to see it in some small vehicle (micro mobility).

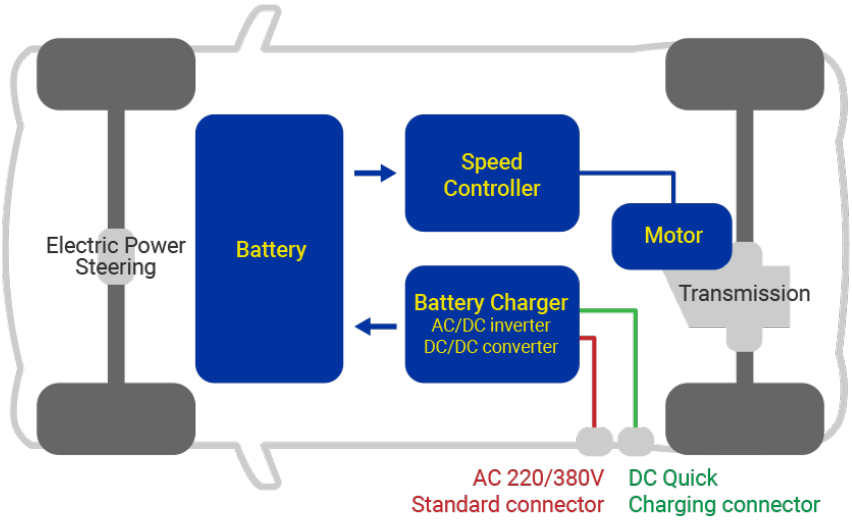

Figure 8 EV components

BEV vehicles are made up of different components, not only the electric motor. Figure 8 represent graphically the components of this type of vehicle. Starting from the charging point is possible to see that there are two possibilities: DC quick charging and AC charging, one of the most important differences beyond the charging time is that the batteries work with DC current, for this reason an AC/DC converter is needed in case of AC charge. The second step is the battery pack that consist of different module (each one made up of cells) linked together in series or parallel based on the voltage and capacity need of the motor. From battery to EM the figure highlights the speed controller but inside that box there are different steps. Certainly, there is a sort of controller that merge the EM request and the battery possibility in terms of: speed request, SOC, Voltage, Capacity and Current. Moreover, there is an important element that convert the DC current of the battery into AC current available for the EM: the inverter. It links the energy source and the power source of an EV. Is necessary to mention that EV car has the capability of regenerative braking, this means that the torque of the wheels is converted by the EM into energy for the battery to recharging it. The challenge is creating an inverter that convert DC current of the battery and provide it to e-motor, but also the revers process: from AC current of motor to DC of the batteries.

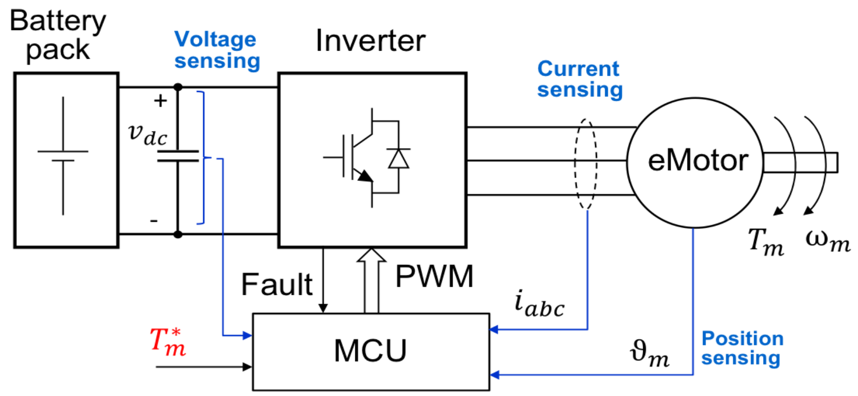

Figure 9 graphical representation of the flow from battery and EM

With higher precision figure 9 describe how EM and battery are linked and the role of the inverter. For what concern MCU (Motor Control Unit) it is a unit that elaborate by an algorithm the torque request, DC voltage of the battery, currents of all the phases of the inverter, motor speed and possible fault. The output of the MCU is a command to inverter that provide the correct current and voltage to the EM.

Another important aspect is the interaction between modules and the devices where the modules are inserted. For this reason, a brief description of what is and how work a BMS is necessary. BMS stand for: Battery Management System and the primary purposes are:

1. Ensure safety condition for operator and for battery-powered system. The Battery Management System (BMS) is required to identify hazardous operational circumstances and take appropriate actions. This might involve disengaging and separating the battery pack from the connected devices, notifying the operator through visual indicators or alarms, and similar measures.
2. Safeguard the battery pack's individual cells from harm in cases of abuse or failure. This could entail proactive intervention through software management or the utilization of specialized electronics capable of identifying failures and segregating the faulty components from both the remaining battery pack and the connected load.

3. BMS plays a crucial role in extending the battery's lifespan during regular operation. It achieves this by collaborating with the load's controller, conveying real-time power limitations that must be adhered to. These limitations prevent overcharging or over discharging of the battery pack. Additionally, the BMS manages the thermal conditions, ensuring that the battery pack operates within its designated temperature range as per its design specifications. Finally act to balance cells with different methods in order to prevent aging phenomena.
4. Fourthly, the BMS is responsible for keeping the battery pack in a condition where it can effectively meet its intended functional requirements. This means preventing the battery pack from discharging to a level where it can't deliver its specified discharge power and avoiding overcharging to a point where it cannot receive its rated charge power at any given moment. This ensures the battery pack consistently performs according to its design specifications.

1.4.2 Battery pack composition and layout

By this paragraph the battery pack previously mentioned are analyzed from the layout point of view. Up to now the typology of battery are analyzed: primary or secondary and service or traction, but also the typology of chemistry and the working principle. Now the focus is on traction battery (secondary type) of the vehicle that are Li-ion one, usually NMC, LFP or NCA. For what concern the packaging and layout, a clarification is needed. Up to now cells and their typology were described (cylindrical, prismatic, pouch and button) but cars can be equipped by prismatic/cylindrical/pouch cells grouped into modules. The market highlight that the most used technology is the modules one. In other word instead of filling the battery pack with hundreds of cells (usually cylindrical), it is made up of modules in series and/or in parallel. Before analyzing the pros and cons of architectures, the definition of modules is necessary. It is a set of cells linked together (series or parallel) and encapsulated with an external case to protect them. At the end a module represents the unitary element of a battery pack. An example could be the service battery Pb-acid of all cars: usually it is made up of 6 cells of 2 V each, but when is refer to “service battery” it is considered the entire module, not the cells. This also represent the definition of unitary element. Finally, in traction batteries, the module/entire pack has an integrated Battery Management System (BMS) that permit to elaborate by algorithms the SOC and SOH (state of health), balance the cells voltage, guarantee safety working condition in case of over temperature and avoid damages to the cells. Clearly the BMS is controlled by the car based on the external condition and the driver request. Moreover, if the temperature is too low or high the battery pack is equipped with cooling and heating system usually by liquid in order to control the temperature of the pack.

This overview is necessary to understand the two big family of battery pack layout in automotive field: cell to pack and module to pack. The third family is represented by swappable battery, but it is not largely used in passenger cars, and it is a developing technology for some smaller applications (passenger cars).

Cell to pack (C2P) [9]

This kind of configuration is organize positioning every cell into the battery pack without other type of packaging like modules. The image below shows how every single cell is positioned and packed inside a black box that correspond to the battery pack of the car.

Figure 10 cell to pack of a Tesla vehicle.

Three are the pros:

- No modules mean less weight and consequently higher range.
- No modules mean more space available and so more cells can be inserted.
- No modules mean less manufacturing process to be done.

On the contrary the cons are:

- Less protection from external intrusion.
- Less sealing compared to module to pack.
- Increase fire risk due to contact to cars' frame.

A clarification is needed: with this configuration only cylindrical cells (by Tesla) and prismatic cells are allowed. This is due to the need of pre-compression of the pouch cells that cannot be done correctly in a cell to pack layout.

Module to pack

This configuration permit to pack in a unit (the module) cylindrical, prismatic and pouch cells. During assembly cells are compressed (particularly pouch) into a case that protect them from external damages and permit a modularity of the battery pack. The packaging returns the single unit, the module that will be mounted in the battery pack in series or parallel.

Figure 11 module to pack configuration

Pros:

- Higher safety condition.
- More structural parts.
- Modularity permit to substitute parts.

Cons:

- Higher number of components and so weight.
- Less optimization of the volume.
- Cooling/heating more difficult.

Swappable module

Last configuration is the less used in automotive industry. The major application are scooters, small motorbikes, E-bikes, and small cars. In fact, all the vehicles just mentioned need smaller battery pack, so the swappability can be done rapidly. This technology can be applied insert and removing one or more modules from the frame of the car or other devices. An important requirement of these kind of modules is the lightness of the device because the swappable operation should be done by a human. For these reasons a normal passenger car with 10 or 20 modules cannot be equipped by swappable technology: the effort of the operator would be too high. An application is the XEV YOYO reported in the figure 12. It is a small passenger car with 130 km of range, 90 km/h of max speed and only two seats. In this case the car presents 3 modules in the back bumper that can be swapped by a tool and changed with charged modules in order to continue the journey. The car can be recharged by swapping the modules or charging the battery pack connecting the car to the grid as a conventional car.

One of the most impeding constraints is the dimensions and weight of the modules. In fact, every element weight around 20 kg, an unacceptable effort for an operator. For these reasons the car maker decides to commercialize the vehicle with the swappable features only in case of share mobility application, otherwise it is a normal EV car. Moreover, in case of interchangeable module, only a trained operator can swap the module with the help of a tool. This example is reported because demonstrate the reason why is very difficult to install these features in a passenger car while it is a small quadricycle.

Figure 12 XEV YO, example of swappable module

Figure 13 NIO swappable station

With a totally different approach the brand NIO and Tesla develop a swappable battery pack for their vehicles. In this case the main character is not the module, but the entire battery pack. As can be seen by the figure 13 of the NIO, the battery pack is dismounted from the bottom and replaced with a charged one. This solution reduces the charging time of a standard EV but on the contrary need a more structured and affordable infrastructure. A the early begin of Tesla swappability of battery pack was taken into consideration, but the carmaker encountered several difficulties in creating an infrastructure for the swap deciding to turn in the direction of implementing fast charging.

An important consideration must be done to understand all the aspect of cell to pack and module to pack. The goal of every carmaker is to increase the range of their car. due to the lower energy density of conventional fuel, the EV cars are disadvantaged compared to ICE cars. To increase the range engineers should work on the energy density with two main options:

- increase the energy.
- reduce the weight.

The first one can be done using a better chemistry and this kind of research are ongoing (use NCA chemistry). The second solution is designing the best battery pack with the highest volume efficiency. Clearly cells to pack are the best solution, Tesla and Chinese company as BYD and CATL are working on this technology in order to has a 100% active material in battery, in other word all the material involved in cells must store energy [10]. In particular an example could be the CATL project on Mercedes and Tesla. The battery brand proposes to reduce the number of modules from more than 30 in into 12 of Mercedes EQS or 4 of a Tesla Model 3 obtaining:

- 20% - 30% increase of volume utilization in the battery pack.
- 40% reduction in the number of parts in a battery pack.
- 50% increase in production efficiency.

The results are 250 Wh/Kg against 170 Wh/Kg, an incredible outcome for an EV [11].
From this number seems that cell to pack is the final solution, but an important aspect must be considered: the circular economy. Environment, pollution and take care of the Earth is a milestone in every aspect of industry, also automotive. For these reasons the already explained technology isn't the best solution because the reuse of the cells from the cars could be difficult due to the assembly and construction process. In other word is very difficult to extract used cells of a cell to pack car, on the contrary the module to pack layout permit to reuse single module of old EV cars and avoid producing more waste.
Try to design battery pack considering also second life must be a goal of each car maker because as already said avoid waste. Moreover, could be also a business, because at the end of the car life the battery is not simply scrapped but the battery pack can be resold and create a new business.

2. Module description and VDA standard

In the previous chapter a battery overview was highlighted: origins of cells, type of chemistry, types of layouts and critical analysis of which is the better configuration for cars' battery pack. Two main solutions were presented: cell to pack (C2P) or module to pack (M2P). In the following chapters the second solution will be take into consideration. The reasons are:

- Large number of applications of this system against the lower number of C2P.
- Second solution is still under development, so not yet mature now a day.
- Better adaptability to second-life purposes.

Moreover, one of the goals of this project is developing solutions for used batteries, the so called "second-life batteries". M2P are the best solution for this kind of application due to the ergonomic packaging, relatively low weight, and simplicity of disassembly from battery pack. On the contrary C2P are more difficult to be remove from the frame due to intrinsic design reason and most of all must by grouped to be a module.

2.1 VDA 3xx modules

The term module refers to a pack of more than one cells that are linked together to reach the correct voltage and capacity. Modules can have different dimensions, volume, voltage, capacity and are designed following the needs of each car maker. In other word there isn't a standard in terms of modules, there isn't a standard voltage module or standard dimensions module, but there are some modules that became enough popular in automotive industry that became a point of reference for the battery maker. One of these references is the VDA 3xx, where VDA is a German association of car maker and 3xx stands for the length of the module in millimeters.

2.1.1 VDA association

Going more in deep with the VDA modules is necessary a focus on the association that formalized a sort of standard module. VDA is a German acronym that stand for "Verband der Automobilindustrie" that can be translated in "Association of the Automotive Industry", it was founded in 1901 and the headquarter is placed in Berlin [12]. The main partners are the German carmaker: Daimler-Mercedes, BMW group and Volkswagen group, but also heavy-duty vehicle like MAN. Moreover, also not German brands join this association like Ford and IVECO group.

The already brand mentioned are leader in their country but also in most of the world market, this gives more affirmation and authority to VDA.

The goals of VDA are to represent the interest of all the companies that join it (more than 650 considering carmaker and supplier) and the exchange of opinions and develop standards in logistics, supply chain and manufacturing fields. Therefore, VDA is the organizer of the International Motor show in Munich and Hanover, and it is part of bigger association at European level like ACEA (Association of European Automobile Manufacturer) and CLEPA (association of European Automotive Suppliers). An example of project done by VDA was the affirmation of the Odette standard in logistic field that define standard dimensions of transports boxes used all over the word in automotive industry [13]. For what concern electrifications and modules, VDA developed a sort of reference for all the supply chains that join the German association.

2.1.2 Module characteristics

In this project the focus was on module VDA390 and VDA355, but VDA develop more than two reference, VDA590 is an example. The choice of 390 and 355 was done due to the relatively low weight (lower than 15Kg) and handy size compared to 590.

In the following sub-chapter, the major characteristics of VDA390 and VDA355 will be highlighted to have an overview of the product preparatory for the project description.

VDA 390 - BYD

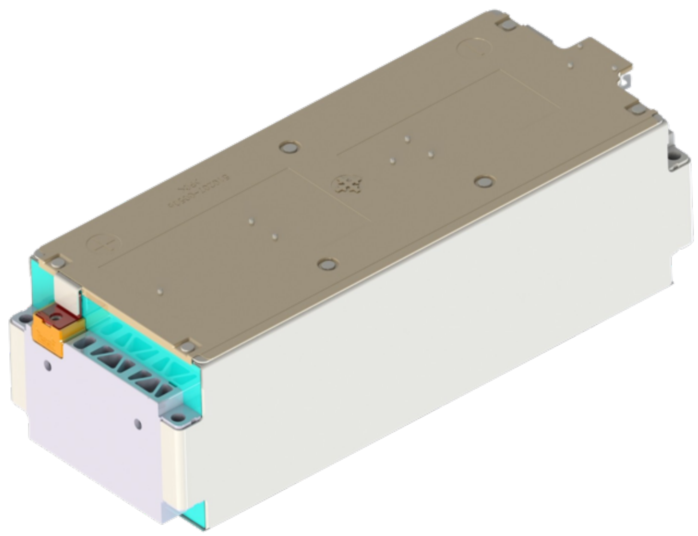

Figure 14 render of a VDA390 module

The name of VDA modules came from the length of the frame, in fact, in this case, the module is long 390.0 mm, 109.0 mm high and 151.5 mm width (390x151.5x109 mm). All the structural frame is made up of aluminum for lightweight reasons. Thanks to this material choice the weight of the module amount to 13.5Kg. The four parts (2 longer sheet and 2 hollow block) are welded each other to maintain together the 6 cells of the modules. The bottom side present a plastic layer that is glued to the lower face of the cells and on the top part there are 7 copper connectors that permit the cells to be connected in series. These devices are welded to the poles of the cells and maintained in position by a plastic cover. On that cover is positioned a flat connector linked to the voltage and temperature sensors. For what concern the voltage it is measured by a simple subtraction between every cell (knowing the nominal voltage of the cells is quite simple to evaluate the single voltage of each). On the other hand, the temperature is measured by a sensor. The module is equipped by two thermistors that use NTC technology (negative temperature coefficient). Finally, another plastic element covers the upper part. The two sides of the module present the power connectors (positive or negative). On the negative side there are also the connectors for acquire data (voltage and temperature). As already said the cells are 6 with a configuration of 6S1P (6 cells in series and 1 in parallel), each cells weight 2.04 Kg and has a nominal voltage of 3.64 V (min voltage 2.9V and 4.2 V max). This configuration permits a total nominal voltage of 21.84V (6*3.64V because the equivalent voltage corresponds to the sum of the voltage of each cell) and a total capacity of 148 Ah (the equivalent capacity corresponds to the capacity of a single cell due to the Kirchhoff laws). The cells in this case are prismatic, but this is not a constraint for VDA modules. In fact, chemistry, number, equivalent voltage and capacity, layout, and type of cell is not a constraint for VDA. On the other hand, the only mandatory requirement are the dimensions (390.0, 151.5, 109.0 mm)

VDA355 - Microvast

As the previous case the “355” stands for the mm of the length, the high is 108.0 mm and the width is 151.0 mm (355x151x108 mm). In this case the metal case cover also the edges of the module but substantially the manufacturing process is very similar to the other one: again, Aluminum sheet parts welded together. The upper and the lower part are covered by plastic layer and the total weight is 11Kg due to the smaller volume. In this case the cells inside are 12 in a 6S2P configuration with pouch technology. Thanks to the lower volume, the pouch can be more than prismatic one, but in this case need a precompression in order to avoid swelling. The figure 15 permit to understand how the cells are positioned inside the module. Moreover, the flat connector is very similar to VDA390.

