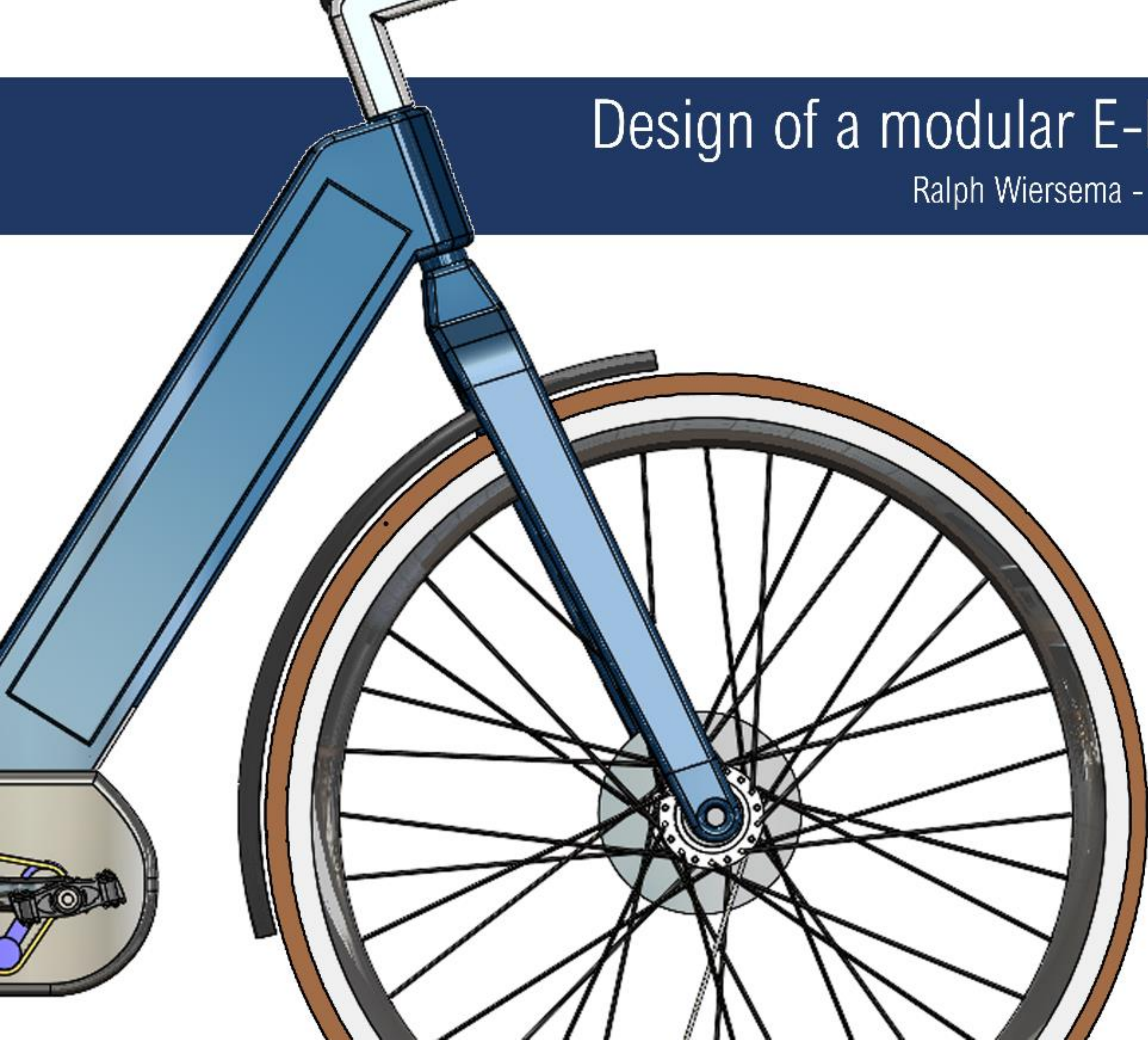
Design of a modular E-bike system

Ralph Wiersema - Master thesis - 2020



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Acknowledgments

The one main criterium for a graduation project was graduating at a company with a rightful purpose. To work on a project that helps make our world a better place and in which I believe to be viable in the future.

the company I have worked for is a world improver by heart. Working socially and sustainably has always been the core business value of the company. At this point, the company is working towards realizing a circular E-bike to make sustainable and convenient mobility available for everyone.

The project seemed to be a perfect fit with my graduation wishes, and I am grateful that I have been able to collaborate with the company to, hopefully, bring them a step closer to making their project a reality and make this world a better place.

Special thanks to:

Ruud Balkenende
Bas Flipsen

Thank you for the support on all the different levels of this project.
I appreciate your help, enormously.

Executive summary

With this project, we aimed to design a modular system to help the company realize a circular E-bike for shared E-bike fleet owners.

The context

Shared E-bike mobility is rapidly growing worldwide. The lack of sustainable end-of-life practices of shared E-bikes results in excessive E-bike waste. The company aims to reduce E-bike waste by designing a profitable circular E-bike in combination with providing a product-service system. Modularity is the driving factor for the circular E-bike, and the product-service system.

The problem

the company aims to design a single modular bike platform that can be used by all fleet owners searching for a sustainable and cost-saving solution. The vision for the modular E-bike is to achieve differentiation and low-costs. However, the specifics for the modular design were not set. To make the E-bike into a viable product, we must choose modules, their location, and the connection between them, which are all interdependent. The initial assignment only focused on connecting the modules. However, to connect the modules, we need to think about the location and the module specifics as well.

Method

We started with understanding the design goals and identifying the challenges. In the research, we analyzed the existing problems for the fleet owners and their origin. We then defined the right approach to implement modularity to tackle the identified problems. Next, we followed a top-down design approach to tackle the identified problems by integrating the specific modular solution. In the design process, we first designed a product architecture for the modules. Second, we designed interfaces to connect these modules.

Findings

In the fleet owner problem analysis, we identified that fleet owners commonly suffer from high total cost of E-bike ownership resulting from the high maintenance and replacement costs of their E-bike fleet. Moreover, we identified that fleet owners require sustainable business operations to meet regulations and to establish a positive brand image. Sustainable business operations are currently un-achievable because the presently used shared bikes have no economic, sustainable end-of-life purpose. We concluded that to become and stay profitable, fleet-owners should reduce the cost of E-bike ownership and improve their sustainability. We identified that a durable E-bike design with a circular end-of-life purpose could solve the main problems for fleet owners. This E-bike sustains long-term value and enables sustainable business practice. The boundary condition for long term circularity is a future robust design. The E-bikes' durability reduces upkeep frequency. Modularity enables the exchange- and interchangeability of (future) functional and aesthetical modules, which are critical for repairability and long-term re-usability of the E-bike. Decomposability of the modular system, thus accessibility of replacement of faulty and obsolete modules, is the key-necessity for E-bike repairability and upgradeability.

Results

We designed a durable modular system focused on circular end-of-life. The company can integrate the modular system in its circular E-bike concept. With the modular system design, we proposed a durable solution for the E-bikes' architecture, combined with interfaces that enable cost-efficient repair and the alteration of functional modules. Although the system is in a conceptual stage, it provides working principles to tackle the fleet-owners problems. The proposed concept Is different from the original companies' platform concept. Still, it gives the company with a specific direction for future concept development. The proposed working principles, however, require more particular decisions and design efforts for practical implementation in the final E-bike design, and to achieve a realistic final E-bike design revolved around the modular system. For the final realization of their E-bike concept, the company should test the principles in real life and decide on a target group to develop its E-bike concept further.

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Confidential appendix:

This report has a confidential appendix which describes a part of the concept vision and a part of the discussion in more detail.

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In this chapter, we introduce the project. We first elaborate on the sustainability of shared E-bike mobility and the goal of the company, which is the context of this project. Then we describe the design brief as formulated by the company, the design challenge, and the research approach in the next section. In the subsequent section, we provide more specific background info of the companies' concept, which we have used as a starting point for this project. In the last section, we visualize the complete structure of this thesis.

1.1 Sustainability of shared E-bikes

In this section, we describe the context of the project. We introduce the relevance of shared bike micro-mobility in the first section. Then we elaborate on the sustainability of micro-mobility in the next section. Subsequently, we introduce the company circular goal.

Shared bike micro-mobility

The growing need for urban transportation has periodically increased the number of vehicle usage on roads. It is ultimately leading to massive traffic jams and high environmental pollution (*Urban Transportation: Trends, Challenges, and Opportunities - Paris Innovation Review*, *2016*). There is a growing demand for eco-friendly transportation. (*Demand for Eco-Friendly Transportation to Boost the Global Pedelec Market Through 2022| Technavio | Business Wire*, *2018*) The rapid development of dedicated infrastructure & bike friendly regulations across the globe is expected to elevate bike-sharing market growth over the forecast (*Global Bike Sharing Market Size to Exceed $10bn by 2025*, *2019*). Customers are moving towards preferring sharing and using over owning. In response to this changing customer demand, manufacturers are increasingly offering products-as-a-service (*Owning Stuff. We're so over It. | Consumer Goods Technology*, *2018*). In recent years, bike-sharing popularity surged. (*The Bikesharing Trend: Past, Present and Future Overview of Bike Shared Mobility - Movmi*, *2018*). The global Bike-Sharing Service market is valued at 1570 million USD in 2018 and is expected to reach 5440 million USD by the end of 2024, growing at a CAGR of 28.3% between 2019 and 2024 (*Global Bike-Sharing Service Market 2019 by Company, Regions, Type and Application, Forecast to 2024 - Verified Market Reports*, *2019*).

Unsustainable shared bike mobility

The bike-sharing industry, consisting of both traditional bike and E-bike offerings, is centered around sustainability, with bikes being one of the most recognized eco-friendly means of transportation. E-bikes are "among the most energy-efficient motorized mode of transportation out there" (*What Is Up With Uber Destroying Tens of Thousands of Perfectly Good E-Bikes? – Mother Jones*, *2020*). Shared mobility operators try to focus public attention on the overall perception of bike-sharing as a climate- and eco-friendly mode of transportation and lifestyle, able to transform the cities positively. (Sustainable Transport, 2018). The bike fleet-owner is an example of a shared mobility operator. The bike fleet-owner is defined explicitly as the owner of a bike-fleet that rents out mobility to its customers by renting out its bikes for short or long-term usage. Examples of fleet-owners are Mo-bike, JUMP by UBER, and E-bike4delivery. The term 'fleet-owner' refers specifically to the E-bike fleet owner throughout the rest of the report unless explicitly stated otherwise.

We question whether shared bike mobility is genuinely sustainable.
In the current shared bike market, fleet-owners of regularly shared bikes employ large numbers of bikes to ensure wide-scale availability to consumers as the means for a competitive advantage over competitors needed to win market share. (*Tech in Asia - Connecting Asia's Startup Ecosystem*, *2017)*. The business practice of dropping large numbers of bikes to gain market share has commonly lead to an oversupply of shared bikes and, combined with lack of fleet-owner management, has resulted in the early end-of-life of significant numbers of shared bikes (*Pinkbike Poll: Who's Breaking Bikes These Days? - Pinkbike*, *2019*).