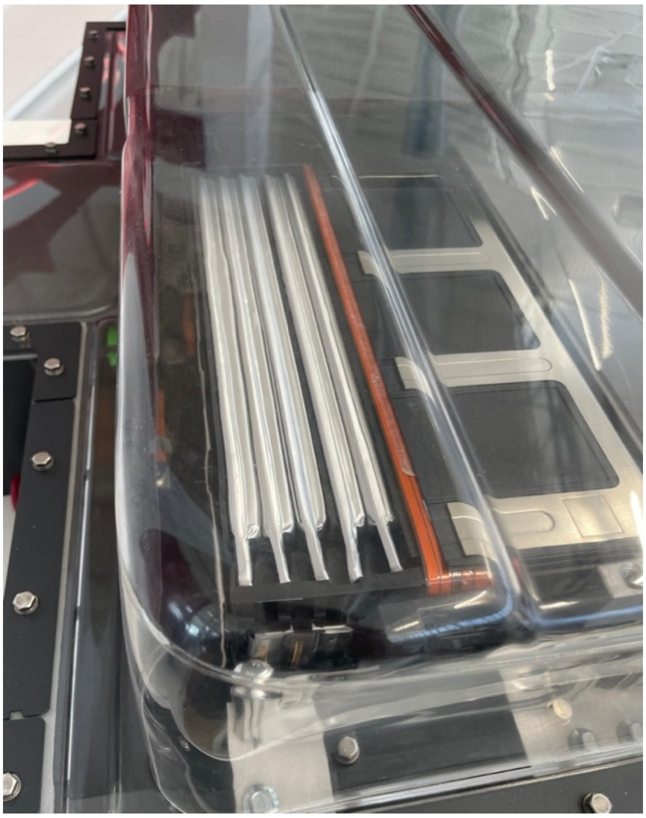

Figure 15 internal view photograph of Microvast VDA355 module

Sensors are not visible from this image because are hided internally due to the different position of the cells compared to prismatic one. Contrary to what might think the equivalent nominal voltage is equal to 22.2V (slightly higher compared to 390 modules) due to 3,7 V cells (3V min voltage and 4.2V max voltage). The equivalent Capacity is 103.6 Ah (51.8 Ah each cell). The capacity is good considering the lesser dimension compared to VDA 390. For what concern the chemistry of the module, in this case, Microvast equipped the VDA355 with NCM pouch cells. In particularly the composition of NCM is 811. As already explained this concentration is a new technology that has 80% of Nickel, 10% of Manganese and 10% of Cadmium that permit a large cost saving due to a low concentration of Cd.

In the following table all the data are grouped considering the two modules in order to see better the differences.

		u.m.	VDA390		VDA355	
Manufacturer	-	-	BYD		Microvast	
Format	-	-	Prismatic	6S1P	Pouch	6S2P
Series	-	#	-	6	-	6
Parallel	-	#	-	1	-	2
Dimensions	LxWxH	mm	-	390x151.5x109	-	355x151x108
Chemistry	-	-	-		NMC 811	
Capacity	Nominal	Ah	148	148	51.8	103.6
Voltage	Nominal	V	3.64	21.84	3.7	22.2
	Min	V	2.9	17.4	3	18
	Max	V	4.2	25.2	4.2	25.2
Energy	Nominal	kWh	0.54	3.23	0.19	2.3
Weight	-		2.04	13.5	0.963	11
Energy density	Nominal	Ah/Kg	0.264	0.239	0.217	0.209

Table 2 data summary of VDA390 BYD and VDA355 Microvast

3. Project Definition: S.L.I.M. – Second Life Interchangeable battery Modules

In this chapter is finally described the definition of the project, which are the goals, constraints, and the analysis behind every steps. The S.L.I.M project, acronym for "Second Life Interchangeable battery Modules," represents an innovative initiative in the field of depleted lithium batteries. "Second Life" refers to the concept of giving a second life to used batteries rather than simply recycling or disposing of them. This approach aims to fully exploit the residual potential of lithium batteries. It is known that lithium batteries, when they reach a state of health (SOH) of around 80%, may no longer be reliable for automotive use. However, in this context, they can find a new life and application thanks to the principle of swappability. This concept implies that these modular units can be easily removed from one application and inserted into another, where they can still play an important role. “Modules" defines the basic unit of these batteries, the smallest functional unit. These modules can be easily combined or separated to adapt to various needs. When connected in series, these modules allow for an increase in the overall voltage, making the batteries suitable for applications that require higher voltages. Conversely, parallel connection allows an increase in total capacity, providing an ideal solution for applications requiring greater energy storage capacity.

In summary, the modularity allows for extraordinary flexibility in adapting these batteries to diverse needs, from small traction vehicles like scooters or electric scooters to home energy storage systems. S.L.I.M represents a sustainable and versatile approach to managing depleted lithium batteries, promoting reuse and waste reduction.

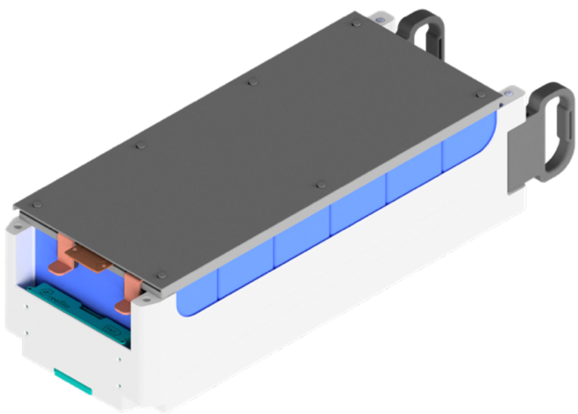

Figure 16 front view of the new VDA390 SLIM project

For what concern the module choice was on VDA390 for different reasons:

1. VDA modules are largely used in electric cars.
2. Reefilla, the company that collaborate for this project already work on that module, so it was easier to have data and physically have that module.
3. VDA390 and VDA355 differ only for longitudinal measure so it's very easy to apply the same modification on both the module.

Is necessary to explain that this is the first case of module conversion, in particularly with VDA modules. In fact, up to now modules for traction battery are designed and manufactured only for that purpose and the same for swappable battery. With this project the goal is create a swappable battery starting from an existing standard from the automotive industry. The idea is to diffuse the standard VDA not only in car application but also for other purpose like house energy storage, scooter, motorbikes, or mobile charging stations as Reefilla do with their products.

The next step is explaining how the project was done, which are the constraints and the benchmarking done to understand the market of swappable battery.

3.1 Constraints

This section delves into the project's initial constraints. As mentioned previously, the modules utilized are VDA 390, and the objective is to completely revamp the module for use in a car's traction battery, as well as for other purposes. Consequently, the first constraint is to preserve the original module's dimensions. Furthermore, in the pursuit of designing a swappable module, the product's weight assumes significant importance. Since the swappable module is meant to be handled manually, it cannot be excessively heavy for practical reasons.

3.1.1 Dimensions

The foremost objective is to preserve the original case dimensions, which are 390.0 mm in length, 151.5 mm in width, and 109.0 mm in height. These specific measurements are crucial in ensuring compatibility and integration with the existing module design. This constraint is one of the most important one because the battery pack are made up of modules that are connected and stacked together, so changing only one of their dimensions could create huge assembly problems.

Hence, two additional dimensions were considered during the design phase. Figure 16 reveals the presence of four holes at each edge of the module, intentionally incorporated by VDA to secure modules within the battery pack and facilitate stacking, allowing for interlocking.

The greater distance measures 374.6 mm, while the gap between the holes arranged widthwise amounts to 133 mm.

3.1.2 Weight

In the previous paragraph the weight of the VDA modules was reported and in 390's case is 13.5 Kg. Considering that the weight of one cell is 2.04 Kg, the weight of the case and all electronics is 1.26 Kg.

The second objective is to maintain the case's weight while introducing new features to transform it into a swappable unit. An example is the presence of the bottom protection in the new frame unlike the original one or introduce a BMS housing.

Thanks to the software Solidworks, used for the design phase of the project, is possible to evaluate the weight of only the metal case of VDA390. Considering a volume of mm^3 and converting it in cm^3 and assuming a constant density of 2,7 g/cm^3 [14] for the aluminum the final weight of the case corresponds to 928.62 g.

3.2 Benchmarking phase

After constraints, the second steps is understand the market offers, this means that a benchmarking analysis is necessary.

The objective of benchmarking is to comprehensively analyze the offerings of competing battery manufacturers in the market and systematically categorize each product based on a set of predefined parameters. This practice is largely employed by companies during the initial stages of designing a new product. It enables them to acquire a deep understanding of the prevailing conventions within a specific product segment, comprehend customer preferences, and strategically introduce a new product that outperforms competitors' offerings.

Considering that battery technology and even more swappable one is in an early stage, company do not provide lot of specifications. For these reasons is almost impossible find complete technical data. In the following sub-paragraph tables illustrate the available specifications and a set of parameters will be considered to formalize the functional objective (FO) of the project. In the design phase, the parameters under consideration are as follows:

1. Overall Module Weight: The total weight of the module must not exceed 15 kilograms; surpassing this limit would render it insufficiently ergonomic and unsuitable for swapping purposes.
2. Material Selection: The choice of material is closely related to the weight criterion. Material selection is a fundamental aspect of the module, as it should not add unnecessary weight to the final product. Simultaneously, it must exhibit sufficient robustness to safeguard the internal cells.
3. Geometry and Shape: the presence of sharp edges or irregularities in the module's geometry can compromise its overall structural integrity.

4. Handles and Gripping System: handles and the gripping mechanism constitute pivotal elements in a swappable battery system. They serve as the interface between the user and the module itself, making them essential considerations in the design process.
5. Connector, it must exhibit a delicate balance between robustness and versatility. A robust connector ensures the durability of the module, while versatility guarantees compatibility across various systems and applications. Hence, meticulous attention is devoted to the selection and design of the connector to meet these dual requirements effectively.

Kumpan

Capacity [Ah]	28.50
Nominal Voltage [V]	51.38
Energy [Wh]	1464.3
Chemistry	NMC
Dimensions [mm]	394 x 89 x 213
Weight [kg]	9.9
Number of cells	150 Cylindrical 14s10p
BMS	yes
Energy density [kWh/kg]	0.148

Table 3 Data of Kumpan module

Figure 17 Kumpan swappable batteries

This technology was used by a scooter company that developed this module. The weight is under the limit, and this is due to a good blend of structural material. The lower segment incorporates soft plastic, serving as a protective element against potential impacts. Meanwhile, the body of the module is constructed from aluminum, lending it structural integrity, and the upper section is composed of rigid plastic for lightweight reasons. The handle system is a large and solid handle that can lift vertically and unhooking the connector. The shape is regular, a rounded shape could be better, but thanks to the material the module is very robust.

Gogoro swappable battery [15] [16]

Capacity [Ah]	-
Nominal Voltage [V]	-
Energy [Wh]	1300
Chemistry	NMC
Dimensions [mm]	-
Weight [kg]	9.0
Number of cells	-
BMS	-
Energy density [kWh/kg]	0.144

Table 4 Data of Gogoro module

Figure 18 Gogoro swappable batteries

Gogoro stands as one of the prominent leaders in the market of swappable batteries and micro-mobility. Their model centers around a comprehensive infrastructure network comprising swappable battery stations (refer to Figure 18). These stations enable riders to stop, swap and restart the riding in a few minutes just like a normal gas station. Unfortunately, Gogoro do not share lots of specifics. However, their battery module aligns with prevailing industry trends in terms of weight. The material employed in its construction consists entirely of rigid plastic, which not only imparts lightweight characteristics but also provides the requisite durability, facilitated further by the inclusion of rounded edges designed to safeguard the internal cells. Finally, the handle is enough comfortable but with only one way to grip it.

Honda Pawer Pack [17]

Capacity [Ah]	26.1
Nominal Voltage [V]	50.34
Energy [Wh]	1314
Chemistry	Li-ion not specified
Dimensions [mm]	298 x 177.3 x 156.3
Weight [kg]	10.3
Number of cells	-
BMS	-
Energy density [kWh/kg]	0.128

Table 5 Data of Honda module

Honda develop a swappable battery with a slightly higher final weight with a full plastic cover. The primary innovation in this product lies in the handle design. Unlike previous cases where a standard handle was employed, the handle system in this case adopts a "T" shape. This design feature allows for two distinct gripping methods or facilitates movement with the assistance of the second hand. However, it is noteworthy that this module incorporates a connector that permits insertion in only one specific orientation.

Figure 19 Honda swappable solution

Kymco ionex [18]

Capacity [Ah]	13
Nominal Voltage [V]	50
Energy [kWh]	0.650
Chemistry	-
Dimensions [mm]	-
Weight [kg]	5.0
Number of cells	-
BMS	-
Energy density [kWh/kg]	0.13

Table 6 Data of Kymco module

The most striking feature is the remarkably low weight. In fact, when examining the stored energy, it becomes evident that this product has been specifically designed for coupling with other modules. As a matter of fact, the handle system, when considering a single module, may not be highly ergonomic. However, when coupled with another module, it offers improved ergonomics.

Moreover, this solution utilizes plastic materials and a prismatic shape with rounded edges to enhance robustness and safety. Notably, the connector is engineered to facilitate module insertion in both orientations.

Figure 20 Kymco ionex swappable batteries

WOW – Scooters [19]

Capacity [Ah]	32
Nominal Voltage [V]	36.5
Energy [Wh]	1150
Chemistry	NCM
Dimensions [mm]	442 x 88 x213
Weight [kg]	7,5
Number of cells	130
BMS	-
Energy density [kWh/kg]	0.153

Table 7 Data of WOW-scooters module

WOW company develop an EV scooter with a revolutionary battery position. If other company insert the modules under the seat, WOW designed a solution with two batteries that are inserted in a designed allocation placed on the left and right part of the seat (illustrated in the figure). This solution simplify battery swapping and increase the storage volume under the seat. To save weight, the cells are covered by plastic material and the final energy density correspond to 0.153 kWh/kg. This means that is the best solution considering the five products analyzed. There are two drawbacks to this solution: a less ergonomic handle and a bulky connector shape.

Figure 21 WOW-Scooter swappable batteries

4. S.L.I.M. Description

In the previous chapter the basis of the SLIM project has been analyzed. In the following lines the focus is on the technical solutions to realize the final frame.

The SLIM project began with the analysis of a preliminary version of a swappable module. In fact, Reefilla initiated this project in collaboration with the company Endurance, with the aim of making the VDA390 module swappable. This project is part of a European initiative called IPCEI, which stands for "Important Project of Common European Interests," aimed at achieving goals of radical innovation and significant technological and production relevance. This is accomplished through a shared effort between the private sector and the public sector of the member states to implement common-interest interventions within the strategic value chains for the European industry. Specifically, the collaboration between Reefilla and Endurance focuses on the "Batteries 1" and "Batteries 2" projects. The innovative objectives of the project revolve around enhancing the environmental sustainability of various segments within the value chain. This includes efforts to reduce emissions and waste generated by production processes and to develop sustainable and eco-friendly models for disassembly and recycling of components and materials in line with the principles of the circular economy.

4.1 Step zero

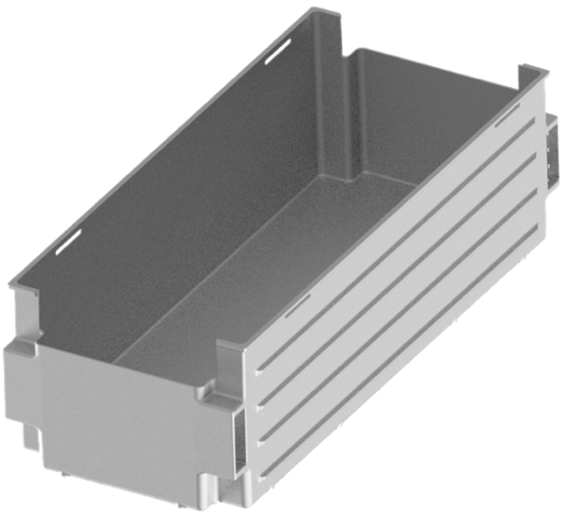

Figure 22 step zero of the project done by Endurance Overseas

Step zero is a prototype of a case capable of accommodating the original VDA390 module. The aim of this phase was to establish a framework for housing modules and create a new standard based on this framework. However, the initial constraints were not met, in fact, the overall dimensions (length, width, and height) exceeded those of the VDA390, making the new case unsuitable for its original purpose. Nevertheless, a significant advancement was achieved in terms of materials and production methods. Endurance Overseas, being a leader in aluminum die casting, utilized a High Pressure Die Casting (HPDC) technique for this prototype. HPDC involves the casting of molten metal (in this case, aluminum) under high pressure into a mold cavity. This method enables the casting of highly complex shapes and ensures complete cavity filling due to the high pressure. Moreover, it results in significantly superior surface finishing compared to low-pressure techniques and allows to produce thinner walls.

4.2 Case

From now on the focus is not the step zero, but an evolution following the pros of the previous versions and the constraints highlighted in the previous chapter.

4.2.1 Cell compartment

To make progress, the initial step involved comprehending the internal dimensions of the current case, which essentially meant measuring the length, height, and width of the prismatic cells compartment. This measurement was conducted using the VDA390 CAD model (bearing in mind that the CAD model doesn't include cells but only the external frame and electronics). Additionally, another crucial data came from the dimensions of the cells. Unfortunately, these measurements were not readily available, and disassembling the VDA390 was not feasible. As a result, an estimation was derived, primarily through direct measurements of the cells using calipers and referencing the internal dimensions measured by the CAD model. The internal measurement by CAD correspond to 148.65 mm and by direct measurements the width of the cells is 147 mm. The difference is due to the internal tolerances and internal protection layers. For what concern the length of the cells the direct measurements correspond to 57 mm. Finally, the height is 103 mm measured directly with the caliper.

Width [mm]	Length [mm]	Heigh [mm]
147	57	103

Table 8 Cells of VDA390 dimensions

VDA390 module permit to contain 6 prismatic cells with a parallel connection. In original application they are glued together, and, in this project, the same assembly procedure is considered. For this reason, the dimensions occupied by the six are: 147 mm of width, 103 mm of heigh and 347 mm of length. An important clarification is needed: between every couple of cells a 1.0 mm of gap is considered for the glue. In fact, 57mm multiplied by 6 is equal to 342 mm and the gaps are five, so the final value corresponds to 347 mm.