Pictures of colorful mountains of the decommissioned shared bikes, as seen in figure 1, do further indicate a lack of sustainable business practices by fleet-owners of shared, regular bikes. The shown images of bikes piles hint towards a design practice within the shared bike micro-mobility market that does not take end-of-life of the bikes into account or a lack of willingness of fleet-owners to prosecute practices needed for sustainable end-of-life of written-off bikes.

Figure 1: Pile of scrapped shared bikes in China.

The mentioned energy-efficiency of shared bikes, used by fleet owners within the shared bike market to imply the sustainable character of shared bike mobility, revolves around only a part of the total bikes' lifecycle and is not mentioning either the impact of production or end-of-life of written-off bikes.
Results of a life cycle assessment of shared mobility states that how environmentally friendly a shared bike dramatically depends on how long it lasts (*Here's How e-Scooter and e-Bike Companies Could Embrace the Circular Economy | Greenbiz*, *2019*). With a life expectancy of up to two years, regular bikes employed by shared mobility operators such as Mo-bike are not designed to last. These bikes can sustain large numbers of users and are relatively inexpensive to manufacture. (*Sustainable Transport, 2018*). The low manufacturing costs of a new (regular) bike allows the shared bike mobility provider to simply replace a bike that has maintenance issues for a new bike rather than investing in repairing the bike. The replaced bike has no end-of-life purpose and ends up at a scrapyard. This practice dramatically contributes to waste and, in addition to that, loss of valuable resources and loss of fleet-owner capital.

In contrast, the JUMP E-bike is designed to last three to five years (*Uber's New Jump e-Bikes Are Easier to Charge and Harder to Vandalize - The Verge*, *2018*) which is substantially longer than the regular shared bike of Mo-bike. Whether the JUMP E-bikes undergo the same fate as the regular shared bike of being replaced when in need of maintenance is unknown, however, their end-of-life purpose is no different from the 'disposable' regular shared bike. Uber, a well-known micro-mobility company (owning JUMP) that uses sustainability as its key selling point for years, just decided to scrap tens of thousands of electric scooters and bikes because recycling them is 'too complicated', shown in figure 2. (*Micromobility Companies Have Used Sustainability as Their Key Selling Point for Years, yet Uber Just Decided to Scrap Tens of Thousands of Electric Scooters and Bikes*, *2020*).

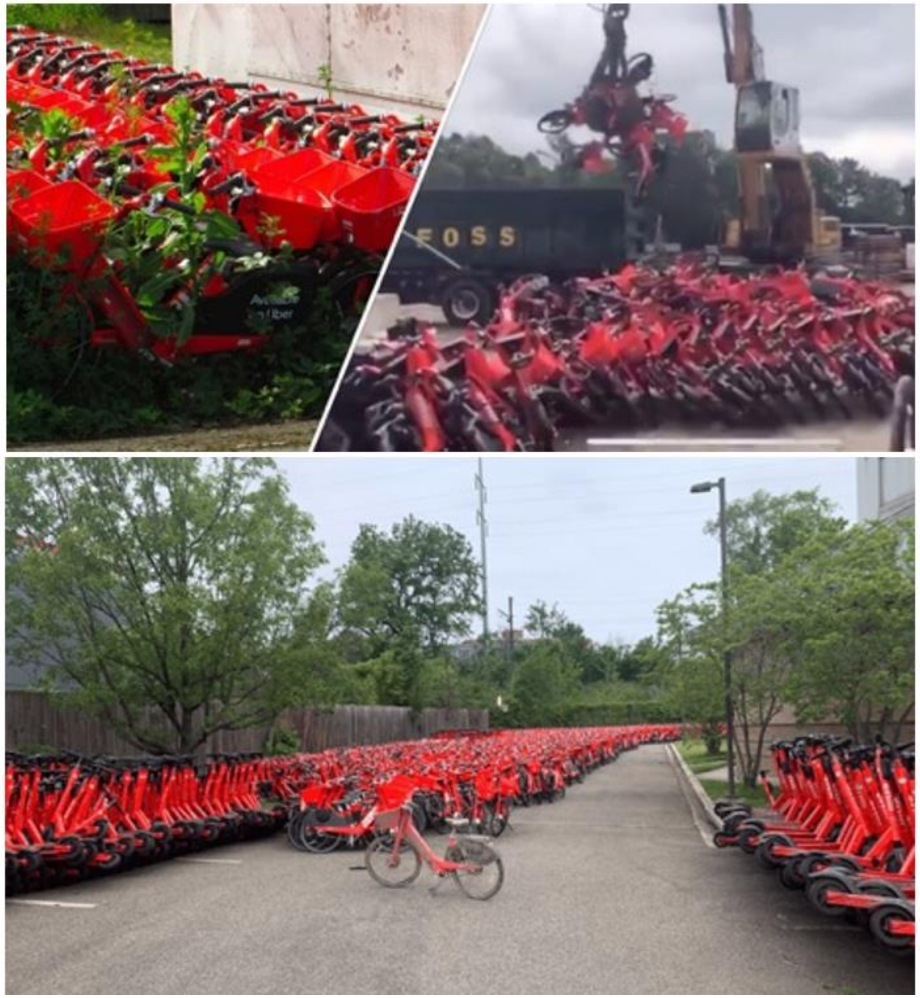

Figure 2: JUMP E-bike (ready to be) scrapped.

1.1.1 A sustainable E-bike solution

The company wants to tackle the unsustainable E-bike practices and has identified an opportunity to end the unsustainable shared bike practices in a profitable manner for both the company as well as the fleet-owners. The enormous worldwide growing potential of the shared E-bike market combined with the observed end-of-life practices of the nowadays shared E-bikes lead to the company's decision to focus on designing a sustainable E-bike.

The company is a bicycle company that found its origin in refurbishing old bicycles. The company refurbishing business found its origin in the vast number of bikes that go to waste every year, of which multiple essential and expensive parts (e.g., the frame) are still in excellent and usable condition. The company took matters in their hand and started refurbishing and selling the old bikes, which is still the core of their business model. The company is selling both refurbished traditional bicycles and a line of retro-looking E-Bikes to consumers. Another business unit of the company is providing refurbishment services to (traditional bike) fleet owners.

The company refurbishing business allows for re-use of functional bike parts, reducing waste while giving people with a relative distance to the job market, for any reason, the opportunity to be involved in something meaningful, to work and to learn for a better career prospect. The described business operations of the company make the company a philanthropic company that differentiates itself from the companies that purely focused on maximizing profitability at all costs.

Refurbishing old bikes is an excellent manner to reduce bike waste and to re-use valuable materials. It is, however, an end-of-life strategy rooted in the nowadays bike design resulting in waste and pollution. Based on their business unit of refurbishing bikes of bike fleets, the company identified high maintenance costs to be the root of worn bikes and excessive bike waste among fleet-owners. Therefore, the company decided to direct its focus to the source of bike waste: the design of the bike. The company's ambition is to design a shared E-bike employed by fleet-owners that completely vanishes waste at the end of its functional life. Optimal scale implementation of their sustainable E-bike is beneficial both in terms of the scale of economies, resulting in lower operation and component costs, and maximal reduction of E-bike waste, of which every fleet-owner as well as the company profits.

The circular E-bike

The company wants to sustain E-bike value throughout its product life cycle by circular design. Circular design searches for a way to deliver a product or a service, which is functional and made of optimum materials to deliver the best performance while minimizing its negative impact along the whole life cycle (Bocken et al., 2016), which is what the company is aiming to achieve.

The company has been focusing on a circular E-bike concept envisioned to be employable by fleet-owners to reduce their total costs of fleet ownership while allowing sustainable business operations. the company aims to minimize end-of-life waste- and capital loss for fleet-owners by retaining the maximum functional value of integrated E-bike components within the product life cycle of the E-bike. Optimal repairability is an essential characteristic of their E-bike concept. Cost-effective repairability should enhance E-bikes' longevity. It should significantly reduce both the cost of upkeep as well as lost capital and material waste at the end-of-life of the E-bike. the company implements a combination of modularity in its envisioned E-bike concept to facilitate circularity. The definition of modularity is the use of standardized and interchangeable components that allow a wide variety of final products through the way they are configurable (Gershenson et al., 2003).

1.2 The design brief

This section describes the project brief by the company and the distilled design challenge that we tackle throughout this thesis.

Modularity is a critical enabler for circularity. A key-characteristic of modularity is module exchangeability. The modules of which the circular E-bike concept is composed require both detachable physical and electrical connections to be exchangeable to achieve the company intended circularity. the company formulates the project brief around modular connections of their circular concept: '*Design of modular E-bike connections to realize the circular E-bike of the company.'*

1.2.1 Design challenge: interdependencies

The main design challenge of this project lies in the interdependencies of module connections to the rest of the E-bike design characteristics that are broadly envisioned but mostly unknown. The current state of the company's concept, more elaborated explicitly in section 1.3.1 *the circular E-bike as a platform*, is in its presented form, more or less an idea that consists of many combined features that require a clear directive decision combined with the significant design effort to be translated into a realistic concept.

The modular E-bike design consists of modules, the locations of the modules in the product (product architecture), and connections between modules (module interfaces); however, none of them are defined explicitly in the presented concept. Only the modules on which the company is now focussing most of its design efforts are relatively clear and specified, whereas possible.

In the E-bike design, however, the E-bikes' architecture, modules, and interfaces are interdependent since, together, they decide on the final aesthetics and performance of the E-bike. The final design of the E-bikes' architecture and the interfaces are specifically depending on the final modules' functioning and forms, as defined by the company. The final design of the modules, however, can be based on the desired product architecture and interface requirements that are needed to reduce the cost of E-bike ownership as well.

As stated, the final module design is not specified, and only some essential but general details on, some of the modules are specified. These details allow for the conceptual design of a product architecture together with module interfaces that can be either be immediately realized into a final product or by slight alterations to either the architecture, interfaces, or the module design itself.

1.2.2 Research approach

While the company is developing the modules, this project focuses on the design of the modular solutions that implement these modules. The modules are generally defined; however, no final aesthetics of modules has been decided on by the company. The complete list and configuration of parts within the modules are not defined, and module forms remain mostly unclear. The motor module differentiates the modular E-bike platform from the traditional E-bike platform. Therefore, the main challenge within this project is the modular design combination of the E-bike product architecture (locations of the modules throughout the E-bike) and the interface design (connections between the modules throughout the E-bike).

To deal with this ambiguity in the requirements and module specifications, we choose a top-down design process. We visualized our process in figure 4. In this process, we first decide on the most feasible product architecture for the modules. If we started with investigating specific connections first, we would spend much time investigating connections that are not used or are not even usable in the concept. By designing the architecture first, we define requirements and constraints for the interfaces, and thereby narrow down the solution space. We decide on this architecture based on the needs resulting from the exploration of problems for the fleet-owners. After defining the product architecture, we have several interfaces between the modules. We can regard these interfaces as sub-problems, that require separate design solutions. By defining the product architecture first, we set boundary conditions for the interface design.