Width [mm]	Length [mm]	Heigh [mm]
147	347	103

Table 9 Cells assembly of VDA390 dimensions

Finally, the internal dimensions of the aluminum case are:

- Length = 350 mm considering 1 mm (both sides) of a plastic cover and 0.5 mm (both sides) of tolerances plus 0.25 mm (both sides) of tolerances between plastic layer and cells
- Width = 148 mm considering 0.5 mm (both sides) of tolerances.
- Heigh = 106 mm, 3 mm more than cell for protection.

Figure 23 Upper view of the frame

For what concern the thickness of the lateral wall is 1.7 mm and 2.0 mm of the bottom part of the case. This thickness came from the suggestion of Endurance Overseas and their studies. The increased thickness of the bottom layer is due to the fact that this part experiences the most significant wear from friction.

4.2.2 Lateral walls

As said previously the thickness of the walls correspond to 1.7 mm and present an extruded cut with a rounded fillet of 21 mm. This design choice was made to minimize the overall weight of the case. The cut is positioned at the upper part of the case, as this area is less likely to encounter impacts. Continuing the description downward, we can observe two extruded elements running

Figure 24 Lateral view of the case

along the entire side of the case. This design facilitates the insertion of the case during the user experience.

4.2.3 Back part

This side of the case correspond to the position of the handle system. The first modification is the hooks holes designed by VDA. In fact, as the image suggest there are 4 smallest extruded elements against 2 bigger elements of the original VDA. This modification is attributed to the presence of the handle system. Originally, the project planned for a single fixed handle with two secondary side grips and a primary front grip. Indeed, given the weight of 13.5 kg and the substantial dimensions, particularly in terms of length, the option to have two grips and the ability to assist with the second hand are essential.

Last element of the back part is the layer of 1.7 mm that divide and protect the cell compartment to the handle system. The substantially difference from the initial project is that originally the layer was represented by an aluminum block welded with the lateral side of the module. It occupies a volume without reason with a waste of space, so no there is no reasons to keep it. As in the side walls, this layer also provides lightening by extruded cut as can be seen from the images 25.

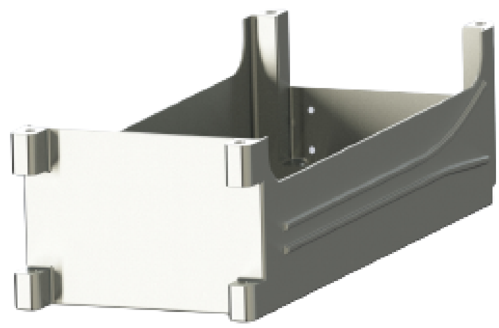

Figure 25 back view of the case

4.2.4 Front part

The frontal part of the case host BMS, power connectors and edges to help the module to be inserted.

BMS

Starting from BMS, in the previous chapter a brief description of what is and what are the requirements were done. On the contrary, in these sections, the focus is on the position and packaging of the BMS. As mentioned in the project description of S.L.I.M. one of the goals is the product reuse, for this reason the design of the BMS case was done with the same sustainability mindset. Firstly, the choice of material diverges from aluminum, which is used for other parts of the case. Instead, a plastic material, PLA, is selected. Specifically, the BMS case is produced using additive manufacturing techniques to minimize material waste, reduce scraps, and lower overall weight.

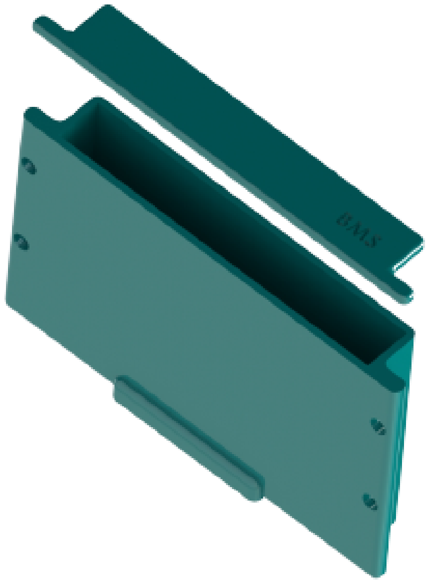

Figure 26 BMS case details

Regarding the assembly phase, the BMS is not directly mounted to the module but packed in a stand-alone case, with this solution is possible to mount and easily dismount the case and replace if necessary. The BMS case is fixed to the case by four M3 screws with easily access from the frontal part of the module. Additionally, the external shape is engineered to be inserted in the BMS compartment with only one way avoiding wrong assembly. Moreover, an arrow suggests the correct way to insert the case. Furthermore, the frontal part of the modules features a specific shape at the bottom to accommodate a step present on the BMS case. This alignment ensures the proper centering of the BMS case within the module during the assembly phase. Focusing on the BMS case, the internal dimensions are width, length and high. The wall thickness is 2 mm, and the external dimensions are. The case is designed to allow the BMS board to be inserted from above and securely wedged inside. To seal the case, a cover with an enough large hole is provided, enabling the BMS to connect to the module.

Power connectors

Power connectors are positioned above the BMS case and are in contact with the module by a layer of non-conducting material. The negative one is positioned at the same point of the original one, on the contrary the positive connector it was redesigned. Initially, the VDA390 module featured the positive terminal on the opposite side from the negative one, as the module was intended for series connections. In this case, it was necessary to reposition the positive terminal at the same side as the negative one for swappable use. The two terminals are connected to their respective counterparts using sliding connectors, where one terminal plate aligns with its counterpart, enabling the flow of current. This solution was adopted because standard connectors available in the market had significantly larger dimensions that would not allow them to fit within the constraints established at the beginning of the project. The drawback of this solution is that the sliding connector requires sufficient pressure on the contacting

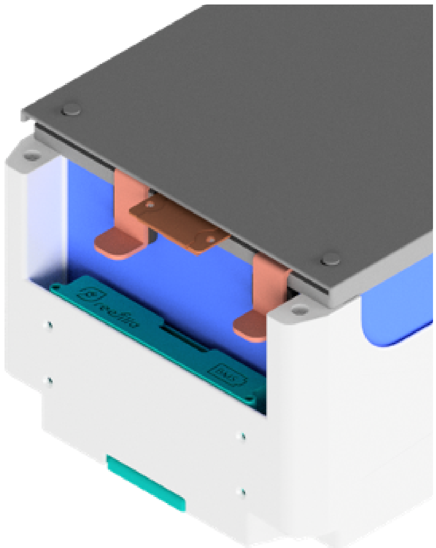

Figure 27 zoom on the "L" shape power connector.

surfaces to allow for the passage of enough current. Furthermore, surface roughness affects efficiency, in addition to the choice of material. In this project not all that aspect was taken into account because the focus wasn't the flow of current of power connectors, so the only aspect considered was the material choice, and due to the fact that Copper was already used for the original connector, also the new solution uses this material. A further improvement of S.L.I.M project could be a study of sliding connectors that involve variable like shape, contact area, force/pressure, roughness, and material.

Another important aspect is the "L" shape of connector since the module is inserted vertically has a surface perpendicular to the weight and permit to has 13.5 Kg on connector. On the other hand, if the use is horizontal, the mass of the module cannot help but there is a perpendicular surface that can be matched and that can be under pressure to ensure current flow. Finally, a hole is present to allow te module to be used as the original purpose and screwed with another module's connector.

"L" shape connector with sliding technology represents one of the best choice for this application because permit a large uses and increase the versatility of the module.

Edges and centering system

One of the functional objectives of the design phase is enhance the ergonomics aspect of the module and facilitate the swapping in each use. In order to fulfill this requirement a deep study was done in the shape of the frontal part.

Figure 28 front part with edges details

The aim of this part of the project is to facilitate the insertion of the case along the x axis, where x corresponds to the length of the module. Starting from the lateral parts the edges were designed with an angle that enhance the robustness of the module and increase the user experience in the insertions. Figure 28 represent the frontal part of the module with a specific zoom on the edges designed at the corners. In particular these shapes the help the centering on the y-axis without compromise the overall dimensions of the case and respect the initial constraints of the project.

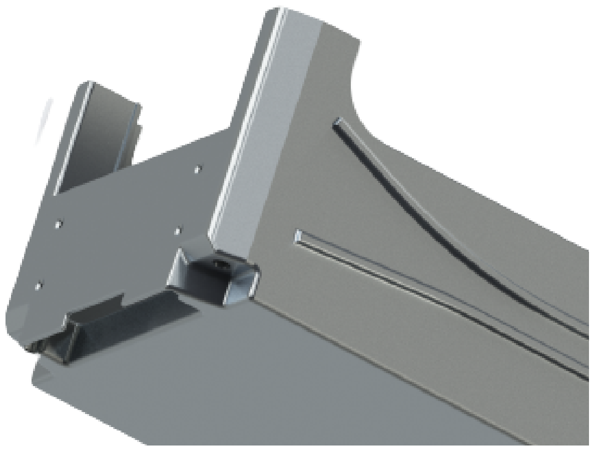

Figure 29 front part with lower insertion detail

With the same work method, the bottom part of the frontal face is designed. In this case the centering involves all the 3-axis due to the shape of this detail. A clarification is needed: the holes in the VDA390 module pass through the entire structure along the z-axis. At the bottom end, where the centering shape is located, the holes have a surface perpendicular to the axis of the hole. This is necessary during the docking process to ensure that the mating part to which the module is attached fits perfectly with the module itself.

4.3 Handling system

As anticipated in the previous chapter the handle system presents different steps of design. The step zero is presented by figure 30, this prototype is needed in order to define constraints and work inside a perimeter to reach the final goals of ergonomics and flexibility of the module. It presents a rigid and fix handle with two lateral grips and one bigger front grip. Subsequently constraints and goals were defined, and the strategy totally change considering a mobile handling system.

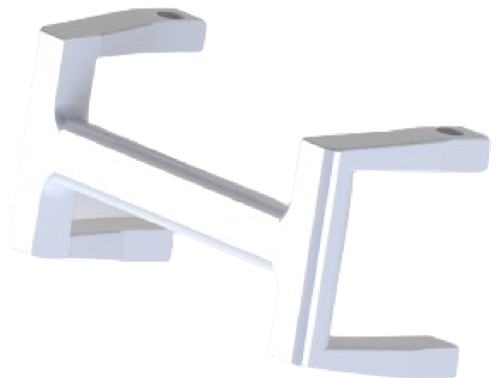

Figure 30 first prototype of handle with one rigid structure

Constraints

Initially, the handle system was not included within the dimensions and thus did not fit with the initial constraints. However, in order to create a 360-degree compatible project with the original VDA390, it was decided to upgrade the handles and completely change the strategy by incorporating the handles within the dimensions of the VDA model (Length, width and height).

Goals

To fulfill all the functional objective of the project a special attention has been paid to ergonomics, lightness, and locking system to enhance the characteristics of the frame. As said before after the step zero there was a change in the design, splitting the original handle into two side.

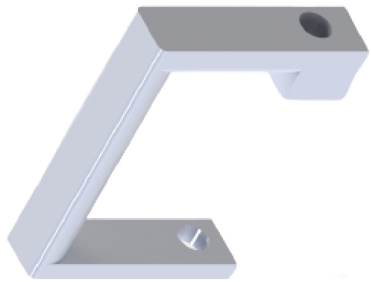

Figure 32 intermediate prototype of semi-handle

Going more in deep, the single handle is linked to the case by the holes designed by VDA by a screw M6. This solution permits a rotation around that axis and then allow to the half-handle to be adherent to the case when is not used. By this design the constraints are satisfied, but the ergonomic of the handling system decrease. In fact, use two small semi-handles do not permit a strong and ergonomic grip, for this reason a soft element made up of plastic material or leather link the two elements improving the total grip without compromising the volume occupied. This soft component is firmly secured at both ends by two buttonholes placed in the semi-handle (visible in figure 32). This solution represents a compromise because the soft handle may not be the optimal solution, but no other alternatives were found to meet the requirements.

Figure 31 final semi-handle prototype

The second aspects considered in the design phase was the weight. In fact, one of the goals of the project is to avoid or contain the weight. For this reason, the handling system spitted is a reduction of weight: from 202.0 g of the first rigid prototype to 179.0 g of the last one prototype. The material choice is again aluminum, but during the design phase some prototypes was created for feasibility study, and they were crafted by additive manufacturing technique. The incredible results are that this plastic semi-handle was able to hold the weight of the entire module. Considering the density of PLA (additive manufacturing material used) of 1.3 g/cm^3 the final weigh amount to 86.5 g with a reduction of weight of 52% from the aluminum semi-handle and 58 % from the first rigid prototype. Certainly, a further investigation on the robustness of plastic solution is needed if the choice falls on PLA solution.

The final goal in designing the handles is to create an integrated locking and fastening system within the handle. In other words, the analysis of previous swappable batteries has revealed the presence of a fastening system that allows the module to remain securely attached to its counterpart. Most of these systems utilize a snap-fit mechanism, whereas Kumpan employs a release and attachment system with a mechanism connected to the handle. By lifting the module using the handle, the system disengages. Conversely, when placing the module into its counterpart and pushing the handle into position, the fastening system securely locks the module in place.

Taking a closer look at the image of the final prototype, two details stand out:

1) Instead of a hole, there is a buttonhole through which the bushing passes, enabling the handle's rotation (also visible in figure 32).

2) One of the two corners near the buttonhole features a curvature.

Figure 33 zoom on closing position of the handle.

The first solution allows the handle to rotate around the z-axis, slide along the x-axis according to the case's reference system and move along the y-axis in order to take up more space. When the handle is open, they are not completely aligned along the x axis, but has an angle between 45 deg to 60 deg. After placing the module, a force perpendicular to it will not only close the handles with a rotation but also, thanks to the buttonhole's shape, distribute this force with a component along the y-axis, thus enabling the outward slide. The second structural element is designed to facilitate both the sliding and rotation of the handle by avoiding impeding. In summary this two-solution permit to split the force into 2 components: one on x axis that permit rotation, and one y axis that permit external shift on y axis.

4.4 Top Part

So far, we have described the main components of the new VDA390 module, starting from the case and its design using SolidWorks, passing through the various design steps, and concluding with a sophisticated handle system that also serves as a locking system. In the current section, however, we will move away from mechanical design and partially redesign the power connection, data connection, and insulating system.

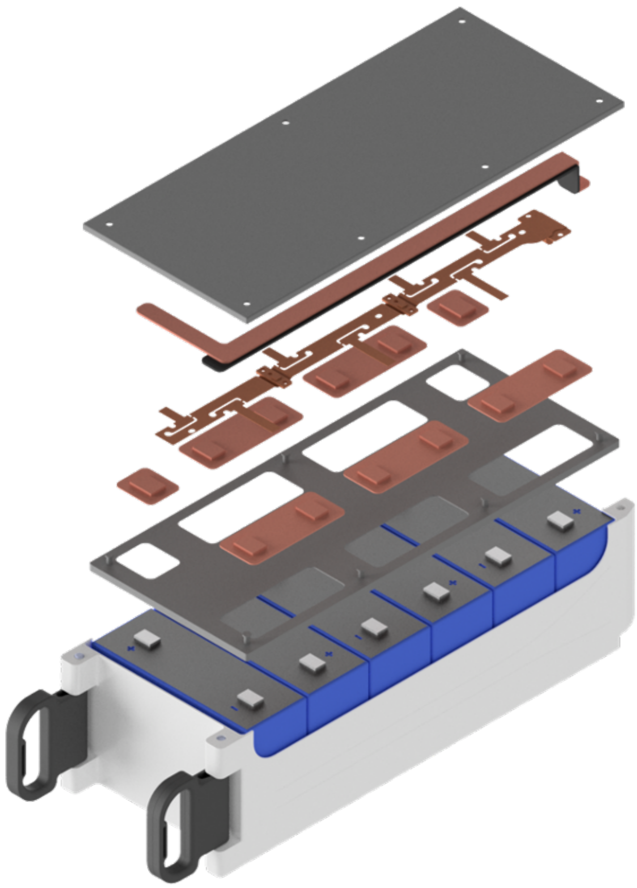

Figure 34 new VDA390 exploded representation

The case containing the cells and the handles alone does not enable the module's operation. It requires a system to connect the cells in parallel, collect data, and deliver power. More specifically, the functions of the top part of the module are as follows:

- Connect the cells

- Connect the BMS to the data collection system

- Connect the cells to the counterpart

- Insulate the connectors and provide protection

4.4.1 Lower cover

The first element analyzed is the plastic cover of the cells. This element is also present on the original VDA 390 with the aim of protection of the upper part of the cells and align the connectors of the cells. In the original configuration this layer is positioned and crimped by the side walls. It presents a particular shaped that permit during the assembly session to position the connectors of the cells. The second use is insulated and prevent unwanted contact between cells and every elements position on them.

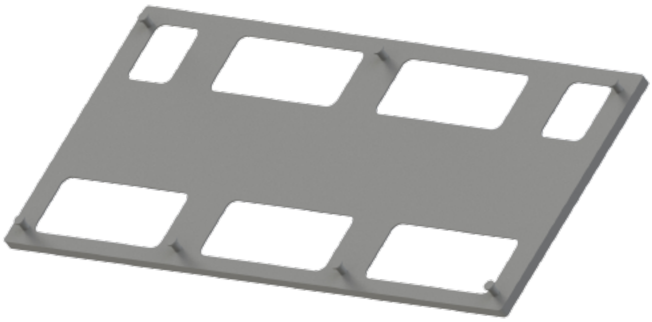

Figure 35 Lower cover detail

The new version is relatively simpler, but the final goals are the same. The holes present on the layer were designed in order perfectly fit the cells connectors and avoid misalignment in the assembly phase. In the original solution the layer is crimped, indeed this solution cannot be considered due to the deep restyling of the case. The new design includes four folds, one for each side, with the purpose of spanning the six cells and anchoring it to the system. Another important aspect are the tolerances, in this case no gaps between cells and layer are considered, so the internal dimensions are the same as the cell's dimensions. Zero gap decision was taken in order to create a slight interference and permit to compact the cells system. Finally, the thickness of the layer is uniform and correspond to 1 mm. The final dimensions are length of 350 mm and 150 mm.

Length [mm]	Width [mm]	Thickness [mm]
350	150	1

Table 10 Lower cover dimensions

4.4.2 Cells Connectors

A said in the previous descriptions, the cells are positioned very close each other (considering 1 mm gap due to glue) and the poles are positioned at the top face. To connect in series, the cells are necessary to link the opposite poles by conductive material. First consideration is about the positioning, the cells must align mirrored in order to obtain a situation in which the opposite poles are coupled. Second step is connecting the opposite with a metal connector that is called "bigger connector" and cover the final poles with a single connector called "smallest connector".

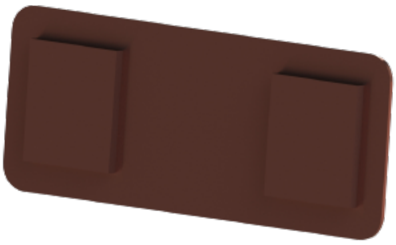

Figure 37 bigger connector detail

Figure 36 smaller connector detail

The difference is only the dimensions: the first one cover a larger area in order to link two poles and the second one cover a single pole. The material choice is copper as the original connectors and the dimensions are: 35 mm width for both cases and 30 mm length for the smaller one and 88 mm length for the higher one. Final dimension is the thickness of the connectors, and it is the same for both the versions and correspond to 1 mm.

Length [mm]	Width [mm]	Thickness [mm]
30	35	1

Table 11 small connector dimensions

Length [mm]	Width [mm]	Thickness [mm]
88	35	1

Table 12 big connector dimensions

Last design features are the shape of the connectors. As the figure suggest the connector is like a cover with a part that can host the cells' poles. In other word the poles aren't at the same level of the cells but 1 mm high, the connector is designed in which the upper part is in contact to the poles and the edges around are in contact to the plastic part of the cells. This feature is not completely new, the original solution uses a similar situation, but this version permits an easier installation.

4.4.3 Data connectors

Up to now it was described the position of a plastic cover and the connection of the cells. In this section the flat connector is described. This element is directly connected to the poles by the connectors and locked in that position by glue. Moreover, two temperature sensors are integrated in the flat connection and positioned equally spaced to acquire data reliably. The position is near the negative pole and run along all the length of the module, moreover, it is glued to the plastic cover previously described in order to be keep in place.

For what concerns the sensors, these flat connectors permit to understand voltage drop between each cell and temperature in 2 points of the module.

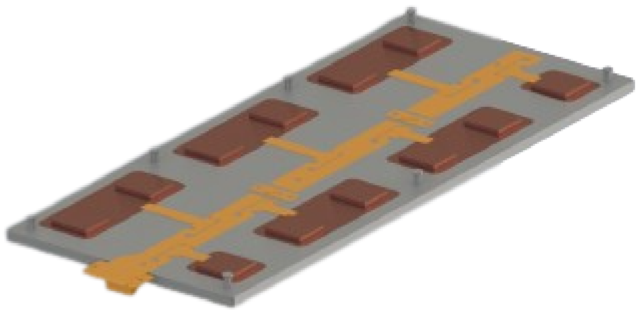

Figure 38 Data connectors (orange), poles connectors (copper color) and lower cover (grey)

Voltage

The voltage of each cell is determined by subtracting one voltage from another. This system relies on the flat connector being linked to each pole connector, and the difference between the voltage measurements corresponds to the voltage of the cells. This approach is maintained in the new version of the module, as it continues to be the most cost-effective and space-efficient solution for assessing cell voltage. By this method, we ensure consistency with the original module's design principles while meeting our objectives for the redesigned module.

Temperature

Ideally, measurements of internal temperatures for each cell would be preferable. However, it should be noted that cells are not typically produced with built-in temperature sensors. Consequently, we must depend on external temperature measurements of the cells. Moreover, considering the cost associated with each sensor, is better to minimize the total number of sensors necessary. By employing a precise thermal model for the pack, we can strategically position a limited number of temperature sensors externally to one or more cells within a module. This allows for the estimation of internal temperatures for all cells, which typically proves to be satisfactory. In terms of sensor types, two main solutions are commonly utilized [20]:

1) Thermocouples: this approach involves two dissimilar metal elements in contact with each other, functioning like a miniature battery. A change in temperature induces a voltage drop, which can be amplified and measured to calculate the temperature.

2) Thermistors: this method is more commonly employed, primarily due to its cost-effectiveness. The working principle of thermistors relies on the change in resistance in ohms with temperature variation. In other words, resistances alter their values as a function of temperature. While conventional resistors are designed to minimize this effect, thermistors are engineered to amplify this characteristic, enabling temperature calculations based on the resistance change. There are two types of thermistors: Negative-temperature-coefficient (NTC) thermistors exhibit resistance that decreases as temperature rises, while positive-temperature-coefficient (PTC) thermistors display resistance that increases with temperature. These characteristics make NTC and PTC thermistors suitable for various temperature-sensing applications, depending on the specific requirements of the system.

The original module is equipped by two thermistors equally distanced between cells, the same kind of sensors and number is utilized in the new version of the module VDA390.

4.4.4 Power connectors and insulator

Proceeding layer by layer, the next step are the power connectors. Originally the negative module’s pole is directly linked to the negative pole of the cells on the right and the positive module’s pole is directly linked to the positive pole of the cells on the left. This solution permit to place the poles of the module in the opposite side favoring the series connection placing one module along the other. Regarding the new VDA390 module, it doesn't have a single primary use; instead, the core of the project is flexibility, allowing the same module to be used for multiple applications. To achieve this, the best solution is to place both the poles on one side and the handling system on the other side. This approach is the best in terms of flexibility. To do that a radical change is needed to transfer the positive pole to the other side of the module. Due to the cells layout the best solution is place a busbar that run along the entire module. To do that different aspect and challenge must be taken into account:

- Available volume and position
- Insulation
- Materials

Starting from the first, the available space is very small, in particular the main problem is the heigh. For what concern the placing, the solution is position the busbar near to the flat connectors, this solution can be possible because during the designing phase all the other components were reduced in dimensions or replaced to create enough space. The second point is closely related to the space requirements. The connector needs insulation from the plastic layer mentioned earlier. Keep in mind that the module has a capacity of 148Ah, and even though the discharging phase is not at 1C, it's essential to consider the worst-case scenario. Finally, the last point concerns the material choice. Following the original module's criteria, copper is once again chosen for its high conductivity capacity. For the same reason, the thickness and width of the busbar remain the same as the original VDA power connectors.

Length [mm]	Width [mm]	Thickness [mm]
331	15	20

Table 13 Positive busbar dimensions

Regarding the negative pole, the original setup utilizes an L-shaped connector. In the new module, the negative pole retains its configuration, and the figure 27 accurately depicts the final arrangement and shape of the power connectors.

4.4.5 Upper cover

The final component in the top part of the new VDA390 module is a plastic protector that serves several essential functions, including:

- Insulation
- Lightweight construction
- Protection

Figure 39 Upper cover of the new module VDA390

The first two point are directly linked to the material choice, in fact again the plastic material is used for this purpose. The choice of plastic material is due to its lightweight nature. Subsequently, it was selected for its excellent electrical insulation capabilities, and flexibility was another key reason. The locking system for the upper cover was copied from the original model for its versatility, easily removing, and cost-effectiveness. The locking system consists of seven holes with a diameter of 0.5 mm, positioned in groups of four on one long side and three on one short side. This arrangement was dictated by space considerations, and there is no fourth hole due to spatial constraints. These holes correspond to pins positioned along the same axis in the lower cover.

Length [mm]	Width [mm]	Thickness [mm]
352.5	152	0.5

Table 14 dimensions of the upper cover

This system ensures that the lower cover and all components described up to this point remain securely attached to the module. However, if access is required, it is sufficient to remove the upper cover, which is secured by a hole-pin system. Specifically, the pin has a cylindrical shape, but the upper end has a larger diameter. This design creates an interference fit between the hole and the upper part, requiring effort to insert and remove the upper cover.

Figure 40 detail of interference pin

The designed system is ideal in terms of lightweight and simplicity, but there are some critical aspects. Firstly, as it stands, it's not marketable because it allows easy access to the poles (not dangerous due to the low voltage of around 22 V), it's not waterproof, and the module is not protected against extreme impacts on the top side. The most challenging aspect is staying within the predefined dimensions of the VDA390 model. The brand-new module exceeds the original model by 3 millimeters. However, the need to move the positive pole to the opposite side prevents it from meeting the height constraint. This doesn't pose a significant issue since, in most applications, the critical factors are the module's length and width. However, there is room for potential future enhancements, such as:

- Enhanced protection
- Waterproofing
- Maximum height compliance

4.5 BMS – Battery management system

In the first chapter a brief introduction of BMS was done. The primary purposes of this component were highlighted:

A. Protect operators from dangerous situation of over voltage and over current from the battery pack.
B. Protect cells and modules from unsafe condition.
C. Prolong the battery life.
D. Maintain the battery pack in a condition in which it can fulfill the requirements.

To meet these four requirements, a list of tasks must be carried out by the BMS. However, before analyzing the tasks, a clarification is necessary. In this project, the design of the BMS has not been considered as it is not the core of the project. Instead, the main goal is to design a new module and configure a hypothetical implementation. Furthermore, the BMS design falls outside the scope of the automotive engineering curriculum and is not of importance for Reefilla. Lastly, the startup in question already possesses plug-and-play BMS solutions that are easy to install in every module.

The tasks that a BMS must do are:

1. Sensing and High-Voltage Control: The BMS needs to measure cell voltages, module temperatures, and battery-pack current. It should also identify isolation faults and control contactors and the thermal management system.
2. Protection: The BMS must incorporate electronics and logic to ensure the safety of both the battery-powered system operator and the battery pack. This involves safeguarding against overcharge, over discharge, overcurrent, cell short circuits, and extreme temperatures.
3. Interface: The BMS is responsible for regular communication with the application powered by the battery pack. It reports available energy, power, and other indicators of battery-pack status. Additionally, it should record any unusual error or abuse events in permanent memory for technician diagnostics through occasional on-demand downloads.
4. Performance Management: The BMS should have the capability to estimate the state of charge (SOC) for all cells within the battery pack. It must also calculate battery-pack available energy and power limits while ensuring cell balancing.
5. Diagnostics: Lastly, the BMS should be capable of estimating the state-of-health (SOH) of the battery, including detecting any signs of abuse. It may also be required to estimate the state-of-life (SOL) of the battery cells and the pack.

While the design of the BMS is not within the scope of this project, it's important to note that the original VDA390 modules do not include a BMS, as they are not intended for standalone use. Conversely, the new module design envisions the individual module being used in various scenarios, necessitating the inclusion of a BMS for monitoring and data collection. To address this need, and drawing on the information provided by Reefilla, a slave master BMS system has been considered. In essence, each module features a BMS slave responsible for monitoring and data collection. The BMS master, on the other hand, can interface with all BMS slaves utilized in each application. It has the capability to process data from the BMS slaves and take appropriate actions in line with the purposes previously listed, such as battery balancing for each module or work in safety conditions.

For instance, in the scenario of a small vehicle application with three modules, the BMS master is installed within the vehicle and communicates with every BMS slave present in the swappable modules mounted on the vehicle.

5. S.L.I.M implementation

Up to this point, the focus has been on the specific product, the VDA 390 module. It's important to specify that the restyling work carried out for the VDA 390 module could be applied to any VDA module. A very similar example is the VDA 355, which could be implemented by simply reducing the length of the cell compartments. All the other features designed and described can be implemented without any modifications: the handles and the locking system, the BMS compartment, and the connector system. The only thing that needs to be considered during the adaptations to any other platform is the type of cells. In the case of this specific project, the cells are prismatic and therefore do not require precompression by the structure. It's a different story if pouch-type cells are considered. In that case, different tolerances need to be considered to achieve compression inside the cell compartment. However, it should be noted that, as of today, in literature and the industrial world, the exact amount of pressure required has not been determined; it is only known that some level of pressure is needed.

One of the goals described at the beginning of this project is trying to reach an higher grade of flexibility from this type of module. Up to now VDA's module are implemented in cars' battery pack in embedded situation. The car maker assembly the pack and mount it to the chassis of the vehicle and no option of swappability can be done. The idea described by this project is a totally different approach: the module mounted in the car should be as designed in the previous chapter to reutilized after the first part of the battery life. In other word after 10 years, hundreds thousands km or better after a SOH under 80% the battery cannot be used for automotive traction but can be feasible for other purpose. Therefore, the concept is to install this module in the battery pack according to the described design but without the handles. At the end of the automotive's life, the battery pack will be disassembled, and the handle system and BMS slave will be attached to each module. Starting from this point the modules can be used singularly or more than one for other application as a second life battery and can fulfill other important requirements. Another type of implementation is utilized the brand-new module with 100% SOH cells for different swappable applications such as traction modules, and at the end of the first life can be implemented into an ecosystem that doesn't require traction energy storage system.

5.1 Microcar application

As already said an example of implementation could be the automotive one. The previous paragraph describes a situation in a standard passenger car, on the other hand, this paragraph will describe a totally different scenario. By "standard passenger car," we mean a four-wheeled vehicle with seating for four passengers, a maximum speed exceeding 130 km/h, and the ability to travel on both regular roads and highways. It's not feasible to consider applying the swappable module designed in this project to such vehicles. The reason for this lies in the fact that these types of cars require a large number of modules (on the order of dozens), which would necessitate significant physical effort from the user and relatively long replacement times for all the modules. The applications of swappability in the automotive context, as described earlier, are feasible when performed by machinery rather than by hand, and they are primarily aimed at replacing the entire battery pack's energy capacity in a single operation.

What will be described in this chapter is the application of the module in a small-sized vehicle, allowing for a maximum of 4 or 6 swappable modules, significantly reducing the physical effort and time required to change the entire battery pack. Additionally, the modules in question will not be second-life modules, as previously mentioned. Second-life modules would have too low state of health (SOH) percentage to be reliably used in a four-wheeled vehicle. In this case, new modules will be used, offering high performance. However, this scenario implementation uses new modules for multipurpose applications, such as home battery storage or two-wheeled vehicles like small scooters or electric bikes. Furthermore, these same modules, after reaching a lower SOH and reduced capacity, can still be used in all as second-life application, except for powering a four-wheeled vehicle. It was necessary to describe this scenario because the project involves the use of second-life cells. However, not all applications can make use of them. Nevertheless, the project remains applicable to second-life technologies and the world of reuse with a focus on module modularity.

Going more in deep with the specific application, the chapter title suggests the type of vehicle that will be discussed. However, when categorizing the vehicle, it is necessary to rely on the regulations currently in force. The Italian regulation follow a more international one published by European authority. Assuming that the product will be commercialized in Italy and Europe no other regulation analysis is necessary. This choice has been made because this category of vehicles would be ideal for the European market, unlike the North American NAFTA and South American LATAM markets. Those markets are not as familiar with electrification for various reasons, and culturally, they are more used to larger and more powerful vehicles. A similar discussion applies to the Asian market.

The categories currently described by the European Union refer to the UNECE [21] classification, which adopts a more specific sub-category with Regulation (EU) No 168/2013, in which the European Parliament approves the market surveillance of two- or three-wheel vehicles. This is followed by Directive 2007/46/EC of the European Parliament and of the

Council of 5 September 2007, which establishes an approval framework for motor vehicles and their trailers, as well as systems, components, and separate technical units intended for such vehicles.

The classified vehicles are divided into bands with identifying letters:

L	Motor vehicle
M	Passenger vehicles
N	freight vehicles
O	Trailers
T	Agricultural vehicles
G	Off-roads vehicle
S	Special vehicle

Table 15 Vehicle classification by the European Parliament

The M category corresponds to the primary classification of passenger cars, which includes four-wheeled vehicles designed to transport no more than 8 people and capable of traveling on all types of roads, including highways. In the case under consideration, microcars or "light/heavy quadricycles" in the Italian classification belong to section L, despite being referred to as motorcycles.

The L category is then divided into more specific subcategories. Leaving aside cases of vehicles with 2 or 3 wheels, the categories that consider 4-wheeled vehicles are L6 and L7 [22]. Specifically, L6 considers vehicles with a maximum speed of 45 km/h, an empty mass of 350 kg, and a motor with a maximum power of 4 kW in the case of electric motors. On the other hand, L7 considers vehicles with a higher empty mass of 400 kg and a maximum motor power of 15 kW. The design choice has been the L7 because they are considered more versatile with fewer limitations, and as described later on, it offers more degrees of development freedom compared to L6 vehicles. Furthermore, designing L7 vehicles can be considered more challenging as they have a higher speed, around 80-90 km/h, and nearly the same dimensions, making them more complex in terms of volume and range to design from a battery pack perspective.

In summary, L6 vehicles can be seen as downgrades in terms of power and energy compared to L7 vehicles. In other words, once an L7 vehicle is designed, it is much easier to adapt its characteristics to the constraints of an L6 vehicle.

In this section, the goal is to demonstrate how the newly designed modules, as explained earlier, can be used in an L7 class vehicle as well as within an ecosystem. Therefore, the analysis that will be presented here will not be specific to all the components that make up a vehicle but will focus on the battery pack of this new vehicle, taking into consideration the final range, energy consumption, and the modules layout starting from one or more electric motors suitable for this category.

The following steps in the design and analysis phase will be listed and subsequently explained. It should be emphasized that there is no specific standard, a single flowchart listing all the steps, but over time, carmakers have outlined the guidelines to follow to advance the project of a new vehicle or a new product in general. The macro phases are 4, namely:

1. concept generation and development.
2. product development and engineering.
3. process development and engineering.
4. pre-mass production and product ramp-up.

The design process begins by considering future market needs, available technologies, and strategic constraints. Multiple product alternatives are hypothesized and evaluated, with one or a few selected for further development and testing. In the automotive industry, the concept phase defines the product's shape, body type, expected functions, distinctive characteristics, preliminary technical specifications, target customers, and initial economic assessment.

Product engineering translates market requirements into detailed technical specifications, including product architecture, geometry, materials, and CAD drawings. Prototypes are created, and testing processes iterate until product validation. This phase also considers styling, layout, cost, and investment targets.

Process engineering transforms component design into manufacturing processes with defined investment targets. Key aspects include plant design, hardware and software design, and work design, ensuring efficient production.

Finally, the product is manufactured using the final production system, tailored to that product. Production rates gradually increase to meet planned performance and address any technological issues.