To find the best solution for the product architecture and interface sub-problems, we identify requirements based on an analysis of the fleet-owners' problems. Solving the sub-problems and combining them in a non-conflicting manner results in the final E-bike concept. The result of this approach is an E-bike concept with specified interfaces between the modules. For the company, this design is helpful because of two reasons. First, in line with their design brief, they gain insights into the interfaces between the modules. Second, and maybe even more important, they now have an improved and more tangible concept, which they can use as inspiration further to specify the requirements for the design of their modules and to realize a viable circular E-bike ultimately.

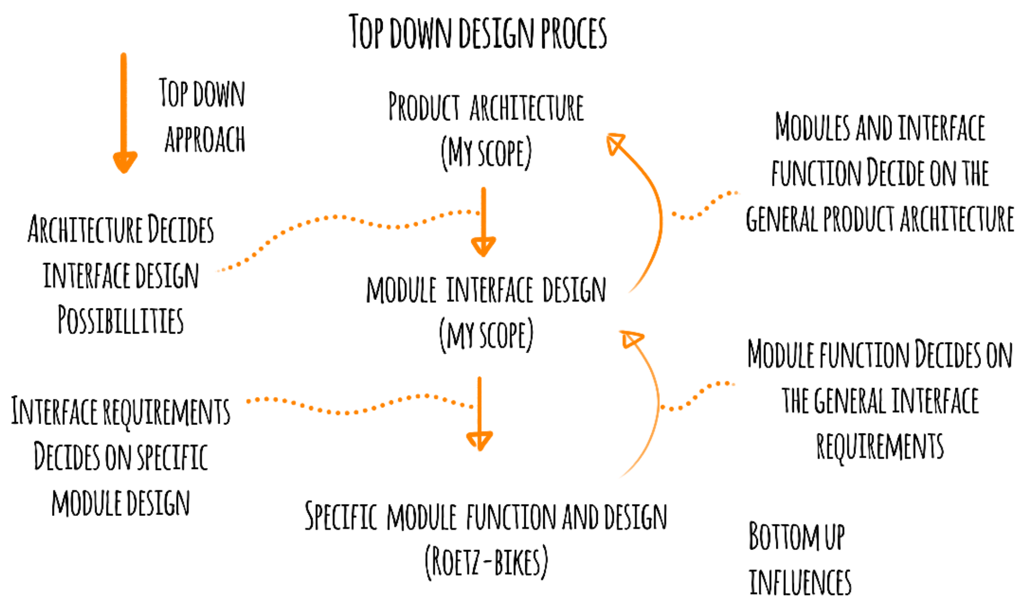

Figure 3: Top down design process of architecture design, interface design and final module design by the company.

Take-aways are located throughout the analyses within these rectangles. We highlight the key-design annotations distilled from the previous section that are considered as important for the final design.

1.3 The modular concept

To design the modular E-bike connections in a viable manner in this chapter, we first briefly describe the current company concept and the accompanied business model.

1.3.1 The circular E-bike as a platform

The company envisions its concept as a platform useable by all E-bike fleet-owners. Traditional (E-)bikes are perceivable as a platform: All traditional bicycles have similar structures and standard parts. Differences in the available parts allow for different product types such as a mountain bike, a cargo bike, a sports bike, or a city bike. The companies E-bike forms an alternative platform to the traditional E-bike. The conceptual E-bike consists of multiple modules that together form an E-bike. A module is an interchangeable component in a modular system (Schilling, 2000). The variety in available modules allows for differentiated E-bikes in terms of functionality, e.g., city bike or a cargo bike, and aesthetics that make the E-bike appeal and fit different fleet-owners and their business models. The envisioned E-bike consists of various modules that can be easily exchanged and maintained. The focus lies on the exchangeability of E-bike specific components: the motor, the motor controller, the belt, the battery, and the handlebar display module.
The implemented modules are designed from scratch by the company, and only some ideas on the motor module and the belt drive exist.

1.3.2 The product-service system

A circular product-service system based on the circular economy principles by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017) is to go along with their modular E-bike design in order to minimize the loss of functional value during the E-bike life cycle. The principle states that repair, maintenance, reuse, refurbish and recycling of modules are prioritized in that order to optimize the long-term value of materials in the system and to minimize leakage of value and waste from the system. The company envisions a similar closed-cycle model to ensure minimal leakage of waste and functional value of their E-bike.

Within the envisioned product-service system, accessible and in-time exchange of E-bike modules combined with efficient repair of the faulty modules are the means for cost-efficient E-bike maintenance. The actual maintenance performance of the E-bike fleet is made accessible by allowing the simple exchange of faulty or worn modules from the E-bike. The modular system should allow for a safe and straightforward exchange of modules in a non-time-consuming manner.

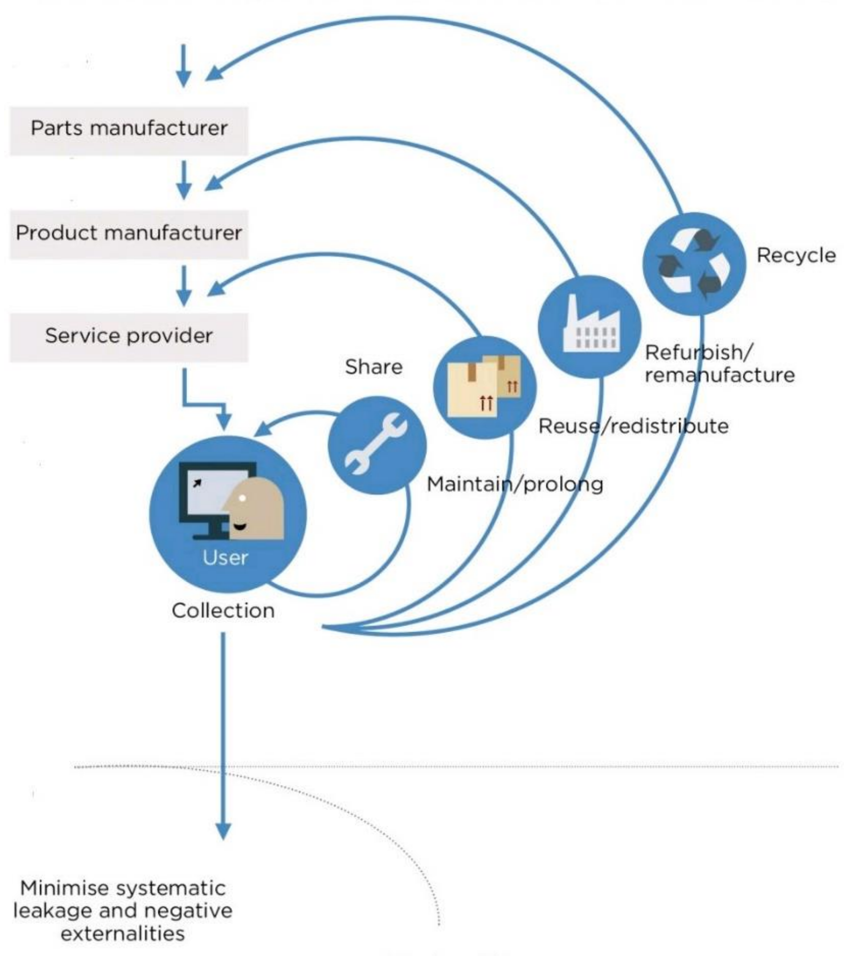

Figure 4: circular model by the Ellen MacArthur Foundation.

1.4 Thesis structure

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We visualized the report structure. We started with the introduction already. The analysis follows the current introduction chapter. The main findings throughout the introduction and analysis come together in the synthesis, which sets the design constraints. In the subsequent design chapter, we revolve our design the requirements set in the synthesis, leading to a final design. In the Evaluation, we conclude on the final design and the project.
We introduce every chapter in the beginning of the chapter.

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In this chapter, we elaborate on two analyses. We first analyze the fleet owners' problems. Then we identify how to implement modularity to solve the fleet owners' problems. We concluded on both analyses separately. In the final section, we conclude on the defined project brief by the company based on the results of both analyses.

2.1 Analysis 1: The fleet owners' problems

The company has identified the E-bike fleet-owners as the target group of their circular E-bike. For their envisioned platform to be interesting for all types of E-bike fleet-owners, the platform has to offer solutions to common critical problems of the different fleet-owners. By understanding these problems, we can focus on a specific and feasible direction for the design of modular E-bike solutions. By focusing on integrating problem-solving design solutions in the circular E-bike concept, the final E-bike design could spark the needed interest for wide-scale implementation by different fleet-owners

We identify the critical problems as well as the origin of these problems for fleet-owners in the current shared E-bike market. The company combines both fleet-owner profitability and sustainability aspects in their E-bike concept. In this problem exploration, we explore the fleet owner's profitability- and sustainability problems to understand if the circular concept solves the key issues.
For the fleet-owners, profitability through the employment of their E-bike fleet is ultimately the most crucial aspect of their business. Currently, for many fleet-owners, unsustainable business operations do not seem to be a significant problem. However, regulation is becoming stricter, and consumers are increasingly demanding more sustainable products. In addition to that, for fleet-owners, sustainability becomes a more critical aspect of their business. We will investigate how sustainable E-bike fleets are currently and what opportunities there are for improvements.

In this analysis, we try to answer two questions:

I. What is driving the profitability problems for E-bikes fleet-owners? Elaborated in section 2.1.1 Profitability of the E-bike fleet.
II. What are the fleet owner incentives for sustainability, and what are current sustainability problems for fleet-owners?
Elaborated in section 2.1.2 Sustainability of the E-bike fleet.

2.1.1 Profitability of the E-bike fleet

Becoming and staying profitable is difficult for E-bike fleet-owners due to the high total cost of ownership of their E-bike fleet. Significant maintenance and the need to replace bicycles often to keep up with the high speed of innovations of E-bikes confronts fleet owners with high costs. Moreover, vandalism and theft of bikes are significant barriers to profitability to many micro-mobility companies (*Micro Mobility Market & Companies I CB Insights*, *2020*).
Besides, due to the high competition within the shared bike market, fleet-owners only have limited pricing power. The high costs combined with limited pricing-power result in slim profit margins for fleet-owners.
To understand the significance of cost reductions for fleet-owners, we have to understand the cost drivers. First, we discuss the maintenance costs, and then we discuss costs involved with replacing E-bikes resulting from vandalism and the need to keep up with improved technologies.