In this specific project, the initial analysis will focus on one aspect of the first point, which involves the development of an L7 class vehicle. The starting point has been the identification of competitors and assessing what the market currently offers. Later on, the examination of existing vehicles was done with an analysis of their key features, such as engine power, range, battery pack size, empty weight, maximum load weight, and so on. Subsequently, after examining the landscape of similar products, an identification of main parameters has been done in order to consider them in the design. These were the targets, or Functional objectives (FO), that must be achieved to be competitive in the market. Subsequently, the initial design calculations of the vehicle have been carried out to determine the technical characteristics (such as the type of engine, battery size, etc.) necessary to align with the Functional Objectives (FO). Following this path, the results were analyzed, since they met the desired goals, the development continued. However, if the results are not as expected, the FO may be revised and adapted to align with the outcomes. For example, if one of the FOs is to have a payload capacity of over 1000 kg, but this would require a significantly higher engine power than allowed by the L7 category regulations, the maximum payload might be adjusted to meet the constraints of the category. Subsequently, with the FOs defined, the project continued with e-motor research in the market. The requirement for this component was to stay in the limit of L7 categories but fulfilling al the tasks. After finding several suitable electric motors, it became possible to calculate the vehicle's energy consumption in kWh/100km and compare the results with direct competitors analyzed during the initial benchmarking phase. The final design step was the module layout analysis (series and parallel) that could meet the motor's voltage requirements and, most importantly, provide enough energy to achieve the range specified by the FOs. It's important to specify that the method for calculating consumption follows international guidelines that every carmaker must adhere to, specifically the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) [22]. The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is a globally harmonized standard for determining pollutant and CO2 emissions, fuel or energy consumption, and range for light electric vehicles (passenger cars and light commercial vans). Experts from the European Union, Japan, and India, under the guidance of the United Nations Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulations, developed this standard, with a final version published in 2015.

On September 1, 2018, WLTP came into effect, replacing the New European Driving Cycle (NEDC) as the test for vehicle registration in the European Union. The requirement for the homologation of new vehicle models/versions occurred on September 1, 2017. More specifically, the WLTC cycle consists of different phases: a low-speed phase, a medium-speed phase, and a high-speed phase, where the vehicle's speed is defined instant by instant. This means that each vehicle undergoing the test will adapt by changing gears to reach the required speed, resulting in specific consumption values for each vehicle. As mentioned earlier, the vehicle must also undergo a high-speed phase to simulate highway driving. Since all classes of vehicles must undergo this type of test, three specific tests have been created to accommodate even the slower or lighter vehicles. The classification is based on a ratio between the vehicle's power and its empty weight [24].

A. First class: ratio equal or lower 22.
B. Second class: ratio between 22 and 34 or equal 34.
C. Third class: ratio higher 34.

To calculate the vehicle class, the rated power of the engines and the curb weight must be provided. In the first case, considering that we are looking at an L7 vehicle with a maximum power of 15 kW, it is possible to use engines with a rated power of around 7.5 kW. Regarding the curb weight, it includes the vehicle's weight with added oils and lubricants, so we can assume it's around 400 kg. Finally, the curb weight corresponds to a fuel level of 90% (not applicable to electric cars) and the weight of the driver. For this value, it's reliable to use a figure of 550 kg. So, the ratio will be calculated as 7500 divided by 475 (curb weight minus the driver's weight), resulting in a value of 15.8. At this point, it is known that the vehicle in question belongs to the first class since the ratio value is less than 22.

To summarize, it is possible to outline a series of steps used for this part of the design and analysis of an L7 vehicle:

1. Benchmarking
2. Definition of Functional Objectives (FO)
3. Research and adaptation of components with respect to FO
4. WLTP cycle calculation
5. Comparison and analysis

5.1.1 Benchmarking

The first step in the analysis is benchmarking, which involves examining the characteristics of similar and/or competing products available in the market to establish a reference for the various features within that product segment. The segment under analysis, as mentioned earlier, includes the L7 vehicle category, which has a peak power of 15 kW and a curb weight not exceeding 400 kg. Subsequently, lower-class vehicles, L6, were also considered since they exhibit highly similar characteristics and are thus worth considering expanding the pool of information for benchmarking purposes. Before listing the evaluated characteristics and considered products, it's important to emphasize that the vehicle being described do not feature swappable modules, only one model has this technology, but only for sharing purpose, not private. This implies that the analysis for this project brings significant innovation in this field, exploring the possibilities of a new game-changing vehicle in the sphere of small mobility. For both L7 and L6 categories, the same characteristics were considered. Specifically, the first element analyzed was the engine. Both peak and nominal power were examined. Subsequently, several battery elements were considered, including capacity [Ah], nominal battery pack voltage [V], the chemistry of the battery, battery pack weight [kg], and energy density [kWh/kg]. Another analyzed element is the maximum vehicle speed, bearing in mind that L6 vehicles are legally capped at 45 km/h. An essential factor is the vehicle's range in kilometers, curb weight, and curb weight with passengers. Other factors include the number of passengers and the location of the drive axle. Lastly, the wheel radius is not to be overlooked as it plays a crucial role in determining motor speed revolutions, wheel speed revolutions, and the final gear ratio.

Electric motor	Nominal power	kW
	Peak power	kW
Battery Pack	Capacity	Ah
	Voltage	V
	Chemistry	-
	Weight	Kg
	Density	kWh/kg
Vehicle	Max speed	Km/h
	Range	Km
	Weight min	kg
	Weight max	kg
	Wheel radius	M
	Traction axle	-
	Seats	#

Table 16 features analyzed for benchmarking.

L7 category

A. For the L7 category, the first vehicle taken into consideration was the XEV YOYO since it's the only vehicle designed to have swappable batteries, this feature can be used only in a car-sharing configuration. Specifically, this model features 3 modules that weigh more than 20 kg each and must be replaced by an authorized person, making it impossible for autonomous swapping.

Electric motor	Nominal power	kW	7.5
	Peak power	kW	11
Battery Pack	Capacity	Ah	143
	Energy	kWh	10,3
	Voltage	V	72
	Chemistry	-	LFP
	Weight	Kg	More than 60
	Density	kWh/kg	0,172
Vehicle	Max speed	Km/h	80
	Range	Km	150
	Weight min	kg	450
	Weight max	kg	836
	Wheel radius	M	0,45
	Traction axle	-	RWD
	Seats	#	2

Table 17 XEV YOYO characteristics

Figure 41 XEV YOYO

B. Microlino

Figure 42 Microlino

Electric motor	Nominal power	kW	-
	Peak power	kW	12,5
Battery Pack	Capacity	Ah	-
	Energy	kWh	14
	Voltage	V	-
	Chemistry	-	NMC
	Weight	Kg	196
	Density	kWh/kg	-
Vehicle	Max speed	Km/h	90
	Range	Km	177
	Weight min	kg	435
	Weight max	kg	700
	Wheel radius	M	0,43
	Traction axle	-	RWD
	Seats	#	2

Table 18 Microlino characteristics

C. Estrima Birò

Figure 43 Estrima Birò

Electric motor	Nominal power	kW	5 (two motors)
	Peak power	kW	11
Battery Pack	Capacity	Ah	100
	Energy	kWh	5,04
	Voltage	V	50,4
	Chemistry	-	-
	Weight	Kg	46
	Density	kWh/kg	0,11
Vehicle	Max speed	Km/h	60
	Range	Km	90
	Weight min	kg	424
	Weight max	kg	-
	Wheel radius	M	0,41
	Traction axle	-	RWD
	Seats	#	2

Table 19 Estrima Birò characteristics

D. Renault Twizy 80

Figure 44 Renault Twizy 80

Electric motor	Nominal power	kW	13
	Peak power	kW	17
Battery Pack	Capacity	Ah	-
	Energy	kWh	6.1
	Voltage	V	-
	Chemistry	-	-
	Weight	Kg	100
	Density	kWh/kg	-
Vehicle	Max speed	Km/h	80
	Range	Km	100
	Weight min	kg	474
	Weight max	kg	690
	Wheel radius	M	0,44
	Traction axle	-	RWD
	Seats	#	2

Table 20 Renault Twizy 80 characteristics

L6 category

A. Citroen Ami/ Fiat Topolino

Figure 45 Fiat Topolino

Electric motor	Nominal power	kW	6
	Peak power	kW	9
Battery Pack	Capacity	Ah	112
	Energy	kWh	5.35
	Voltage	V	48
	Chemistry	-	-
	Weight	Kg	65
	Density	kWh/kg	-
Vehicle	Max speed	Km/h	45
	Range	Km	75
	Weight min	kg	471
	Weight max	kg	637
	Wheel radius	M	0,45
	Traction axle	-	RWD
	Seats	#	2

Table 21 Fiat Topolino characteristics

B. Microlino Short, same external aspect but different characteristics

Electric motor	Nominal power	kW	
	Peak power	kW	12.5
Battery Pack	Capacity	Ah	-
	Energy	kWh	6
	Voltage	V	48
	Chemistry	-	-
	Weight	Kg	161
	Density	kWh/kg	-
Vehicle	Max speed	Km/h	45
	Range	Km	91
	Weight min	kg	435
	Weight max	kg	660
	Wheel radius	M	0,43
	Traction axle	-	RWD
	Seats	#	2

Table 22 Microlino short characteristics

C. Estrima Birò, same as microlino case

Electric motor	Nominal power	kW	3.5 (two motors)
	Peak power	kW	4
Battery Pack	Capacity	Ah	100
	Energy	kWh	5,04
	Voltage	V	50,4
	Chemistry	-	-
	Weight	Kg	46
	Density	kWh/kg	0,11
Vehicle	Max speed	Km/h	45
	Range	Km	100
	Weight min	kg	424
	Weight max	kg	-
	Wheel radius	M	0,41
	Traction axle	-	RWD
	Seats	#	2

Table 23 Estrima Birò characteristics

D. Renault Twizy 45

Electric motor	Nominal power	kW	4
	Peak power	kW	8
Battery Pack	Capacity	Ah	-
	Energy	kWh	6.1
	Voltage	V	-
	Chemistry	-	-
	Weight	Kg	100
	Density	kWh/kg	-
Vehicle	Max speed	Km/h	45
	Range	Km	100
	Weight min	kg	474
	Weight max	kg	-
	Wheel radius	M	0,44
	Traction axle	-	RWD
	Seats	#	2

Table 24 Renault Twizy 45 characteristics

It is necessary to make a clarification about the data. As possible to see from the tables, unfortunately, not all the selected features are available and accessible on the various websites and technical specifications. Having said that, the collected values are sufficient to evaluate the different vehicles and proceed with the analysis with the FO.

5.1.2 Definition of FO

Regarding the Functional Objectives (FO), not all the characteristics previously listed in the tables are fundamental. For this reason, only specific characteristics need to be included in the FO that will be useful for performing the calculations. Specifically, the calculations required in the initial design phase of a vehicle primarily focus on three elements.

The first element is the maximum slope that a vehicle can overcome starting from standstill. In particular the minimum slope is 20% that correspond to 9 degrees. For this purpose, vehicle dimensions like max weight and tires dimensions are mandatory.

The second limit is the max speed of the vehicle. In this case the L7 cars has a predetermine max speed, for this reason the amount of effort (torque and power) is evaluated to understand if the e-motor can fulfill this target.

Finally, the last element to consider is the technical constraints imposed by the vehicle class, particularly the peak power of the motor (15 kW for L7) and an empty weight not exceeding 400 kg.

In conclusion, it is important to consider that the process of defining Functional Objectives (FO) is an iterative one. The initial parameters are established by matching similar cars with the set objectives, and then they are modified and adapted based on the calculations performed. In the context of this analysis, parameters such as initial weight, wheel radius value, and maximum speed have been evaluated multiple times and adjusted, for instance. Furthermore, the FO may vary slightly depending on the technical characteristics of the electric motors adaptable to the project. Therefore, depending on the specific electric motor used, the FO may undergo slight changes to accommodate it.

The considered Functional Objectives (FO) include the empty weight, the weight at maximum load, the maximum speed, the range of autonomy in kilometers, the traction axis, the number of seats, the wheel radius, and the peak power of the motor. In particular, the initial values were 400 kg for the empty weight and 750 kg for the weight at full load, a maximum speed of 80 km/h, a range of 150 km, rear-wheel drive, 2 seats, and a wheel radius of 0.42 meters, with a motor capable of delivering 15 kW of peak power, as per the L7 vehicle regulations.

Min weight [kg]	400
Max weight [kg]	750
Max speed [Km/h]	80
Range [km]	150
Traction axle	Rear Wheel drive (RWD)
Number of seats	2
Radius of wheels [m]	0.42
Peak power [kW]	15

Table 25 initial FO

The empty weight of the vehicle has been set at 400 kg in compliance with regulations and will not be further modified. On the other hand, the weight at full load was initially set at 750 kg to align with other vehicles. It's worth noting that the benchmarking vehicles considered were the XEV YOYO due to the available data and the possibility of swappable modules, and the Renault Twizy because has a substantial amount of data available.

The maximum speed of 80 km/h was chosen because, apart from the Microlino case, all other L7 vehicles have this maximum speed. Similarly, the range was set with the goal of improving competitiveness compared to other vehicles since electric vehicle range is a significant focal point nowadays.

Regarding the number of seats and the traction axis, all vehicles in the L7 and L6 categories have the same configuration due to vehicle dynamics and space constraints. Increasing the number of passengers would significantly reduce the range, and the motor's power would not be sufficient. Furthermore, it would dramatically increase the vehicle's weight.

As for the choice of rear-wheel drive, it is preferable from a dynamic and weight distribution standpoint, as it would provide better acceleration. The motor power has been set to the maximum allowable limit according to regulations, and finally, the wheel radius was set at 0.42 meters for optimal final gear ratio.

5.1.3 EM implementation

Regarding the implementation of the electric motor, extensive research was conducted to find an existing motor that could be adapted for the purpose of powering a vehicle. Finding the right electric motor can indeed be challenging, as major car manufacturers often delegate the production of custom-made components to fulfill all the required specifications. In the case of this analysis, the central focus was not on the dimensioning of the motor component, or the inverter, but rather on demonstrating how the VDA390 modules from the SLIM project could be used for this purpose.

The research conducted brought attention to two different motors that represent the same product but operate at different voltages, resulting in different final characteristics. The manufacturer of these motors is Rawsans [23], specializing in electrical components, including electric motors. They offer various product lines, primarily divided into two categories: motors for new vehicles and motors for conversion.

Due to the voltage requirements of the electric motor, the motors for conversion were chosen as they allowed operation within voltage ranges suitable for the VDA390 modules in question. Moreover, these motors closely resembled the benchmarking vehicles, making them a suitable choice for this analysis.

Model	R11B55	R11B75
Application	Tour bus/A00 class	A0 class SUV
Cooling type	Natural	Natural
Motor type	AC induction	AC induction
Battery voltage [V]	40-72	48-120
Peak Power [kW]	17	21
Peak Torque [N]	120	130
Peak speed [rpm]	6500	6500

Table 26 Characteristics of EM analyzed.

The first implementation step was to calculate the required torque of the motor to start from a standstill, at maximum load, on a 9-degree slope, which corresponds to a 20% gradient. To calculate this value, it was necessary to assess the forces acting on the rear axle's wheels. Therefore, a free-body diagram of the car on a 20% slope was drawn, and equations concerning vertical and horizontal forces, as well as moments, were calculated. The figure 46 illustrates how the calculation was performed.

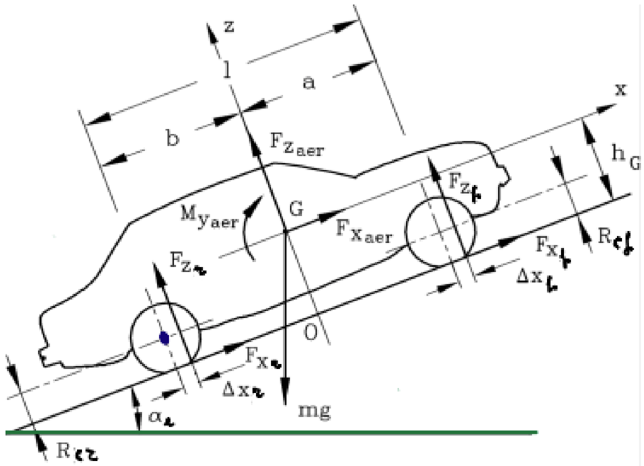

Figure 46 free body diagram of a generic car

$$m \cdot g \cdot cos(\alpha) = Fz_r + Fz_f$$

$$m \cdot g \cdot sin(\alpha) = Fx_r$$

$$m \cdot g \cdot sin(\alpha) \cdot h_g + Fz_f \cdot l = m \cdot g \cdot cos(\alpha) \cdot b$$

Equation 3 free body diagram equations

From what can be inferred from the equations just described, especially from the second one, the driving force Fx_r has been applied to the real axle of the car that correspond to the traction one. Continuing with the second equation, the term "m" represents the fully loaded mass of the vehicle: initially, it was set to 750 kg, but after iterative processes, it has been possible to increase the maximum mass to 800 kg to be below only one of the competitors (XEV YOYO 836). Regarding the slope angle, the maximum allowed by law is 20%, which is equivalent to 9 degrees. Finally, "g" represents the gravitational acceleration and is approximately equal to 9.81 m/s^2. Knowing the force applied to the axle, is possible to evaluate the torque at wheels. To compute this number, the radius of the wheel is necessary. Compared to benchmarking products it has been assumed a radius of 0.43 m.

$$Fx_r \cdot R = 800 \cdot 9{,}81 \cdot \sin(9°) \cdot 0.43 = 1497.5N \cdot 0.43m = 643.91Nm$$

Equation 4 Wheel torque at maximum slope

The final value corresponds to the torque needed from the wheels, and so axels, in order to move the vehicle. Before continuing is necessary to specify that in the next steps the final ratio and the efficiency of the EM are necessary. For what concern the final ratio it is very different from ICE cars (internal combustion engine) because that kind of vehicle need gearbox. In fact, for Electric car the flexibility and the elasticity of the EM itself is enough to fulfill the requirement. The torque/power curve permit to have the max torque from the beginning and this means that is easily start running the vehicle. On the contrary the ICE cars provide instantly torque and power for these reasons IC vehicle need gearbox and the clutch. For what concern the final ratio it represents the ratio between the engine rotation and the wheels rotation. In ICE car the final ration is not fixed but change by the change of the gear, on the contrary the EV car does not need gears (some models implement a dual shift gearbox), so the final ratio is fixed. Usually, τ corresponds to 9:1 where 9 are the rotation of the EM and 1 of the wheels [26]. In this specific application the final ratio was fixed to $\tau = 0.115$ due to a great balance between rpm of EM and torque requested.

For what concern the efficiency of the propulsion system, again the EM and ICE one is totally different. First at all the ICE has an average efficiency lower than η =0.3 in some cases, on the contrary the EM has an efficiency from η =0.8 to η =0.97. This large difference is because the ICE as to convert the chemical energy inside the fuel into thermal energy and then into kinetic energy for piston moving and al transmission components. On the contrary the EM doesn't convert the chemical energy stored in the battery, but the battery directly converts it and transport it to the EM through the inverter. So, the energy stored into the battery arrive to the EM and is converted to kinetic energy. In this case the efficiency of EM is spitted into two different situations, to be more precise the project considers an efficiency of 0.8 at low RPM and 0.9 at high rotational speed.

$$\frac{Fx_r \cdot R \cdot \tau}{\eta} = \frac{643.91Nm\ 0.115}{0.8} = 92{,}6Nm$$

Equation 5 minimum EM torque to overcome maximum slope

To evaluate the most suitable situations and the limits of the vehicle, a sensitivity analysis was evaluated. The graph as on x axis represent the weight of the vehicle, on the y axis the torque needed, and the curves represent the dependency of the torque from the weight at different level of slope.

The lower blue line determines the torque necessary to overcome a slope of 20% as function of the total weight of the car. Considering the 800kg case, the minimum torque necessary is 75.89 Nm.

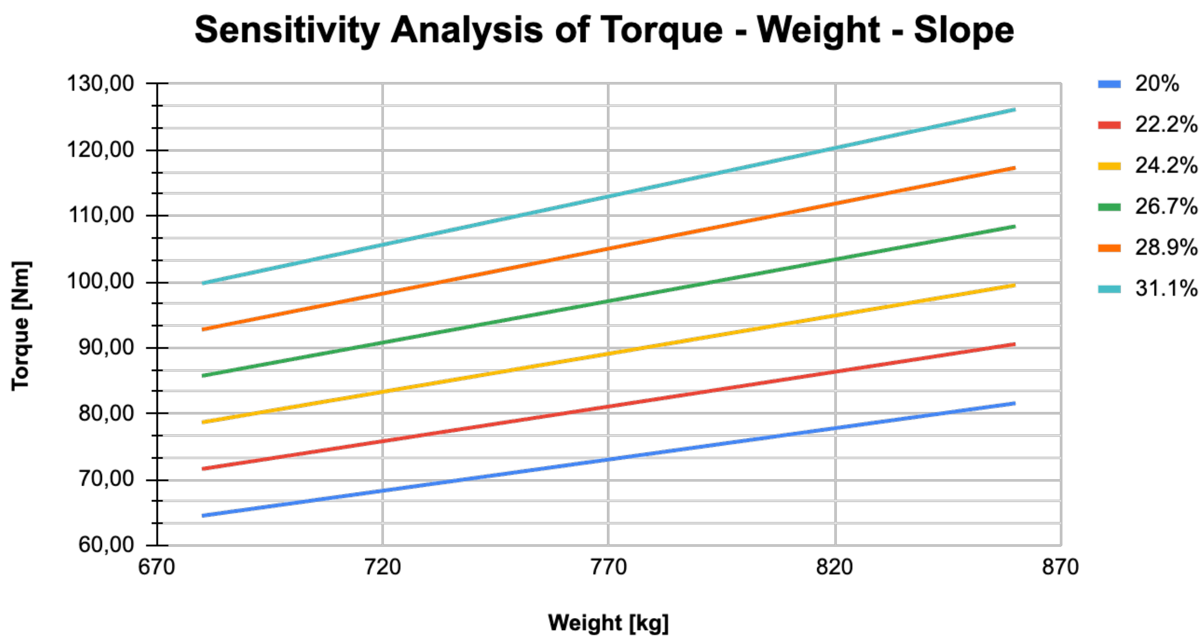

Figure 47 sensitivity analysis of torque- weight - slope

The second calculation that needs to be done during the concept phase of a vehicle is to evaluate the required torque, required power, and engine RPM at maximum speed. In the initial case of starting from a standstill on a steep slope there was no consideration about external resistance due to the lower speed (approximately zero). However, in this case, the predominant part of the consumption and required power is due to external resistance. The external resistance is primarily due to two factors: tire rolling resistance and aerodynamic resistance. Going into more detail, each of these two factors has dependencies on the velocity. In fact, we can summarize the total vehicle resistance with an equation "R", where "A" corresponds to all factors that do not depend on velocity and remain constant as velocity changes. "B" represents the multiplicative factors of the square of velocity, leading to a parabolic dependence, and finally "C", the factors that depend on velocity to the fourth power.

$$R = A + B \cdot V^2 + C \cdot V^4$$

$$A = m \cdot g \cdot (f_0 \cdot \cos(\alpha) + \sin(\alpha))$$

$$B = m \cdot g \cdot f_2 \cdot \cos(\alpha) + \frac{1}{2} \cdot \rho \cdot f_0 \cdot (C_x - f_0 \cdot C_z \cdot S)$$

$$C = -\frac{1}{2} \cdot \rho \cdot f_2 \cdot C_z \cdot S$$

Equation 6 Resistance equation with dependance to velocity of a vehicle

Generally, when calculating R for passenger cars, the contribution of aerodynamics along the z-axis (vertical axis) is not considered because it has minimal influence despite the fourth power dependence on velocity. However, for competition vehicles, this parameter is taken into consideration. At this point, the calculation of velocity simplifies to two basic factors: A and B.

$$R = A + B \cdot V^2$$

Equation 7 Simplify resistance equation.

The factor A and B summarize factors of rolling resistance and aerodynamics, they have been assumed based on previous experiences from academic courses and are in line with standard values. It's worth noting that typically these values, even if different, do not deviate excessively. This means that even if they are changed, the results obtained do not vary significantly from those obtained with the standard values.

f0 and f2 represent the rolling resistance factors, the first one is not related to speed and the second one to the square of the velocity. Rho, ρ, represent the volumetric density of the air, C_x is a coefficient used to measure the aerodynamic resistance encountered by a solid body when moving through a fluid and finally S is the frontal surface of the vehicle.

f0	0,0095
f2	0,000056
ρ [kg/m^3]	1,225
C_x	0,45
S [m^2]	1,63

Table 27 Parameter for resistance equation R

As mentioned earlier, f0 and f2 were determined based on experienced information. Rho is a constant, but C_x and S are specific to each vehicle's shape, meaning that each vehicle has its unique values. Since the goal here is not to design the entire vehicle, this aspect was not fully developed. To assign values to these two constants, benchmarking played a significant role. Typically, a passenger car tends to have a C_x value between 0.2 and 0.3. It's worth noting that in recent years, there has been an increased focus on aerodynamic development due to the emergence of electric vehicles, aimed at reducing consumption and increasing range. For motorcycles, the Cx value tends to be higher, around 0.8 to 0.9 [27], especially for non-faired ones. For reference, the Renault Twizy has a Cx of 0.64 [27], while the XEV YOYO has a Cx of 0.35 [28]. The significant difference might be attributed to the fact that the Twizy has more exposed wheels, making it less aerodynamically efficient. The values chosen for this project align with the mentioned norms and specify a Cx of 0.45 and a frontal area of 1.63 m^2.

After calculating the resistance at various speeds, the required motor torque, necessary power, and operational speed, considering the same final ratio (0.115), need to be determined. The torque at the rear axle is obtained by multiplying the resistance by the wheel radius, while the required motor torque is obtained by multiplying it by the final ratio. Subsequently, to calculate the motor's angular velocity, the vehicle's speed is converted into wheel angular velocity by dividing it by the wheel radius. Then, the result is divided by the final ratio to obtain the motor's angular velocity in radians per second, which is then converted into revolutions per minute (rpm).

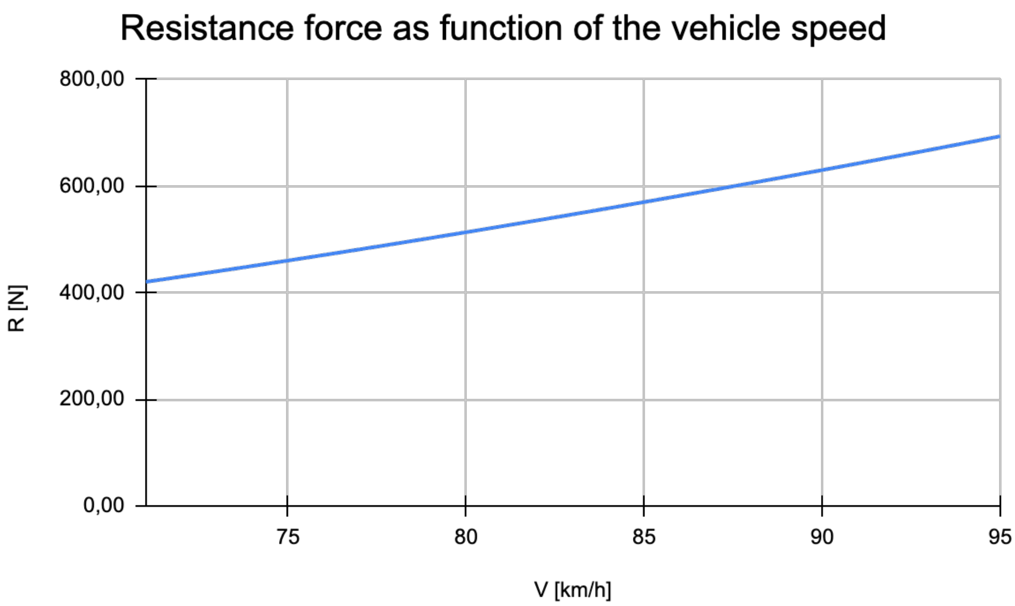

Figure 48 Resistance force as function of speed

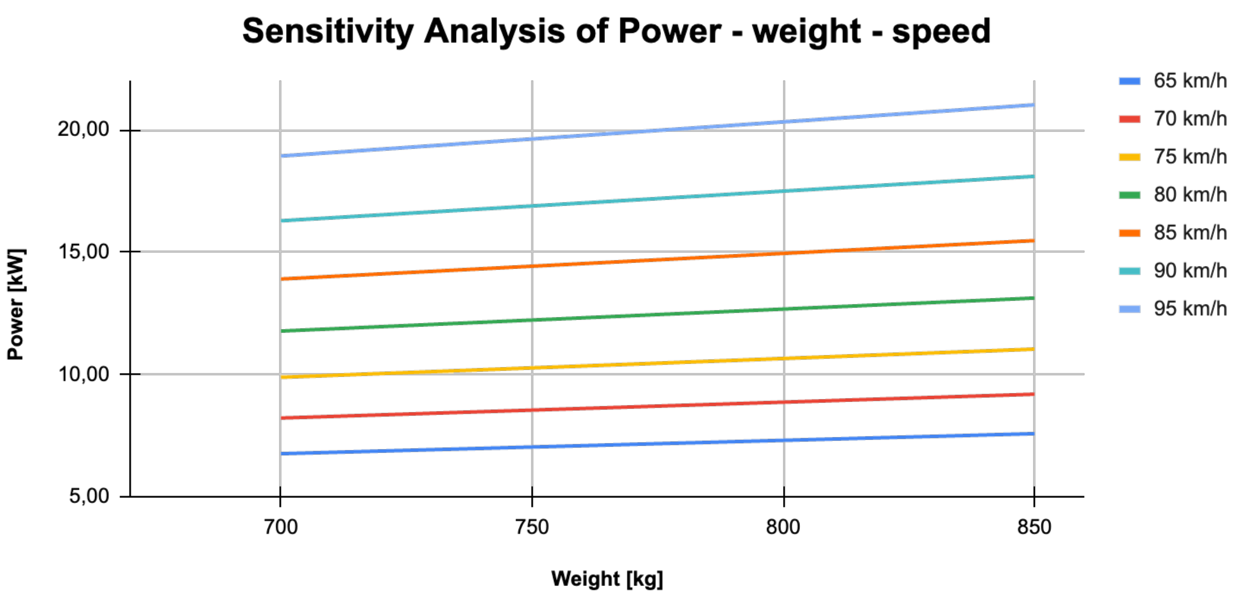

Figure 49 Sensitivity Analysis of Power - Weight - Speed

As done in the previous test, a sensitivity analysis was also conducted in this case to determine the optimal solution. As depicted in the graph, considering the upper limit of 15 kW due to the L7 class, the best scenario for maximum weight and maximum speed is with a vehicle weighing 800 kg at a maximum speed of 85 km/h.

Up to this point, we have discussed the two procedures for establishing the foundations of a vehicle based on its Functional Objectives (FO). Specifically, we have calculated the minimum torque required to start from a standstill on a maximum slope of 20% and then determined the power, torque, and RPM required to reach the vehicle's maximum speed. At this stage, it is possible to conduct a more in-depth analysis by applying what has just been calculated to electric motors capable of meeting these parameters. In other words, electric motors that fall within the minimum effort limits required by the two tests explained earlier but are below the power limit required to be equipped on an L7 class vehicle. At the beginning of this chapter, two motors that could be used in this application were mentioned, and their characteristics were presented in the table. Now, with the peak characteristic curves of these motors, it is possible to carefully assess their feasibility and determine if they can even improve the vehicle's characteristics such as maximum speed or maximum weight capacity.

The following graphs represent the torque and power curves of the R112B55 and R112B75 motors, which were previously introduced.

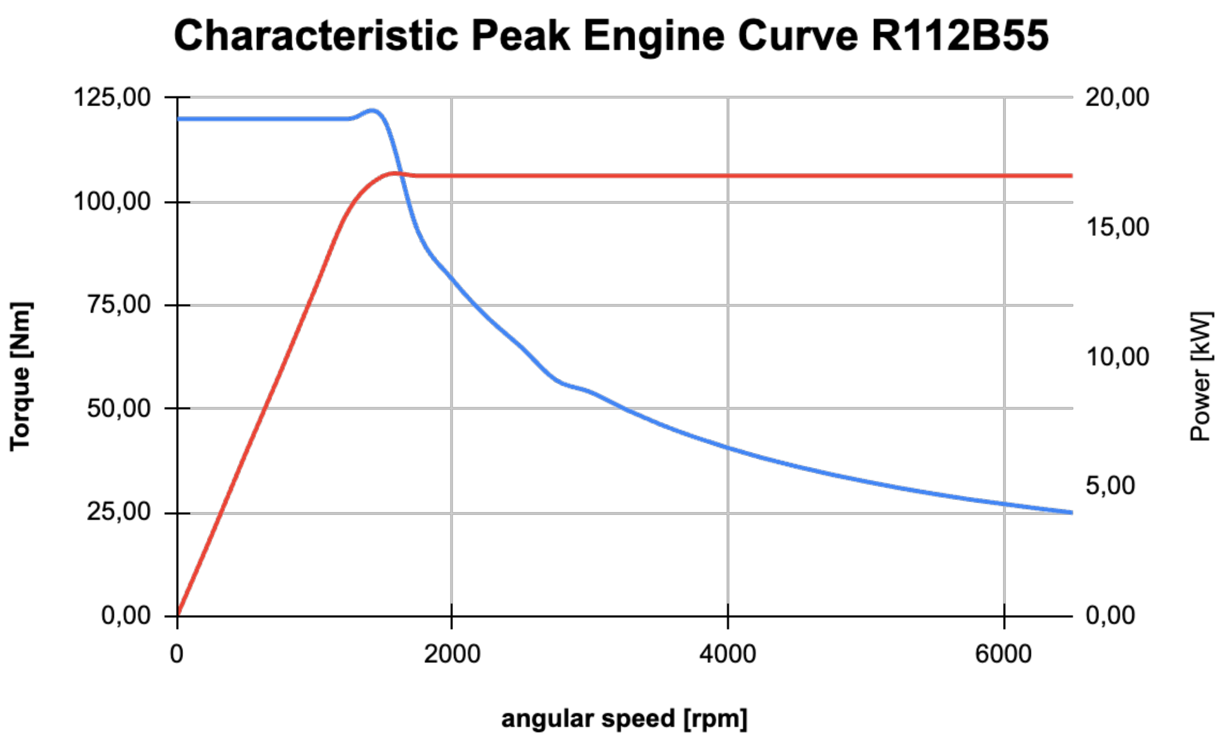

Figure 50 Characteristic Peak Engine Curve R112B55

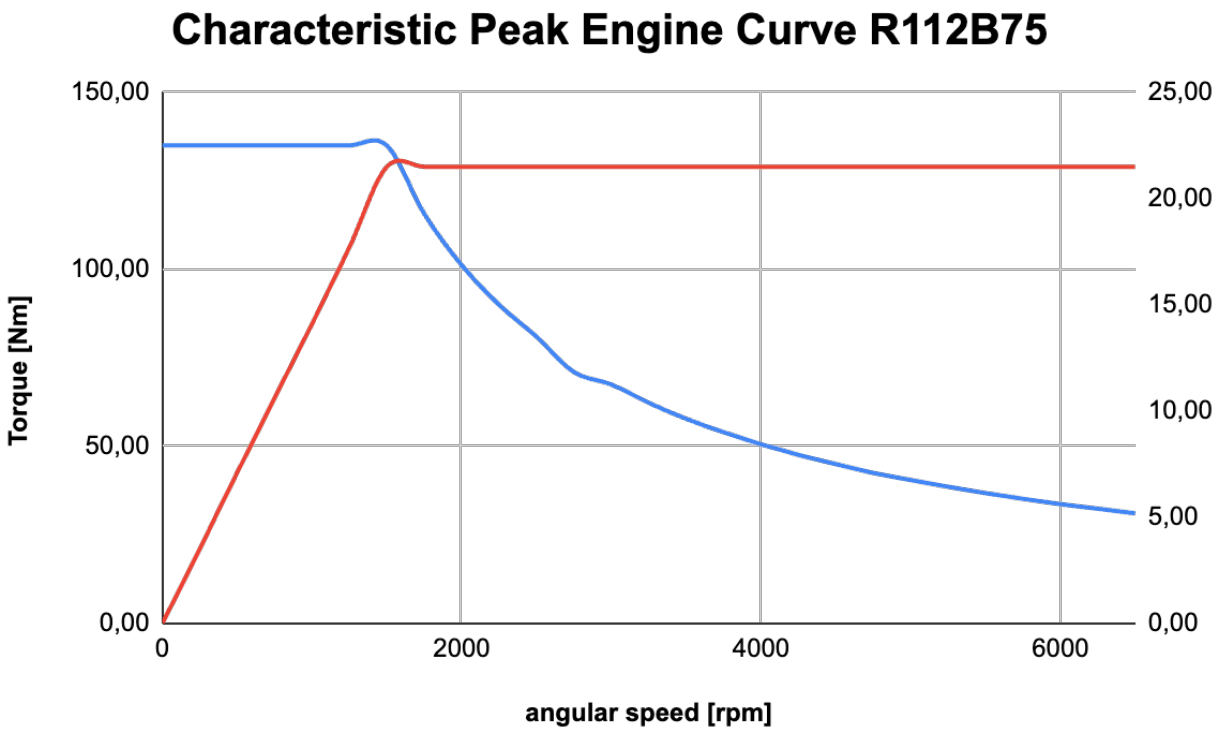

Figure 51 Characteristic Peak Engine Curve R112B75

Considering the results of the sensitivity analysis and the torque and power values described in the two graphs, it is indeed possible to improve the performance of the vehicle in question. As mentioned earlier, the weight at full load has been increased from 750 kg to 800 kg. Due to vehicle dynamic issues is not advisable to excessively increase this value, despite the potential for improvement in the maximum slope. In fact, it's essential to remember that we are dealing with a heavy quadricycle of class L7, not a passenger car. On the contrary, thanks to the figure 47, it can be observed that it is possible to start from a standstill on slopes steeper than 31%. This result is more than satisfactory since the legal maximum limit is 20%. The slope of 31% represents the limit for the smaller motor, the R112B55. On the other hand, the larger motor, the R112B75, could approach slopes of around 34%.