Maintenance costs

Shared bikes are ridden up to 15 times more than personal bikes and endure relative rough usage due to their shared, un-personal, character (*The Bikeshare Planning Guide*, *2018*). Besides, the E-bikes are exposed continuously to their usage-environment. The heavy use of the shared E-bikes makes regular skilled maintenance a necessity. The evident poor condition of bikes negatively influences consumer trust and will result in a drop in ridership (*Micro Mobility Market & Companies I CB Insights*, 2020. Therewith, fleet-owners must keep their E-bikes in good condition. Maintenance costs are a result of the upkeep of the shared E-bikes. High maintenance costs of bike fleets have been one of the biggest challenges to the long-term viability of bike-share programs (*Five Bike Share Trends Enhancing Customer Interaction and Solving Operational Challenges*, *2020*). The costs of running a bike share, including operations, maintenance, and support, usually make up around 60% of the total cost of bike share *(Chrysanthou, 2009*).

Maintenance costs can be reduced by reducing repair frequency and by easing the repair itself. A durable design that is easy to repair is desirable to minimize fleet-owners' costs of E-bike ownership. Reduced maintenance costs are achievable by reducing the actual repair costs as well as reducing the frequency of performed repairs. Durability, the ability of a design to last for its designated life in its particular environment, is critical in the design of a maintenance-free system (*Factors Affecting Design*, n.d.). The actual maintenance costs are a result of the breakdown of traditional bike components integrated within the E-bike in combination with the integration of more advanced and complex E-bike components.

Take-away

Maintenance costs can be reduced by reducing repair frequency and by easing the repair itself. A durable design that is easy to repair is desired to reduce fleet-owners' costs of E-bike ownership.

We should better understand which components break down most often to identify the components that require the most cost-efficient replacement. First, we discuss which traditional bike components break down frequently. Then we discuss how the integrated E-bike components further increase the repair costs.

Breakdown of traditional bike components

Traditional E-bike implemented within the E-bike requires the highest maintenance frequency and must be optimally accessible for repair and maintenance. We split the maintenance costs of traditional components into wheel-related maintenance and maintenance to other components. The vast part of performed bicycle maintenance is wheel-related. Wheel-related maintenance: accounts for between 50%-90% of overall maintenance, depending on the bike share scheme (*Five Bike Share Trends Enhancing Customer Interaction and Solving Operational Challenges*, *2020*). Both the inner and outer tires are susceptible to usage wear and puncturing risks. To reduce wear of outer tire and tire replacements, they need to be correctly inflated. Also, the wheels need frequent maintenance, for example, for spokes break, rim cracks, wheel strokes.

Adding to the high maintenance frequency of tires, the traditional mechanical bike parts, which are in both regular bicycles and E-bikes, the company identities the components most susceptible to breakdown and maintenance frequency. These components include:

- The drivetrain components: the chain wears relatively quickly. The chain needs to be tensioned right and wears down the gears when worn or rusty.
- The brakes: both brake pads and brake lining in brake caliper: wear down due to friction.
- The saddle and bike handles: wear through regular usage.

Take-away

Traditional E-bike implemented within the E-bike require the highest maintenance frequency and must be optimal accessible for repair and maintenance.

Breakdown of advanced E-bike components

The combined incorporation- and positioning of advanced E-bike parts and traditional bike components makes E-bike maintenance more complicated and time-consuming compared to traditional bikes. The advanced characters of the E-bike parts make fine-tuning more difficult for inexperienced mechanics, resulting in increased time per repair and the associated costs. Failure of relatively expensive or hard-to-reach parts causes the bike to become economically unworthy to repair, rendering the other still perfectly functioning parts useless.

Accessibility of faulty components is an essential factor for decreasing the costs of repairs. Therefore, we identify the accessibility of E-bike components and the separability of these components from the E-bike as important characteristics for the final E-bike design. Although specific E-bike parts, such as the motor module, are less prone to breakdown/wear than traditional parts, they can still fail. The motor controller and battery are most susceptible to breakdown in comparison to the rest of the E-bike components. We identify this in Appendix 6.3, *The modules.*

Take-away

The combination of traditional bike and E-bike specific components make repair and fine-tuning complex. The E-bike components must be accessible and easily separable from the E-bike.

Replacement costs

Replacement costs are the costs resulting from the purchase of the supplies required for employing and upkeep of the shared E-bike fleet. These costs result from inevitable usage- and environmental wear, technological obsolescence, or theft. We describe E-bike depreciation through wear and vandalism as well as technical progress.

E-bike depreciation through wear and vandalism

As stated in section *maintenance costs*, The E-bike is susceptible to heavy usage and vandalism as well as being regularly exposed to influences from its usage-environment, e.g., the weather or lousy infrastructure. If a shared bike is not sufficiently robust of weather-proof depreciation will kick in fast (Chrysanthou, 2009). Besides, the E-bike specific parts have a high initial value, but their performance and value degenerate when used. The battery is a good example: expensive when purchased but loses much value straight after usage. The battery and the motor make up about 65 percent of the cost of the e-bike. After three years, they might work up to 60 percent of their capacity and have no more than 20 percent of the original value (*How Fast E-Bikes Depreciate? How Fast E-Bikes Lose Value? – Easy E-Biking – Helping to Make e-Biking Simple, Practical and Fun*, *2020*). High costs come from full replacements of complete E-bikes or the components as the result of wear, break down by overload, and vandalism. To cope with these high costs, existing shared E-bikes are generally robust with minimal features and sealed off components. These characteristics reduce the risk of degrading E-bikes through vandalism and the weather (*Jump Just Made All New E-Bikes to Fix Everything Wrong with e-Bike Sharing*, *2018*).

Take-away

E-bike depreciation results from usage- and environmental wear as well as vandalism. E-bike features are to be minimised and its components should be robust and well protected against the weather.

E-bike depreciation through Technical progress

In comparison to the hardly changing traditional bike, the E-bike is more technical and, therefore, more expensive. Discarding E-bikes after only a short lifespan is, therefore, driving the high costs for fleet-owners of electric bikes. Cost-savings on replacement are achievable when the lifespan of the E-bikes is prolonged. Currently, the upgradeability of the shared E-bike is a non-existing feature. Lack of upgradeability makes future technical obsolescence of the E-bike's inevitable. E-bike components are not interchangeable for newer models.
As technology advances, enabling better-performing parts, customers demands for innovations within shared E-bikes grow and pressure fleet-owners to keep up with their E-bike fleet.

Technological progress results in obsolescence and replacement of already integrated E-bike parts even though these 'older' parts function fine. As a result, the E-bike is susceptible to devaluation resulting from new technology: new technology negatively affects the value of older 'sudden- inferior' technology. Technological progress enhances the devaluation E-bike even further when production of older implemented technology is (suddenly) discontinued, and spare parts become scarce, expensive, or even unavailable. They are resulting in time-consuming and high costs of repair or complete loss of E-bike value.

Current developments of E-bikes focus on weight, size, range, and connectivity. The current design focus of E-bikes is on traditional bicycle aesthetics. In the future, it will be almost impossible to differentiate e-bikes from traditional bikes based on appearances alone (*E-Bikes: Bosch & Co about the Future of Electric Bicycles*, *2017*). Motors will gradually become smaller, lighter, quieter, and more integrated. Batteries, too, will become smaller and lighter over time together with enhanced battery capacity (*Future of EMTBs: What to Expect in the next 5 Years*, *2020*). Technical advances such as advanced braking systems, automatic transmission with internal gearboxes seen in the automotive industry are making their way into the E-bike (*Automatic Transmission Is the Future of E-Bike Drivetrains – Revonte*, *2019*). The development of Display E-bike monitoring systems enhances the riders' comfort. It allows for further optimization of E-bike technology and optimal performing components, which will ultimately result in a highly advanced E-bike *(Top 5 Innovations for the Display Bicycle* | *Svava, 2020*).

The E-bikes' susceptibility to technological progress compromises long-term E-bike value and repairability. Upgradeability of the E-bike allows the E-bike to sustain overall value while ensuring the availability of spare parts required for low-cost repairs.

Take-away

Long-term E-bike value retainment and repairability are compromised by the E-bikes susceptibility to technological progress. Upgradeability of the E-bike allows the E-bike to sustain overall value whilst ensuring availability of spare parts required for low-cost repairs. A design focus on traditional bicycle aesthetics is emphasized with future E-bike aesthetics moving towards the traditional bike aesthetics.

Insights on fleet owner profitability

In the previous discussion, we argued why for fleet-owners, it is difficult to become profitable. We focused mainly on the costs side. Because of the high competition and vast growing market, companies are trying to capture market share by undercutting each other in the price of their service. Therefore, for fleet-owners, it is currently difficult to recoup their high costs by increasing prices.
Fleet-owners should show positive earnings prospects to attract investors. Therefore, fleet-owners should try to find ways to reduce their costs more than their competitors. We identified that a significant opportunity for reducing the costs lies in reducing the maintenance and replacement costs. Both expensive repairs and replacement practices ultimately translate into the extensive loss of fleet owner capital and resources. Maintenance costs are reducible by decreasing the frequency of repairs and the costs per repair. A durable E-bike design is necessary to reduce the frequency of repair. Accessible repairability is needed and to decrease the costs of repair. Fleet owners should both try to prolong the life of the E-bikes and aim for low-costs end-of-life strategies to reduce replacement costs.

2.1.2 Sustainability of the E-bike fleet

The bike-sharing industry frames itself as being centered around sustainability, with their shared bikes being one of the most recognized eco-friendly means of transportation (Bieliński et al., 2019). In the introduction section 1.1 *Sustainability of shared E-bikes* of this report, we questioned whether shared E-bike mobility is genuinely sustainable. It is important that the bike-sharing industry focuses on sustainability for the sake of the environment. However, the customers of the circular E-bike concept are the fleet-owners. To understand if sustainability is also essential for these fleet-owners, we discuss, first, why fleet-owners should care about sustainability and, second, what makes it difficult for them to become more sustainable.

Fleet owner Incentives for sustainable business operations

Although it is currently more profitable for fleet-owner to dispose of ten refurbish old bikes, there are two reasons why fleet-owners should reconsider this approach in the future. First, cities experience problems with sharing services and form more strict policies and regulations. Second, increased consumer awareness of environmental issues increases the demand for more sustainable services.

Regulation: the fleet-owners need for a sustainable E-bike

Oversupply, lack of operational management and bankruptcy of bike mobility providers lead to abandoned broken bicycles scattered throughout cities, resulting in a negative impact on public spaces, with the responsibility to clean up the mess ending up with local governments and bikes ending up in landfills (China Still Sorting Through Its Bike-Share Graveyards - The Atlantic, 2018). The ill-considered shared bike introduction by shared mobility operators has negative implications on the reputation of shared mobility providers and lead to new restricting regulations and policies for market introduction aimed at the shared mobility market.

One example is that bike-sharing companies are obliged to have the ability to dispose of their damages and irreparable bicycles in an environmentally friendly way, even after declaring bankruptcy (*How to Clean up Bike-Sharing Firms' Mess Chinadaily*, 2018). Another one is a mandatory life-cycle assessment of the intended mobility form, which needs to be passed with acceptable results before cities permit its market introduction. This life cycle assessment evaluates the environmental impacts associated with all the stages of the vehicle's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or re-use (*This Is How Startup Dott Makes Shared Mobility Sustainable in Europe - INFO*, *2018*).