The discussion takes a slightly different turn when considering the power-weight-velocity curves, as it's crucial to keep in mind the upper power limit imposed by regulations. In this case, setting a power limit of 15 kW and having set the maximum acceptable weight at 800 kg, the vehicle's maximum achievable speed would be 85 km/h, 5 km/h more than the FO initially set at the beginning of the analysis. This allows us to achieve an electric motor power of 14.95 kW while staying below the L7 limit. Bearing in mind that the FO in terms of max speed is equal to 80 km/h, 5 km/h more allows us to offer a highly competitive product on the market. However, at this point, it's essential to ensure that the motor operates within its torque and RPM limits at that power level. In this case, the required torque at that speed corresponds to 31.32 Nm, and the motor's RPM would be approximately 4560 rpm. As can be seen from the figures 50 and 51, both motors in question are capable of satisfying the required torque and RPM, making them suitable for this application.

Certainly, updating the Functional Objectives (FO) based on the advancements made in these initial tests is feasible. In the upcoming chapters, we will compute the vehicle's energy consumption with the aim of attaining a 150 km range on a single charge.

Min weight	400
Max weight	800
Max speed	85
Range	150
Traction axle	Rear Wheel drive (RWD)
Number of seats	2
Radius of wheels	0,42
Peak power	15

Table 28 intermediate FO

5.1.4 WLTP cycle evaluation

The WLTP cycle, as explained previously, is now being applied in this project. The reason for this application is to understand the energy consumption of the hypothetical vehicle that has been designed. So far, the first two tests have been conducted to establish the project's boundaries, from maximum uphill torque to the power required to reach the maximum speed. Among the other parameters necessary to complete all the Functional Objectives (FO), understanding the vehicle's energy consumption and subsequently its range of autonomy is crucial. This is where the core of the analysis lies. Knowing the vehicle's energy consumption, understanding the design limits of the motor, its voltage requirements, and having constraints in terms of volume and weight for the battery pack, it becomes possible to formulate a hypothesis for a modular battery pack with a certain number of modules, a specific voltage, and capacity.

The first step in calculating energy consumption is to use a database containing the WLTP cycle. It’s essential to know the vehicle's speed instant by instant and, consequently, calculate its acceleration. There isn't a predefined discretization, but for this application, it is reasonable to discretize the cycle second by second. The database used has been acquired from the UNECE website, which stands for the United Nations Economic Commission for Europe. The file in .xls format consists of an introductory first page explaining how to apply the model, followed by subsequent pages categorized according to the vehicle class. As mentioned before the class vehicle in this case is the first one, in fact the ratio between power and weight is equal to 15.8 that is lower than the limit of 22. Then if the max speed of the vehicle is lower than 70 km/h the test is made up of two low phases, on the other hand if Vmax is equal or higher than 70 km/h the cycle is made up of low phases + medium phases + low phases. The total cycle, made up by the low phases and middle one is represented by the following three graphs. More in deep the total cycle lasts 1611 seconds (589 +433 + 589) with a total distance of 11.415 km (3.324+4.767+3.324). As can be observed, there are some stops time that correspond in total to 358 seconds (22,2 % of total time), the max speed is 64,4 km/s reached in the middle part (49,1 km/h in the lower part). The average speed [km/h] without stops is 27,6 in the lower part and 44,6 in the middle one, on the other hand the average speed including stops [km/h] correspond to 20,3 and 39,6 respectively.

	duration	stop duration	distance	% Stop	V max	avg V no stop	avg V with stop
	[s]	[s]	[km]	-	[km/h]	[km/h]	[km/h]
low	589	155	3.324	26.3%	49.1	27.6	20.3
medium	433	48	4.767	11%	64.4	44.6	39.6
total	1611	358	11.415	22.22%			

Table 29 WLTP class 1 specifications

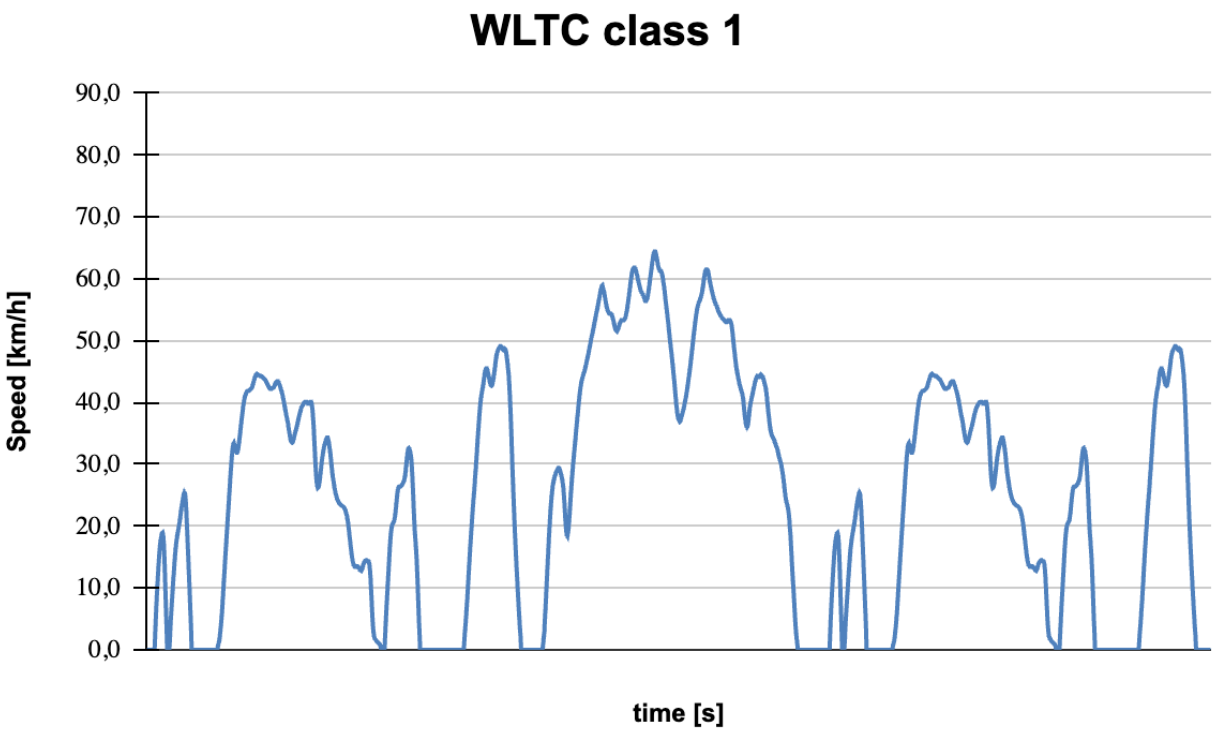

Figure 52 WLTC class 1

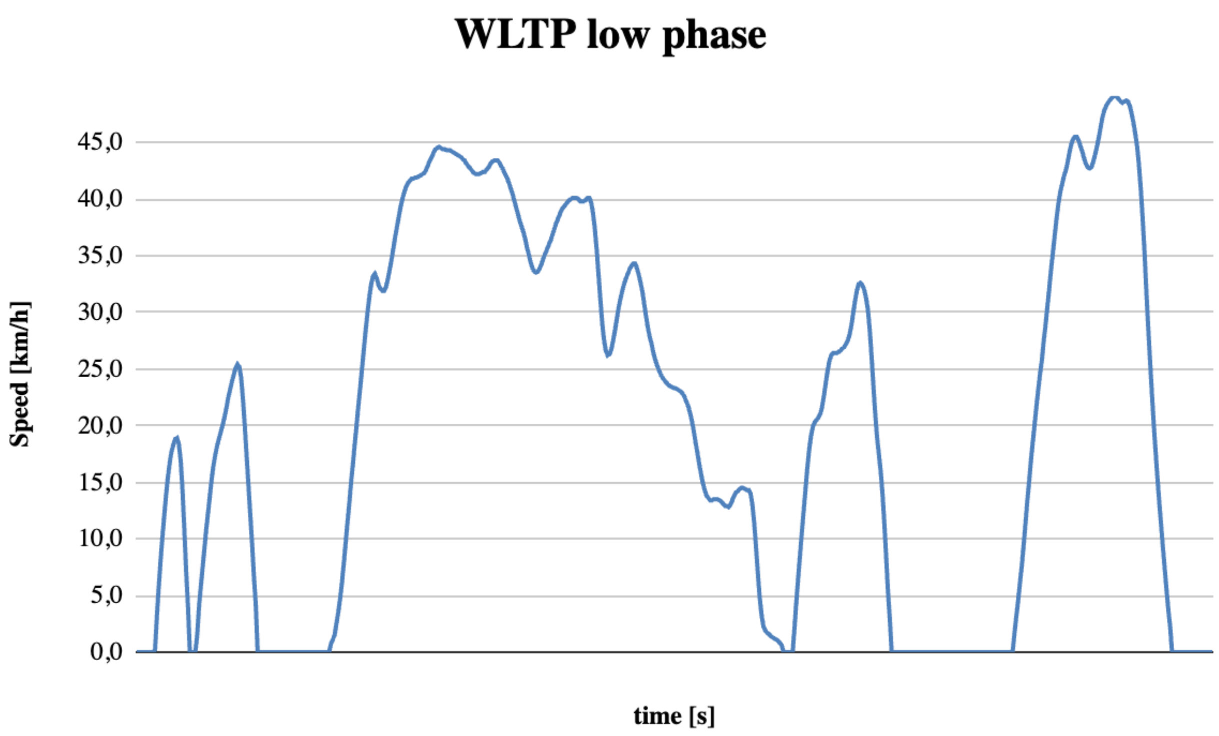

Figure 53 WLTC low phase

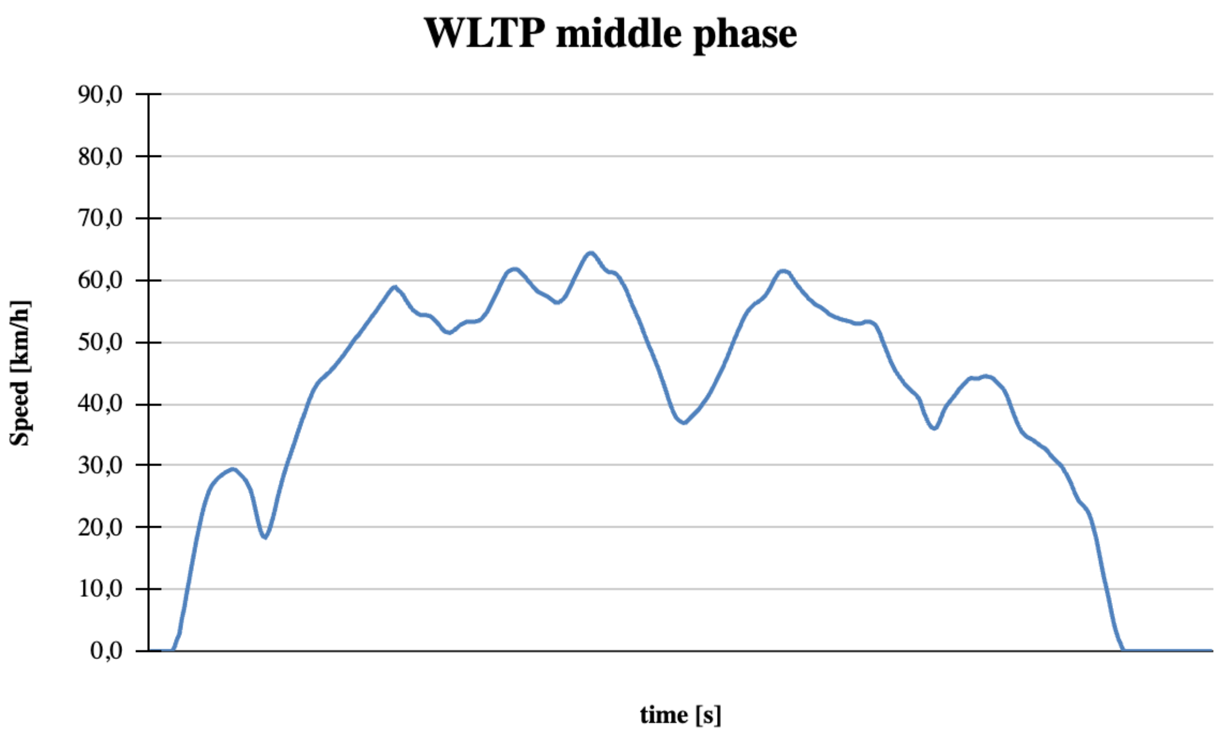

Figure 54 WLTC middle phase

Before beginning the process of calculating energy consumption, it's essential to clarify the assumptions made during the design phase. Firstly, in the consumption calculations, the method described earlier regarding vehicle resistance as a function of speed has been used. Therefore, the values of Cx, rho, and S remain the same, same for the values of f0 and f2 concerning rolling resistance. The vehicle's weight should be the curb weight without considering the driver, which is 75 kg. Therefore, the total weight of the vehicle amounts to 450 kg (400 + 50 + 75 - 75). Regarding the slope, a worst-case scenario has been considered, where the vehicle travels on a slope of 2.25 degrees, corresponding to 5%, which is the maximum allowable gradient on highways. The final ratio remains unchanged at 0.115, and the wheel radius is consistently 0.43 m. As mentioned before, the EM efficiency is variable from 0.7 to 0.9. Therefore, a constant efficiency of 0.8 has been considered for a conservative analysis. Furthermore, it's necessary to consider losses primarily due to battery efficiency, which must convert chemical energy into electrical current, and also the efficiency of the inverter, as it converts the current from DC to AC. Finally, services such as air conditioning, various screens, and lights have also been quantified with their consumption. The table summarizes the numbers, providing a total efficiency of the vehicle, including the inverter, battery pack, and services, while the motor is considered separately. In conclusion, regenerative braking was not considered in the calculations because the process of recharging the batteries by the motor precludes an analysis of the inverter, understanding the voltage range it operates on, and calculating how much energy the motor can recover. Since the project does not involve the design of the vehicle's components, this operation is not considered because it would go beyond the scope of the work.

Inverter	0.97
Battery Pack	0.95
Services	0.95
TOTAL	0.86

Table 30 efficiency of the vehicle

Regarding the calculation, it was performed instant by instant. Initially, the speed was converted from km/h to m/s. Acceleration was calculated by taking the difference between the previous instant's velocity and the velocity at the subsequent instant, relative to the second under consideration. Subsequently, a control parameter was introduced, which means that for acceleration values less than 0, it was set to "0," and for values greater than or equal to 0, it was set to "1". These values will be necessary in the upcoming calculations to exclude moments of deceleration and zero velocity, which are assumed not to be included in the calculation.

At this point, after filtering the velocity data, we can proceed with the calculation of external resistance. As mentioned earlier, we use equation number 6 on an instant-by-instant evaluation.

After calculating the resistance, it is multiplied by the wheel radius to determine the torque required to overcome the resistance at the drive axle. To calculate the motor's torque, it is necessary to multiply the result by the final ratio and divide it by the motor's efficiency (0.8 in this case).

$$T_w = R \cdot R_w$$

Equation 8 Torque at wheels

$$T_m = T_w \cdot \frac{\tau}{\eta}$$

Equation 9 Torque at motor

Subsequently, to calculate power, it is necessary to calculate angular speeds. First, the angular speed in rad/sec is calculated from the vehicle's speed by dividing it by the wheel radius. Then, the motor's angular speed is determined by dividing the wheel's angular speed by the final ratio, and it is subsequently converted to rpm (revolutions per minute) for ease of reading.

$$Wheels\ angular\ speed = \frac{V_{veh}}{R_w}$$

Equation 10 Wheels angular speed

$$EM\ angular\ speed = \frac{Wheels\ angular\ speed}{\tau}$$

Equation 11 Electric motor angular speed

Finally, it is possible to calculate the instantaneous power required based on the external resistance on the vehicle. This is done by multiplying the previously mentioned motor torque by its angular speed in rad/sec. To conclude, power is converted into energy by multiplying it by the unit of time. Typically, energy is defined in terms of kilowatt-hours (kWh), but in this case, the smallest unit of time is the second. For this reason, to obtain energy from the previously calculated power, is necessary to divide it by 3600, which is the number of seconds in an hour.

$$P_{instant} = \frac{T_m \cdot EM\ angular\ speed}{1000} = [kW]$$

Equation 12 instant power provided by the EM

$$E_{instant} = \frac{P_{instant}}{3600} = [kWh]$$

Equation 13 Instant Energy consumed by the car

It's important to remember that the calculated energy corresponds to instantaneous energy, instant by instant, excluding moments when acceleration is less than zero. Certainly, during these periods of deceleration, the energy consumption of the battery pack is zero. However, electric cars and electric vehicles, in general, often consider regenerative braking, which results in negative energy values, effectively reducing the vehicle's net energy consumption. In this project, regenerative braking was not considered for the reasons previously mentioned, resulting a more conservative analysis. The final step in calculating the consumed energy was to sum the energy expended for each phase, instant by instant, and then multiply the energy of the "low" phase by two. This multiplication by two is done because for first-class vehicles the WLTC cycle includes two low phases separated by the middle phase.

$$E_{low} = 0{,}1844\ kWh$$

$$E_{middle} = 0{,}2783\ kWh$$

$$E_{cycle} = 0{,}6471\ kWh$$

Equation 14 Energy phase by phase and of the cycle

The calculated energy refers to a single WLTC cycle, which corresponds to 11,415 km. To calculate the consumption in kWh/100 km, a proportion is needed.

$$Energy\ consumption = \frac{\frac{E_{cycle} \cdot 100}{Cycledistance}}{\eta_{inv} \cdot \eta_{bat} \cdot \eta_{serv}} = \frac{0{,}6471 \cdot 100}{11.415 \cdot 0.97 \cdot 0.95 \cdot 0.95} = 6{,}48\ \frac{kWh}{100km}$$

Equation 15 Energy consumption of the car

Finally, with the equation 15 the energy consumption of the hypothetical L7 class vehicle is evaluated highlighting a great result.