The mentioned regulations raise barriers for unsustainable business practices, which translates into sustainable business models becoming an obligation for operators within the shared E-bike market. This obligation forces fleet-owners to create a sustainable product and creates the need for a more sustainable or circular E-bike.

Take-away

Business practices have led to regulations of the shared mobility market. Fleet-owners need an E-bike that meets regulations and run their business which emphasizes the importance of sustainable E-bike design.

Brand image: the fleet-owners want for a sustainable E-bike

The attention for sustainability under consumers is growing (*Corporate Sustainability & Consumers: 3 Trends Every Company Needs to Know | Antea Group USA*, *2019*), and thus, adopting more sustainable ways of working is becoming attractive for businesses as well. Companies are making a global shift towards more environmentally sustainable ways of working to improve their brand position (*Why Environmental Sustainability Is Becoming Big for Business - The One Brief*, n.d.).

In a world where sustainable business operations are becoming the norm, unsustainable shared mobility practices as currently performed are by no-means viable in the long-term. Moving towards a circular business model allows shared E-bike operators to build a strong reputation and engage customers, suppliers, and their employees as well (*John Egan*, *2020*). At the same time, the circular model, when done right, allows for longer-lasting products and re-use of components/materials and, in addition to that, optimal preservation of functional value, which is interesting from an economic perspective. Finally, reducing the needed virgin material and created waste will reduce pollution, which is something from which all of society and our planet ultimately benefits.

Take-away

Moving towards a sustainable business model fits the growing consumer desire for sustainable products and can have many benefits for the fleet-owner making the circular E-bike interesting for fleet-owners.

Sustainability issues

With the previous discussion, we made clear why fleet-owners should become more occupied with dealing with sustainability issues. Significantly, the lack of end-of-life purpose and the high wear and tear that requires frequent replacement, makes the business unsustainable. Now, we discuss why the current fleet-ownership is unsustainable.

No sustainable end-of-life strategies

Current shared E-bikes lack sustainable end-of-life purposes resulting in the E-bikes getting scrapped at the end of their functional life. The said end-of-life practice implicates that scrapping decommissioned E-bikes is the most economical option for fleet-owners. This practice, however, is far from sustainable. To make the E-bike sharing more sustainable, the E-bike should have an accessible end-of-life purpose such as re-use or repair.

Manufacturing practices that prohibit sustainable end-of-life

The current E-bike design does not allow for the interchanging of parts. Therefore, future devaluation of advanced components is inevitable. Currently, the E-bike frame design forms a framework for selected parts, often manufactured by other companies. For example, E-bike frames are fully customized to precisely fit a Shimano or Bosch proprietary system consisting of battery & motor. This design habit does not allow for upgradeability or backward compatibility, more specifically the integration of both older and newer other shaped parts with different specifications. If a part in a proprietary system breaks down, it can only be replaced by the same part from the same brand due to its specific fit or combined function dependence. Devaluation or breakdown of a single part in combinations with discontinuation of spare parts can render all perfect functioning other parts useless. E-bike design revolving around specific components makes the fleet owners' fleet value dependant on the component-manufacturing-party for long-term and cost-effective repairability of their E-bike fleet.

An E-bike employed by a fleet-owner that has the intention to last, meaning it will need inevitably need repairs throughout its life, depends on the constant availability of spare parts. The dependency on the continuation of components and spares of manufacturing companies is one of the main reasons why old E-bikes have a low resale value. It goes so far that if the battery requires replacement, the bike has almost no market value at all and is unlikely to fetch more than scrap value (*Disadvantages of Electric Scooters - User Guide to Electric Scooters and Electric Bikes: A Review of Advantages, Disadvantages, and Problems, with Advice, Tips, and Guidance for Use*, 2017). Discontinuation of product lines resulting in the lack of spare parts needed for repairs diminish the resale value of the E-bikes. Because of the susceptibility to technological advances and the little resale value of the E-bike, the depreciation costs of E-bikes per year for the fleet-owner are relatively high compared to the depreciation costs of traditional bikes.

Take-away

Economical end-of-life strategies are required to reduce unsustainable scrapping practices of shared E-bikes by breaking dependence on proprietary systems combined with interchangeability of components.

Insights on fleet owner sustainability

Fleet-owners should have economic end-of-life strategies for their E-bikes, such as cost-effective re-use or repair to make their E-bike sharing practices more sustainable. Exchangeability and interchangeability of components could enhance the E-bikes' lifetime and enable cost-effective E-bike repair and re-use of the E-bike and its components. The interchangeability of Fleet-owners enhances the future robustness of the E-bikes and, with this, reduce the yearly depreciation costs of the fleet. Upgradeability and backward compatibility combined with the availability of spare parts requirements for a future robust E-bike design and long-term re-usability of its components.

Take-away

Future-proof-ness of the E-bike is compromised by current E-bike design and manufacturing. New modules must be continuously implementable to break dependence on (older) proprietary systems. Availability of spare-parts is another boundary condition for future robustness of the E-bike.

2.1.3 Acquired insights from the problem analysis

The problem analysis shows that E-bike fleet-owners have difficulties in combining low-cost and sustainable business operations. The fleet-owner desired profitability leads to practices of choosing relatively cheap replacements over more costly repairs. Replacement of shared E-bikes cuts maintenance costs; however, replacement impairs the fleet owner's ability to run sustainable business operations. Sustainable business operations are becoming increasingly essential to meet governmental regulations and, as a response to consumer demand.

The fleet-owners' difficulties to economically run a sustainable business operation find their origin in the current E-bike design that is both costly to repair and lacks end-of-life purposes. The inevitable loss of functional value and capital of the fleet-owner resulting from replacement practices based on the current integral E-bike design explains the opportunity for an alternative circular E-bike.
Durability and end-of-life are the most important E-bike design take-aways.

Design for durability

The design of the E-bike, components, and connections for robustness and durability enhances the longevity of the E-bike and sustains the functional value of the integrated components. Design for durability reduces the frequency of required maintenance and repairs needed for the upkeep of the E-bike and its performance. Theft and vandalism proof-ness have to be taken into consideration to minimize the instant loss of value for fleet owners and to ensure a long functional life for the E-bike components.

Design for end-of-life

Design for end-of-life aims to sustain functionality, and thereby capital value throughout the E-bikes' life-cycle and reduces the impact in terms of lost resources and pollution when the E-bike is decommissioned. The circular design ensures optimal functional value throughout the E-bikes' lifetime and minimal waste at the end-of-life of the components. Figure 8 visualizes the R-ladder of the circular economy. By thinking about the lowest chain R-principle during the design of the E-bikes, we can achieve a more sustainable end-of-life (Kishna et al., 2019). Future proof E-bike design is a critical boundary to achieve the said circular end-of-life purposes.

Future proof-ness as the means for circular end-of-life

For E-bikes to become genuinely circular, they should be designed to be future proof. An E-bike is future-proof if it sustains its desirability in the long-term. Making the bikes future-proof is essential in designing the for end-of-life. For example, it does not make sense to repair a bike if it is not desirable for re-use in the future. An E-bike is future-proof if it enables optimal retaining of E-bike and component value over time and sustains the feasibility of re-use of the E-bike or its components. Constant availability of spare parts, functional and aesthetical customization of the E-bike combined with a design focus on a timeless, practical design, which means having a sustained purpose and fit to consumer needs, allow the E-bikes to be future-proof (*Sustainability guide – product, 2017*).

Durability and end-of-life of the E-bike, as elaborated, form the key-focus of the E-bike design and are the design principles to serve the stated fleet-owners' critical needs. The E-bikes' Durability its end-of-life form the key-focus of the E-bike design. The envisioned product-service system and end-user constraints such as required E-bike comfort restrict the design options in terms of the E-bikes functioning and aesthetics.

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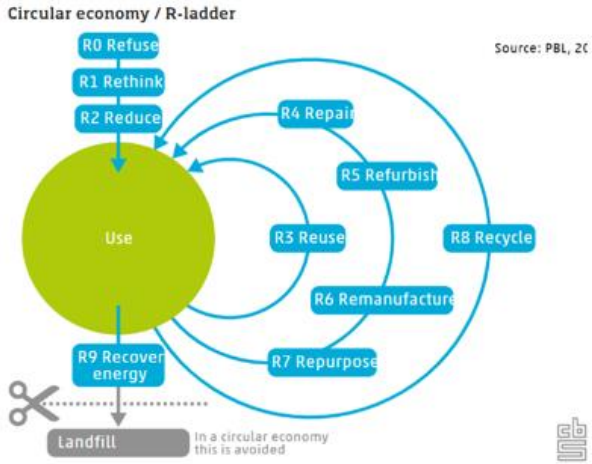

Figure 5: R-principles of circularity.

Take-away

Design for durability (robustness) and design for end of life (re-use, repair *combined with* future robustness through practical design with time-less customization options) are the key design principles to tackle critical fleet-owners' problems.

2.2 Analysis 2: Modularity

As we concluded from the analysis 1: design for durability and design for end-of-life are the main principles in the design of an E-bike solution to tackle the problems which result in the high total cost of E-bike ownership- and unsustainable business practice for fleet-owners. This analysis explores and identifies how to implement modularity in the E-bike concept design to achieve future robust solutions for fleet-owners and the long-term viability of the circular E-bike concept.

In this analysis, we try to answer a specific question distilled from the results of the first analysis.

- ➔ In what specific manner is modularity to be implemented to achieve the fleet owner's needed durability and end-of-life E-bike characteristics.

The upcoming chapters elaborate on the modularity analysis. The chapter first identifies the modularity of existing E-bikes. It then defines how to implement modularity into an E-bike that is both durable and has circular end-of-life purposes. The section concludes with the final implementation of modularity within the E-bike to achieve the intended problem-solving purpose for fleet-owners, as distilled from the analysis.

2.2.1 The modularity of existing E-bikes

An E-bike is generally perceived to be a super-modular product already: every part can be replaced in the current E-bikes. The traditional E-bike design, however, is not focused on optimal repair specific purposes, part replacement, or an end-of-life specific purpose other than recycling. In existing E-bikes, to reach a particular part, many other parts will have to be removed from the system, which makes repairs complicated and time-consuming. Apart from enhancing E-bike circularity, modularity can also be implemented to create a better fitting bike to the final user group. Modular customization could create competitive advantages for fleet owners, as elaborated in the next section.

E-bike customizability as a competitive advantage

The Chinese operated Mo-bike introduced its shared bikes in the Netherlands. However, the bike has been perceived as highly uncomfortable by the Dutch: The bike is small, heavy and takes much effort to pedal (*Hoogleraar Nas: 'Ik Geloof in Deelvervoer' - Fietsersbond*, *2018*). The Mo-bike is designed for Chinese use. Chinese people are generally short, which has affected the bikes' geometry. Also, the Chinese are not used to the comfort of their bikes as the Dutch. The cultural differences translate in the Dutch less willing to rent the 'uncomfortable' Mo-bikes as opposed to the Chinese who have no bike comfort reference frame. Customer satisfaction is a necessary precursor of customer loyalty (Martisiute et al., *2010*). Based on the relationship between customer satisfaction and customer loyalty, one could doubt if the Mo-bike in its current form can be successful in a country like the Netherlands. The same recounts for other shared micro-mobility E-bike companies that follow similar principles as Mo-bike.

Employing a single un-adapted E-bike design in regions that culturally or geographically differ is not likely to result in optimal user comfort and customer satisfaction, which could compromise the E-bikes' profitability due to the resulting reduced- or lack of usage. A proper customizable modular E-bike can bridge the gap of customer satisfaction per region by offering functional and aesthetical E-bike alteration options that fit the needs and desires of consumers in different regions. Examples are the implementation of alternately frame/saddle/handlebar geometry, a better motor, or other tires for better functioning in mountainous areas or personalized aesthetics for specific cities.

Appearance and usability, which is better than average, are factors that create product attachment, described as the emotional bond consumer experiences with a product (Arnheiter & Harren, 2006). Enhanced product attachment, meaning the consumers will love, like, or trust the product longer (*Sustainability guide – product, 2017*) is likely to result in enhanced E-bike usage. In addition to that, cut-to-fit customization of the E-bike to fit consumers' preferences and to out-perform E-bikes of local competitors can induce the competitive advantage needed by the fleet-owners to gain market share.

Enhanced product attachment through functional and aesthetical customization of the E-bike may subsequently promote product longevity as a result of more protective product behavior (Ruth Mugge Rick Schifferstein Jan P.L. Schoormans, 2006). Enhanced E-bike longevity reduces the need for E-bike replacement, which is both desirable in terms of running a sustainable business and reduction of fleet-owners' total costs.

Take-away

Alternative modular design enhances the circularity of E-bikes relative to existing E-already modular E-bikes. In addition, modularity can induce competitive advantages for fleet-owners by enabling functional and aesthetical differentiation to specifically fit consumer cultures and the usage environment of different regions. Enhanced resulting customer satisfaction enhance customer loyalty and product attachment which could increase E-bike usage and may enhance the E-bikes' longevity.

2.2.2 Durable modularity with an end-of-life purpose

As stated in 2.2.3 Main design principles to solve the fleet-owners' problems, Design for future robustness of the E-bike drives the viability of end-of-life purposes of the E-bike. A modular system is characterized by the possibility to exchange the implemented modules, and modularization is the most efficient and most used product architecture approach when future robustness should be enabled (Greve & Krause, 2018). A modular system allows the interchanging of modules or the addition of modules to maintain or alter system performance. Modules can be removed separately in a non-destructive manner and re-used in new configurations. Functional binding, interface standardization, and decomposability are vital factors for a modular product (Parker, 2010).

- High levels of functional binding: or 'functional mapping' is the compartmentalization of functions of a system. One-to-one mapping of functions to components results in the possibility to add or subtract functions from a product by addition or removal of components. Functional binding reduces the interdependence of components within a system and allows for the addition or removal of separated functional modules.
- Interface standardization: standardized interfaces allow modules to be used and re-used in multiple products and enable compatibility of the modular system with earlier and next-generation modules.
- Decomposability is the term that is most often associated with the flexibility of a modular system and captures how easily a system is separated into its various components. (Vickery et al., 2016). Easy decomposability makes component swapping practical, which enhances the repairability of the product.

Take-away

Modularization enables future robustness which is required for circularity of the E-bike. Functional binding of modules and decomposability is required for optimal interchangeability of modules and standardized module interfaces enable variety of module combinations.

For a durable modular design with an end-of-life purpose, a variety of modular product characteristics require a focus that revolves around the integration of quality functional and aesthetical modules that can be interchanged by the same or alternative modules in an accessible manner. The next sections separately elaborate on the design principles that are required to achieve the modular characteristics needed for a durable modular system as well as the end-of-life of the modular system.

The durability of the modular system

Design for durability, e.g., against usage, vandalism, and the weather, of the modular E-bike, reduces the required maintenance/repair frequency and allows components to sustain their (re-use) value. The initial modular design should thus focus on durable design. Durable design is enhanced by:

- Usage of quality and robust components and connections: use of quality and robust components and connections reduces the risk of system breakdown (Arnheiter & Harren, 2006).
- Minimizing components and product features: minimizing the number of components reduces the risk of breakdown (Arnheiter & Harren, 2006). Stripping unnecessary features helps to reduce the number of system components.
- Protected and sealed of modules: components are to be protected against external influences such as the weather to minimize wear and breakdown.

Take-away

Usage of quality or robust components, minimizing components and protection of the components against vandalism and the weather enhances the E-bikes' durability.

End-of-life of the modular system

As visualized in Figure 8, the R-principles, the most optimal principles in terms of sustaining E-bike and component value after product use, thus at the end-of-its intended functional life, is re-use. Re-use is followed by repair, which enhances E-bikes' longevity and enables the reusability of components when they inevitably breakdown. Recycling is the last resort option if the E-bike or its parts cannot be refurbished, remanufactured, or repurposed. This section elaborates on modularity to achieve re-use, repair, and recycling as end-of-life purposes of the E-bike and its components.

Re-usability of the modular system

Re-usability is the most optimal end-of-life scenario in terms of sustaining the functional value and minimizing waste of unbroken E-bikes and components.
As described in 2.1.3 *Acquired insights from the problem analysis section future proof-ness*, future robustness of the E-bike concept is an essential characteristic for the E-bike to be able to sustain feasibility needed for long-term re-usability within the circular system. Factors that influence future-robustness of the E-bike are:

- Timeless functioning and adaptable performance: E-bike module performance should match the current and future fleet-owners' requirements (Arnheiter & Harren, 2006). The E-bike should, therefore, be upgradeable, or even downgrade-able, a company that requires minimal performance, has no desire for expensive over-performing components. The possibility for upgrades requires space reservations for alternative performing modules within the E-bike (Juuti et al., 2019). Interfaces between modules require standardization to continuously allow the mounting of new/alternative modules to the modular system. The interchangeability of the modules allows for maximal longevity of the components implemented within the E-bike.
- Timeless aesthetics and adaptable aesthetics: the modular system must be either timeless or aesthetically adaptable to current and future aesthetical preferences of different E-bike fleet-owners. Aesthetical preferences of consumers change over time, which runs the risk of the modular product becoming 'old-fashioned.' Future desirability of the E-bike could be enabled by timeless-design, the addition of aesthetical modules, separate aesthetical customization of modules, or a combination (Arnheiter & Harren, 2006). Aesthetical customization of the E-bike enhances the personalization of the E-bike and enables long-term coherence of the E-bike aesthetics to fleet owners' preferences.

Take-away

Long-term re-usability of the E-bike depends on the future robustness of the E-bike. Both function and aesthetics are to be time-less or continuously adaptable to fit (future) fleet-owners needs. Space reservations and standardized interfaces for alternative modules are to be taken into account in the modular product design intended for circular longevity.

Repairability of the modular system

Repairability is a crucial requirement for the long-term re-usability of the E-bike and its components. It consists of two factors to be optimized in the modular design: the act of repair itself and the availability of means required to repair the E-bike. Both depend on a variety of factors taken into account during the modular design.

- The act of repair depends on the accessibility to the repaired component: accessibility enhances the ease of repair and reduces the time-consumption for repair. Accessibility to components thus on the decomposability and the process of decomposition itself needed to access the faulty module. The act of repair is enhanced by:
    - Accessibility of the module connections: For the modules to be exchangeable in the first place, the connection should be reachable (Arnheiter & Harren, 2006).
    - Minimal interdependencies between components: greater interconnectedness in the product architecture creates greater interdependence among modules. The interconnectedness between modules results in more significant difficulties in diagnosing, isolating, and repairing product failures (Om et al., 2007). A minimal number of connections between modules reduces the complexity of the product and the required decomposition performance needed to perform maintenance.
    - Easily separable interfaces between the components: Easy separable connections between- and within components that are to be taken apart enhance the ease of decomposition and enhance the accessibility of repairs (Juuti et al., 2019).
    - Standardized positions and connections: standardized positions of connections and cabling allows for the performance of intuitive and identical reparations (Juuti et al., 2019).

- The means for repair: Availability of resources required for the repair is a prerequisite for the ability to perform the repair. The needed resources for repair are:
    - Availability of spare parts: The availability of spare parts is a requirement for repairs. The usage of commodity parts throughout the design enhances the availability of spare parts (Arnheiter & Harren, 2006).
    - Availability of tools: the tools required to be able to perform the repair are to be available to perform the repair.
    - Availability of technological and human resources: someone or something must perform the repair. The modular design should allow the intended target group to be able to perform the repair. The repairs are likely to be performed by the fleet owners' workforce, characterized in Appendix 6.4, *Benchmark for ease of maintenance.*

Take-away

The ease of repair depends on accessibility of the modules and their connections and is enhanced by minimal module interdependencies, easy separable connections as well as standardized positions of modules and connections. Repairability relies on availability of spare parts, tools and someone or something to perform the repair.

Recyclability of the modular system

Although the envisioned circular model aims to delay complete loss of functional and material value optimally, all E-bike components inevitably reach the point of wear or breakdown that is beyond repair, repurposing, or remanufacturing, meaning they can only be recycled. The circular modular E-bike, as envisioned in terms of repairability/re-usability, is to be optimized to be taken entirely apart, which also enhances the recycling of separated materials. Usage of similar materials throughout the product allows for better recyclability: the product does not need to be taken apart to be able to recycle the separated materials fully but can be fully recycled at once or in sub-assemblies or 'similar materialized chunks.' The (permanently) linked components should be composed of the same materials while minimizing material usage among components minimizes the loss of resources when recycling. Avoidance of coatings/paint, enhance recyclability of materials, however, should only be avoided when unnecessary for the material longevity.

Take-away

Separability of components enhances recyclability whilst minimization of materials minimizes material loss resulting from recycling. Recyclability could be further enhanced by redundancy of the separation of components which is allowed by interlinking components composed of the same materials.

Modular product architecture

The product architecture, or the arrangement of modules within the modular E-bike, defines how the modules must interact to achieve targeted functionality.
A well-designed product has a well-structured product architecture of which every component has a detailed function and does not contain needless components. Maximizing the number of functionalities per component and therewith reducing the number of components in the product leads to an overall integral product in which the components are interlinked based on their variety of individual functionalities. On the contrary, a truly modular system has many components that have their specific function within the final product, which significantly reduces the number of connections between components (Celona et al., 2007).

The categories of modular systems are bus-modular and modular systems. We visualized the structures in figure 7. The modules in a modular system are interconnected, whereas needed. In contrast, the modular bus system consists of is a base unit to which all the varying modules are attached primarily and not to other module variants (Juuti et al., 2019). A bus-modular product structure has the least amount of interdependencies between modules and thus allows for independent interchanging of modules. (Thomas Celona, 2007). Minimal interdependency between the modules reduces the complexity of the E-bike, enhancing its repairability.