To calculate the vehicle's range, it is necessary to configure the car's battery pack. In this case, to proceed, several factors must be considered: the energy contained in the batteries, which is closely linked to capacity and voltage and the ability to be swappable, only the XEV YOYO allows this and only for car-sharing purposes. There is also the voltage of the battery pack, which is linked to the operating voltage of the motor, and finally, the volume occupied by the battery pack, for absurdity, it is unthinkable to install 10 modules in a microcar.

First, we need to differentiate the electric motors analyzed in the "75" case. The operating range for these motors is between 48 and 120 V DC. This means that the electric motor requires a minimum and maximum operating voltage, which is converted to alternating current by the inverter. The inverter requires batteries capable of delivering a maximum of 120 V and not less than 48 V. Returning to the batteries, this means that beyond the nominal voltage, when the module is discharged, the voltage cannot drop below 48 volts. Conversely, at maximum charge, it is not possible to exceed 120 V.

VDA390

VDA 390	
module capacity [Ah]	148
module weight [Kg]	13,5
cells in one module	6
min cell voltage [V]	2,9
max cell voltage [V]	4,2
nominal cell voltage [V]	3,64
max voltage module [V]	25,2
min voltage module [V]	17,4
nominal voltage module [V]	21,84

Table 31 VDA390 characteristics

At this point, we can consider the VDA 390 case as the fundamental unit. The table allows us to understand its characteristics, highlighting a minimum voltage of 17.4 and a maximum voltage of 25.2. For these reasons, a minimum of 3 modules in series and a maximum of 4 are required. At this point, it is possible to configure the battery pack in 3S1P and 4S1P modes. An additional step could be taken by inserting a second series in parallel to double the capacity and thus obtain a battery pack with a larger range. However, as mentioned earlier, it is not possible to increase the number of modules excessively as it would lead to vehicle dynamics problems and disproportionate space occupation relative to the vehicle's dimensions. For this reason, configurations of 3S1P, 4S1P, and 3S2P have been considered appropriate.

Finally, it is possible to calculate the range for each configuration simply by multiplying the energy of the battery pack by 100 and dividing it by the previously calculated consumption. We can say that in the single-series cases, the goal has been achieved with 146 km in the 3S1P case and almost 200 km with the additional module. Lastly, in the case with 6 modules, autonomy of nearly 300 km is achieved.

3S1P			
number of series module	3	Capacity [Ah]	148
number of parallel modules	1	Energy [kWh]	9,46
total number of modules	3	Peso [Kg]	40,5
Min Voltage	52,2	Energy density [kWh/Kg]	0,234
Max Voltage	75,6	Range [km]	146
Nominal voltage	63,9		

Table 32 3S1P module configuration

4S1P			
number of series module	4	Capacity [Ah]	148
number of parallel modules	1	Energy [kWh]	12,61
total number of modules	4	Peso [Kg]	54
Min Voltage	69,6	Energy density [kWh/Kg]	0,234
Max Voltage	100,8	Range [km]	194,7
Nominal voltage	85,2		

Table 33 4S1P module configuration

3S2P			
number of series module	3	Capacity [Ah]	296
number of parallel modules	2	Energy [kWh]	18,91
total number of modules	6	Peso [Kg]	81
Min Voltage	52,2	Energy density [kWh/Kg]	0,234
Max Voltage	75,6	Range [km]	292,1
Nominal voltage	63,9		

Table 34 3S2P module configuration

VDA355

VDA 355	
module capacity [Ah]	103,6
module weight [Kg]	11
cells in one module	12
min cell voltage	3
max cell voltage	4,2
nominal cell voltage	3,7
max voltage module	25,2
min voltage module	18
nominal voltage module	44,4

Table 35 VDA355 characteristics

It is possible to go through a similar process to use the VDA355 module in this vehicle. This would allow us to use lighter modules and improve ergonomics. However, compromises will need to be made in terms of range. As you can see in the same configurations, only the 4S1P and 3S2P can be compared.

3S1P			
number of series module	3	Capacity [Ah]	103.6
number of parallel modules	1	Energy [kWh]	6.71
total number of modules	3	Peso [Kg]	33
Min Voltage	54	Energy density [kWh/Kg]	0,203
Max Voltage	75.6	Range [km]	103.7
Nominal voltage	64,8		

Table 36 3S1P module configuration

4S1P			
number of series module	4	Capacity [Ah]	103.6
number of parallel modules	1	Energy [kWh]	8.95
total number of modules	3	Peso [Kg]	44
Min Voltage	72	Energy density [kWh/Kg]	0,203
Max Voltage	100.8	Range [km]	138.2
Nominal voltage	86.4		

Table 37 4S1P module configuration

3S2P			
number of series module	3	Capacity [Ah]	207.2
number of parallel modules	1	Energy [kWh]	13.43
total number of modules	3	Peso [Kg]	66
Min Voltage	54	Energy density [kWh/Kg]	0,203
Max Voltage	75.6	Range [km]	207.3
Nominal voltage	64,8		

Table 38 3S1P module configuration

The same operation has been done for the "55" motor, which this time has a usage range of 40 - 72V. Unlike the first case, in this situation, it is not possible to place 4 modules in series because it would exceed the upper limit of 72V. Therefore, the only possible configurations are 3S1P and 3S2P. The obtained values do not differ from the tables mentioned above because in the implementation of the WLTC cycle, no distinction was made based on the type of motor, assuming the same overall efficiency of 0.8.

5.1.5 Comparison and analysis

While the previous chapter is completely dedicated to evaluation and computation, this paragraph analyzes the results and compare the already presented application with the benchmarking previously presented. The areas of focus are consumptions, range and battery layout.

For what concern the consumption, after WLTC evaluation, the hypothetic vehicle presents an energy consumption of 6.5 km/100km excluding regenerative braking. Compared to the other L7 vehicle the results are largely better, in fact XEV YOYO present 7.4 km/100km, Microlino 7 km/100km, Biro 7.4 km/100km and Renault Twizy 6.3 km/100km. If regenerative braking is taken into consideration, it would decrease even further, but this feature hasn't been developed because isn't the component development core of the projects. Even if the result is sufficient reliable further progress could be implemented to obtain more precise results. The first one is the components design, above all the inverters. This element is the link between the battery pack and the e-motor, transform the DC current into AC for traction and if designed is also able to transfer the regenerative energy from the e-motor back to the batteries. Therefore, is substantial component in a traction system.

The second parameter used for the comparison is the vehicle range. This number is evaluated by a simple calculation coming from the consumption and the energy stored in the battery pack. In this precise case the analysis was done considering both the VDA390 and VDA355 modules, because are the target components for swappable applications. In the previous chapter the VDA390 was deeply re-designed, but the 355 model can be easily adapted for this evolution to be swappable. Considering the number of modules and the voltage range of the motors the best modules layout is the 3S1P and 4S1P. In the case of 390 the range is in line with competitors reaching 146 km and 195 km respectively. On the other hand, the 355 case present a reduction of energy and a consequently reduction of range orbiting 104 km and138 km.

Model name	Range [km]
YOYO	150
Microlino	170
Microlino XL	230
Birò	90
Twizy	100

Table 39 competitors' range

As the table above suggest that the L7 vehicle developed is in line with other competitors if the 390 modules are considered. On the other hand, for 355 models the range is low in 3S1P consideration, so for this reason the 4S1P configuration is better.

Last element considered are the modules and their layout. This argument is strictly related to the range and compare the different type of modules and their types of layouts. Continuing methodically VDA390 will be considered first. This module presents an higher weight (around 13.5 kg) and this means also higher energy stored. The layout choice in this situation could be a standard configuration with a 3S1P that gives around 140 km to the vehicle to be in line with competitors. Moreover, a special edition of the car could be realized adding one more module for a 4S1P battery pack reaching around 200km, position the vehicle a little step ahead. Technically this implementation is not difficult because all the modules are linked in series remaining in the voltage range of the e-motor request and without changing the capacity of the battery pack. A distinct scenario is the VDA355, for this module the standard/special edition cannot be done due to poor range of the 3S1P configuration (around 100km) that position the car at the last position compared to the others. For this reason, in the case of 355 only one layout is available.

Finally, a weight consideration must be done to have a comprehensive view. As already evaluated the 390 modules are the best in terms of range and are suitable for creating two configurations, 130 and 200 km. On the contrary the weight if the single module is 13,5kg, this value does not influence deeply the final weight of the car, but the problem is the ergonomics. Moving 3 or more modules of 13.5 kg is worthy compared to 355 modules that weight 11 kg. On the other hand, the lighter ones provide lesser energy and range. There isn't a best situation, but a trade- off analysis must be done. Certainly, if the regenerative braking will implemented the range of 355 increase but this precludes a further analysis.

5.2 Reefilla application

As deeply analyzed in previously chapters, the SLIM project has the aim of generate an ecosystem of multipurpose swappable module. The last chapter investigate in detail every step that has been done to implement re-design VDA module into a small vehicle. By this chapter a second application is described, again the mobility is at the center, but also home energy storage will be analyzed.

5.2.1 Fillee

Before going in deep on application, a description of Reefilla and Fillee is necessary. The company was founded in Turin during the 2021 with the support of Polytechnic's incubator I3P. The aim of their business is providing charging solutions for electric vehicles, among the others they offer the first mobile charging service in Italy. The idea of Reefilla is based on 3 main problems of the mobility revolution:

1. Charging station availability: up to now the main challenge in the mobility revolution is evolve the charging infrastructure by placing enough charging station for EV. It is evident that if there is no upgrading of the infrastructure, the charging problem will be more consistence, enhance also by the fact that the installation request increase day by day.
2. Charging anxiety: the range problem is well known in the mobility sector; the lower energy density of the battery pack reduces the maximum range of the vehicle compared to ICE one. This is translated in anxiety for the driver that are used to drive more than 500 km and refill the car in a few minutes with ICE car.
3. Charging experience: actually, the charging station has different providers, this can be translated into different apps that must be downloaded to use it. Moreover, the services are not very reliable, and this could create problems increasing the charging anxiety.

Reefilla start from these 3 problems and try to solve it with an innovation: the mobile charging. With BEV vehicle, the charging phase is totally different to ICE cars. Instead of refueling in a few minutes during the journey, the EV vehicles should be recharged during parking time like during night or during working hours, substantially when the car is stop. Reefilla provide a service of mobile charging that is complementary to standard charging stations that are not available or not enough.

To do that the company design a mobile charging device, a sort of large power bank for cars calling it Fillee (figure 55). This device presents a variable number of modules linked together with different layouts to achieve up to 14 kWh of energy. Considering that the new Fiat 500 has a battery pack of 24 kwh, this device can charge 58% of that car or the 42% of the electric Dacia Spring.

Figure 55 Fillee AC version

More in deep the device has a steel structure with two independent wheels to be easily moved. Inside the bottom compartment the Fillee host the battery modules, while in the upper part there is the head of the device. All the electronics is included in the upper part, including the Iot, a component that permit to monitor and control the charger remotely. Moreover, the Fillee is provided of a DC/AC inverter that transform the continuous current of the batteries into alternated one for the cars. About that the last version of Fillee charge the cars with AC current providing 6 kW of power. In the next months a further improvement will be done, in fact a DC version of Fillee is work in progress. It will contain up to 8 modules reaching 19 kWh of energy and a charging peak power of 35 kW. In the previous case the charging time is around 2 hours and half, while in the DC models is half hour.

Both the devices weight from 95 kg to 115 kg depending on the version, this sems an high number but considering the lower energy density of batteries this solution is necessary to provide enough energy. In the next future the goal is to reduce the weight maintaining the same energy or on the contrary increase the energy maintaining the same weight.

For what concern the module inside the Fillee initially were Kumpan: swappable module from scooters' company that provide 1476 Wh each. The old version of Fillee contains 6 of these modules for a total of 8.856 kWh. For energy density reasons, the second generation of Fillee change completely the architecture passing to a car's battery module, the VDA390 and 355. This version increases the energy up to 14 kWh but losing the swappable features. In fact, the Kumpan version were utilized changing the 6 modules when were discharged and continuing the charge of the car.

5.2.2 S.L.I.M. implementation

After a brief description of Reefilla and what Fillee is, this section analyzes the application of S.L.I.M. in the mobile charger. As already said the charger contains 6 modules VDA390, they are stacked one above the other and screwed to work in a safety condition. This situation permits to charge completely a vehicle and after that need an operator that transport the Fillee to the Reefilla head quarter to be recharged. The contribution of SLIM in this situation is the swappability of the module inside the Fillee. Since the new module has the same dimensions of the original VDA, can perfectly fit inside the device, and after complete discharge of the Fillee, all the six modules can be substituted in a few seconds.

This solution changes the unit base of the Refilla's charging methos. While up to now the Fillee is the smallest unit for Reefilla, with SLIM the focus moves from mobile charger to module. In fact, the operator should swap modules and not move Fillee.

Practically, up to now, the Fillees are moved by a van that can contain 4 of them. If SLIM will be applied, the van can move the same number of Fillees, but has enough empty space to transport other modules. This means that after a first discharge of a Fillee, the operator swaps the module inside and the device is ready to charge another vehicle. The alternative is to bring back the Fillee to the head quarter, charging it and come back to the parking station. This solution permit to save time, energy of the electric van and money, obtaining a more efficient service.

Going more in deep is possible to evaluate the utilization ratio of a single Fillee. At numerator there are the total number of modules, on the denominator the modules inside a Fillee are multiplied by the number of devices. In one single van.

$$Utilization\ Ratio = \frac{\#\ modules}{\#modules_{Fillee} \cdot \#Fillee}$$

Equation 16 Usability rate of a Fillee

Up to now the #modulesFillee correspond to 6, the #Fillee is equal to 4 and #modules correspond to the modules contained in all Fillees so equal to 24. Using these data with the equation 16 the usability rate of a single device is equal to 1. Adding 12 more module in one van, the usability rate increase of 50% reaching 1.5. The already described situation permit to charge 6 cars with one van and one operator, increasing the service efficiency of single van saving time and money.

The number of module (12 in the example above) must follow a precise criterion. In fact, there are two important constraint that must be considered:

- Max weight allowed by the van, in this case the vehicle utilized is a Mercedes Vito with 600 kg allowed.
- Max weight of dangerous material, Lithium is considered as an unsafe material, ADR (a specific regulation) allow max 330 kg of lithium.

5.2.3 Home energy storage application

In this paragraph another application of the slim project will be described. As the title suggest the aim of this application is to store energy in home application, in particularly when the home grid is provided of photovoltaic solar panel to produce electricity. This electricity vector must be stored, and usually is converted into chemical energy of batteries.

Reefilla is designing an application of the Fillee as a home energy storage able to store a larger amount of energy compared to competitor. The project consists of to connect the device to the panel in order to store energy, but also connect the Fillee to the domestic grid in order to power all the home appliances. The philosophy is to use the energy of the solar panel during the day, when the energy cost is higher. On the contrary, during the night the energy stored in Fillees can be reintroduced to the grid obtaining a credit from energy company. This system can decrease the energy cost an also use green energy preserving the environment. This application is also very useful when an electric car or other devices such as scooter are recharged by the Fillee.

A similar situation but with a Fillee equipped by swappable module can create an ecosystem. Imagine a Fillee connected to solar panel and to the home grid, but in addition has swappable modules that can be utilized in a scooter application or small car described in the previously chapter or can still be used as a simple mobile charger for EV vehicle.

Conclusions

This project starts with the goal of optimizing modules enhancing versatility and designing it with more than one application. Constraints and goals influenced all the steps in designing phase of the brand-new VDA modules. Indeed, the final product can replace the original VDA for the automotive purposes, but also can increase considerably his applications creating an ecosystem. The outcome of this redesign is an evolved VDA390 module with recycled aluminum case produced by high pressure die casting manufacturing technique. The evolution includes reduction of weight, increased ergonomics and enhanced flexibility that permit to use this module for different purpose.

Subsequently the second part of the thesis is a feasibility study of a quadricycle vehicle with a battery pack equipped with the brand-new module. This configuration is not the first one since XEV brand commercialize the YOYO model, but that car does not allow swappability by the customer themselves but required equipped stations and specialized technicians. On the other hand, the hypothetical car is equipped by 3 or 4 modules that weight 13.5 kg, this means that are sufficiently lighter to be moved directly by the customer avoiding time loosing and availability of swappable stations. Moreover, the results of car's range are incredibly good considering the assumption, placing the final product in a competitive position compared to the benchmarking. As described the module doesn't have only one application but versatility is at the center of the project, for this reason other applications were described in the second part of the thesis. Firstly, the SLIM project, is introduced into Fillee, obtaining a smart mobile charger equipped by swappable module. This configuration of the charger significantly increases his efficiency and the utilization ratio of the devices. In fact, after a first discharge, the module contained in the Fillee can be swapped with charged one doubling the charging capacity of the device. Finally, an overview of home energy storage was analyzed, describing the ecosystem equipped by the brand-new module.

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