We identify the bus-modular structure as a feasible architecture in terms of minimizing the number of module connections. The resulting low complexity of the bus-modular structure enhances the repairability of the E-bike.
Standardized, separable interfaces between the modules and the bus-module combined with reserved module space throughout the bus-module enable (future) re-usability by different E-bike fleet-owners by its allowance of integration of alternative modules. The low complexity, resulting in easy exchangeability of modules, from the bus-modular architecture, is a desirable characteristic in realizing the company envisioned circular E-bike product-service system.

Take-away

A bus modular product architecture minimizes the number of interdependencies between modules and therewith minimizes the product complexity. A bus modular product architecture is desired for optimal accessibility and exchangeability to the incorporated modules within the E-bike.

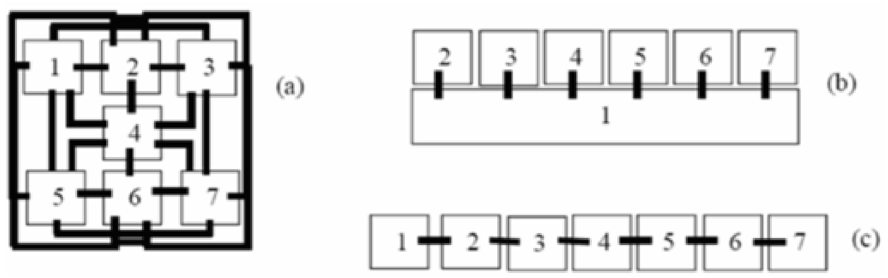

Figure 6: Product structures of a fully integral (a), bus-modular (b), and modular system (c).

2.2.3 Acquired insights from the modularity analysis

A modular design has great potential to enable a future robust E-bike that enables low-cost E-bike repairs and has a circular end-of-life purpose.
In addition to that, modular E-bike design can reduce the typical total cost of E-bike ownership, sustainability problems for fleet-owners and can even enable competitive advantages. A well-designed bus-modular system enhances the E-bikes' repairability due to its optimal accessibility to faulty modules. With the durability of the components of the modular system taken into account, it also allows for the long-term re-usability of the E-bike through the allowance to replace and upgrade the implemented functional and aesthetical modules to suit different (future) fleet E-bike owner's needs.

2.3 Conclusion on the project brief

This section compares the conclusions from both analyses with the design brief of the company.

Different modular solutions

The initial project brief ''*Design of modular E-bike solution(s) to realize the envisioned circular E-bike of the company.''* revolves around modular solutions to make the E-bike platform as the company envisions a reality.

The project brief, however, does not distinguish modular solutions aimed to specifically solve fleet-owner problems and modular solutions that allow functional differentiation of the platform, or more specifically, alteration of the E-bike into, e.g., the city-bike or the cargo-bike. The project brief does not separate the essential solutions and the solutions that are not explicitly needed by the fleet-owner to run the combination of low-cost and sustainable business operations.

The E-bike concept has solved the critical problems that result in the high total cost of ownership of their E-bike fleet and tackles the fleet owner's inabilities to run sustainable business operations economically. The described problem-solving ability is critical for the potential value of the concept to the fleet owner and the final success of the circular E-bike concept. We integrate modularity in the final E-bike design for the well-substantiated purpose of solving the fleet owners' problems. A modular E-bike design specifically focussed on durability and end-of-life purpose is aimed for throughout the design process.

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In this chapter, we elaborate on the distilled concept vision from the analysis and the initial companies' concept, the requirements for the intended durable and circular E-bike design, and the solution space for the final design. The combination of conclusions we distilled from the analyses is the fundament of the chosen design direction and their translation into the final E-bike concept.

3.1 Concept vision

We envisioned a more focused based on the insights resulted from the analysis phase in combination with the described company E-bike concept. This concept vision forms the basis of the performed search for design solutions throughout this project.

Modular drivetrain solutions as the E-bikes' design fundament

We envision a durable modular E-bike solution that reduces the total cost of E-bike ownership and enables optimal circular end-of-life purpose as the most interesting aspect of the circular E-bike for fleet-owners. The drivetrain allows for minimal, low-cost maintenance and is future-robust through accessible exchange-and interchangeability of modules. The modular solution is long-term reusable through its timeless, practical function combined with customizable performance as well as aesthetics, and comfortable E-bike usage. The vision is depicted in figure 8.

We translate the identified fleet-owners desires into a specific focus on modular drivetrain design. The modular drivetrain forms the fundament of the E-bike platform to which the rest of the future E-bike (platform) design revolves. We envision a basic E-bike design revolved around the modular drivetrain to be re-useable in a circular system by re-applying the aesthetical modules.

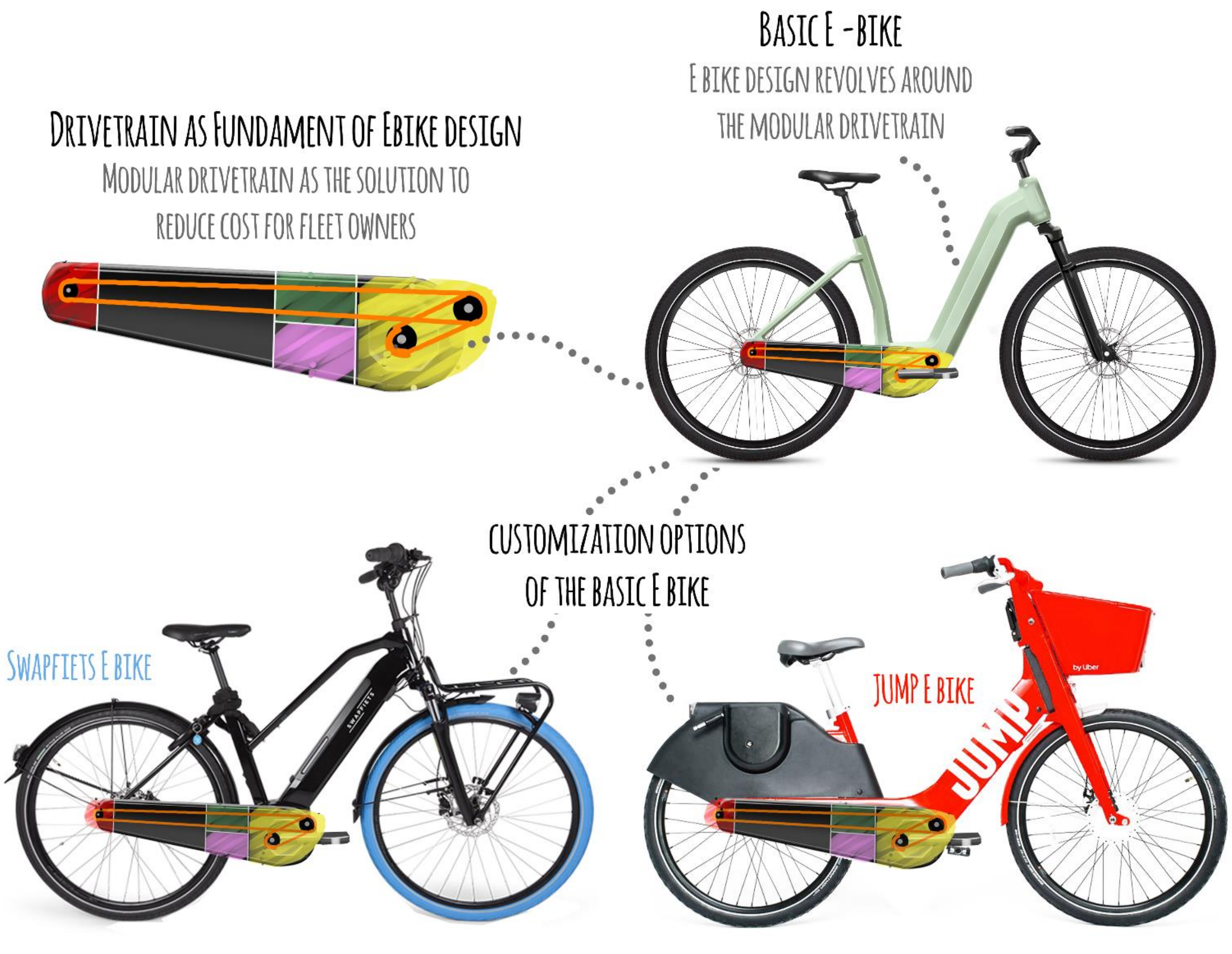

Figure 7: vision of the modular drivetrain as the fundament of the final E-bike design.

3.2 The specified design brief

Based on the analyses, we defined a more specified design brief. The conclusions of the performed analyses emphasize the significant fleet-owners' need for their profitability and sustainability problems to be solved. We translated this need into a concept vision able to tackle the identified problems of the fleet-owner as its key selling point. As stated in the conclusion section 2.3, *Conclusion on the project brief*, the companies design brief does not distinguish problem-solving and modularity to achieve the E-bike platform. We defined a better fitting design brief to realize the concept we envision in which we focus on the fleet owner's problem-solving ability of the circular E-bike.

> Design brief
> 'Design a durable modular drivetrain system for the circular E-bike focussed on the associated product architecture and module interfacing to achieve total cost of ownership reduction and circular end-of-life purpose for fleet owners' E-bikes.

Best case, the company can directly fit their modules in the system or adapt their final module design to fit the to be designed architecture and interfaces with minimal effort and without compromising the modules functioning.

3.2.1 Specified scope

As described in 1.3.1, *the circular E-bike as a platform*, the drivetrain system is composed of the motor module, the motor controller module, the display module, the belt, the battery, and the required wiring to interconnect the modules. We define the objectives as the design of feasible modular drivetrain system architecture and the design of fitting modular interfaces to (inter)connect the modules within the drivetrain system. We visualized the objectives in figure 9. Note: none of the modules are defined explicitly by the company, module visualizations are either existing or self-made based on some known details provided by the company.

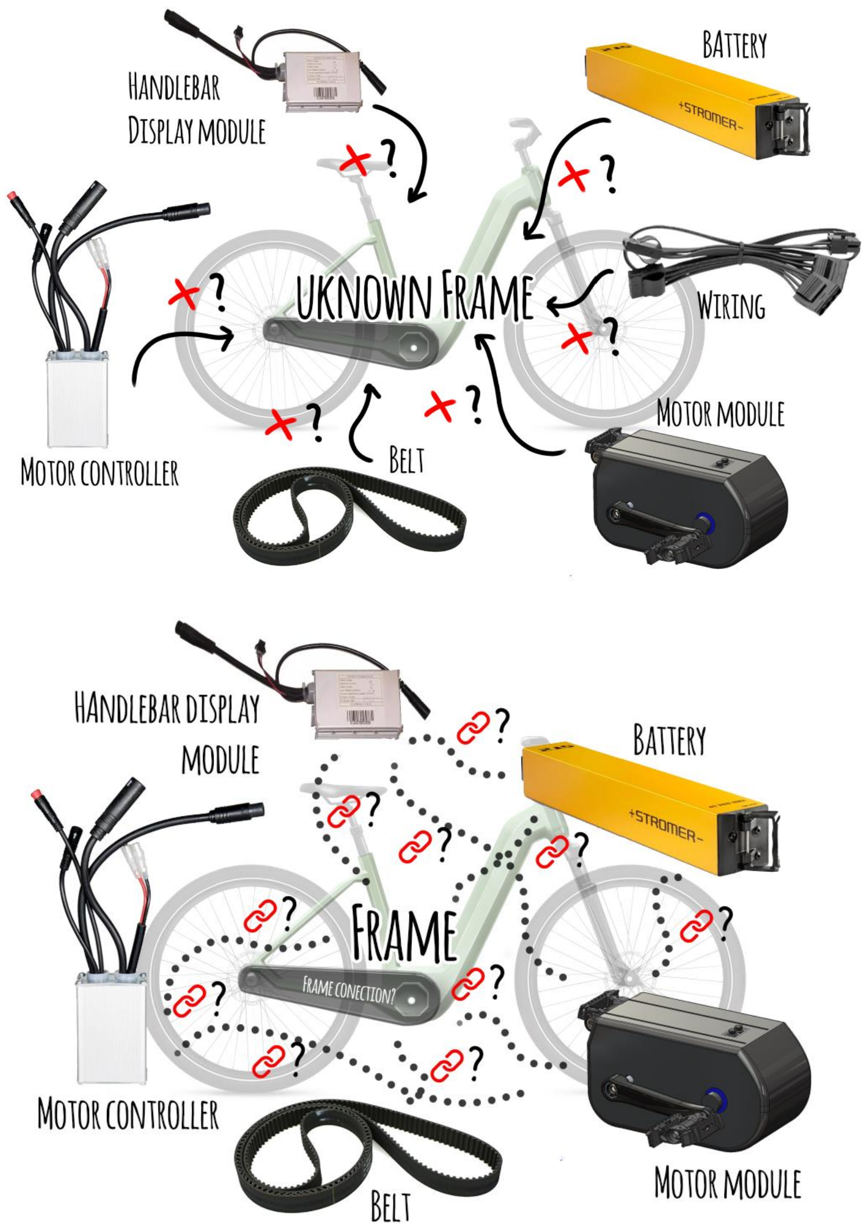

Figure 8: Component locations and component connections are to be defined.

3.3 Design requirements of the modular E-bike system

The circular E-bike concept, and thus the modular drivetrain system, need to meet a set of design requirements to fulfil the desired problem-solving capabilities for fleet-owners. The overarching requirements for the modular design solutions are durability, circular end-of-life, and the final fit of the design within the product-service system as envisioned by the company. We define and specify the three overarching principles in this section.

3.3.1 Durability

Design for durability lays the focus on the longevity of the E-bike and its components by design for E-bike endurance against intended and un-intended usage and the external environment. Durable design reduces the total cost of E-bike ownership. It enhances sustainable business practice by sustaining the component condition and minimizes the maintenance frequency. Design requirements for durability are:

- The Integration of quality components and connections. *Bounded by the total allowable cost of (quality) components.*
- The Integration of robust components and robust connections.
- Endurance against the usage environment: the E-bike is weather-proof, and critical components are safe from debris.
- Minimization of features and components.
- Locked or hidden E-bike components and connections against vandalism and theft.

3.3.2 Circular end-of-life

Design for circular end-of-life lays the focus on sustaining E-bike and component value and the minimization of waste during- and at the end of the lifecycle. Design for end-of-life reduces the total cost of E-bike ownership. It enables sustainable business practice by reuse, repair, and recycling of the components. We separately describe the requirements for each of the three end-of-life practices.

Reusability

Design for re-usability lays the focus on future-proof-ness of the E-bike. The E-bike should sustain its desirability in the long-term. Requirements for re-usability of the E-bike are:

- A practical, timeless function of the E-bike and its incorporated features.
- The effortless re-usability of the E-bike and the modules.
- Performance alteration possibilities of the E-bike by repeatable interchangeability of its functional modules. Interface standardization and space reservations for future modules within the modular system to enable upgradeability and backward compatibility
- Meets standardized bike geometry and has adaptable geometry required for time-less E-bike comfort adjustable to users in different usage regions.
- Time-less E-bike architecture design: E-bike aesthetics comparable to traditional bike design.
- Aesthetical alteration possibilities of the E-bike by repeatable alteration of aesthetical modules.
- The constant availability of spare modules.

Repair

Design for repair lays the focus on cost-efficient E-bike upkeep to minimize maintenance costs. Relies on the easy maintenance and repairs through the accessible exchangeability of modules from the E-bike when needed. Requirements for the repair of the E-bike are:

- Decomposability of the E-bike: Minimal interdependencies among removable modules, accessibility of module connections combined with easy separable, possibly tool-less, interfaces.
- Exchangeability of modules: accessible removal and re-mounting of modules to or within the modular system in a safe manner for both the person performing the repair and the module itself.
- Standardized component positions and connections for intuitive maintenance.
- Wide-scale availability of means for repairs: spare-parts, tools, someone/something to perform the repair.

Recycling

Design for recycling lays the focus on low cost reclaiming of materials as a last resort for faulty or worn components. Requirements for optimal recycling are:

- Easy separation of components or usage of the same materials among interlinked components to make separation redundant.
- Avoidance of material coatings and paint that do not enhance material longevity.

3.3.3 Fit with the product-service system of the company

Design for fit within the product-service system lays the focus on fleet-owners optimally profiting from the potential maintenance cost and waste reduction through the usage of the service system in combination with the E-bike concept. Easy module exchange, repair, and transport allow for cost-efficient operations and influence the modular interface design. Modular requirements for a proper fit to the product-service system are:

Ease of module exchange, repair, and transport

- Modules are quick and safely exchangeable and are well protected against weather and debris during transport and the exchange.
- Module interfaces enable efficient and damage-free transport and should enable cost-efficient module repair.

3.4 Solution space

We define the solution space of the design of the modular E-bike system by the constraints of the implemented modules in the modular system, the desired E-bike aesthetics, and the required E-bike comfort. We elaborate on these conditions in separate sections in this chapter.

3.4.1 Design constraints by the modules

The product architecture- and interface solution space revolves around the modules and their functioning within the E-bike. All modules are to need a firm fixation within the modular system that enables them to be repeatably and efficiently exchangeable and interchangeable within the modular system.

We design the product architecture based around the module location constraints, module accessibility, and the resulting aesthetics of the final module location. We limit the solution space of the interfaces by the locking ability, separability, and durability of interfaces related to the modules and their positioning within the modular system.

We visualized the modules that we implement within the design of the modular drivetrain in figure 10. We refer to the appendix 6.3, *the modules* for an additional overview and information on the modules.

MOTOR MODULE

Dimensions (LxWxH): 320x170x175mm
Location constraints within E-bike:
Bottom bracket in line with standardized E-bike geometry for comfort
Elektrical connections:
2 Ingoing connections from the motor controller.
Mechanical connections:
Connected to the frame with a no-play allowance. Fully defined in all degrees of freedom in a high force enduring manner.

MOTOR CONTROLLER

Dimensions: 52x82x28mm
Location constraints within E-bike:
None specific.
Elektrical connections:
1 Ingoing connection from the battery.
2 Outgoing connections to the motor module
1 Outgoing connection to the SMART module
Mechanical connections:
No-play connected witin its desired position.

BATTERY

Dimensions: 486x73x71 mm
Location constraints within E-bike:
In the downtube in terms of E-bike aesthetics and E-bike handling. No fixed constraint. Optimal postion for ease of removal in a weatherproof and theft proof manner.
Elektrical connections:
1 Outgoing connection to the motor controler
Mechanical connections:
No-play connected witin its desired position.

DISPLAY MODULE

Dimensions: 60x80x30mm
Location constraints within E-bike:
None specific.
Elektrical connections:
1 Ingoing conection from the motor controller
2 Outgoing conections to the front and the back of the frame.
Mechanical connections:
No-play connected witin its desired position.

BELT

Dimensions: Length as needed.
Location constraints within E-bike:
Connected to the motor module gear hub axle and the rear axle of the E-bike.
Elektrical connections:
None.
Mechanical connections:
No slipping off and tensioned for optimal efficiency of translating the outgoing force to the rear axle.

WIRING

Dimensions: Lengths as needed.
Location constraints within E-bike:
None specific.
Elektrical connections:
Interconnects the modules where needed.
Mechanical connections:
Fixed in a non-hindering position for module accessibillity.

note: the elektrical connections and module dimensions have been specified, the dimensions of the modules are educated assumptions which has to be taken into account in terms of design solutions.

Figure 9: module specifications based on existing E-bike components and an enlarged E-bike motor.

3.4.2 E-bike Aesthetics

Long term desirability is required for the E-bike to last within the intended circular system. The E-bike must be long-term coherent with the E-bike fleet-owners' aesthetical preferences through either timeless or adaptable aesthetics. As stated in section 2.1.1, the *profitability of the E-bike fleet* E-bike depreciation of advanced E-bike parts through technological progress, future E-bike aesthetics will be indistinguishable from regular bicycles.

The location of the battery has a significant impact on the final E-bike aesthetics, as could be seen in figure 11. An E-bike design trend is integrating the battery in the frame (*De E-Bike Met Accu in Frame | Elektrischefietsen.Com*, *2019*). Integrating the battery allows for a sleeker-looking frame that comes as close to the traditional bicycle frame as possible. Therefore it seems the most natural to locate the battery in the downtube. The downtube is relatively thick in traditional bicycles; thus, locating the voluminous battery within the downtube enables a balanced recognizable, traditional, or even nostalgic E-bike look. At the same time, the invisibility of the battery within the downtube conceals inevitably outdated battery technology and enhances the simplistic character of the E-bike design.
The E-bike aesthetics resulting from downtube battery integration are desirable in terms of creating a timeless E-bike design. The openness of the drivetrain further enhances the simplistic character of the E-bike, elaborated in Appendix 6.5, *E-bike aesthetics, and structure*. A timeless minimalist E-bike is further customizable via, e.g., aesthetical modules or wrapping to suit the differentiation preferences of the fleet-owner.

Redundancy of the split frame through the downtube battery

When we locate the battery in the front of the E-bike, a frame split becomes redundant: Customizability of the rear frame an unnecessary feature due to the similarities in rear frames among existing E-bikes. The front frame could be joined directly to the rear frame, which results in a single frame architecture. Removal of the frame split allows for reduced electrical and mechanical complexity of the final E-bike design is further elaborated in Appendix 6.6, *Product architecture design*.

Figure 10: E-bike aesthetics based on battery position and an openness of the belt without a chainguard.

3.4.3 E-bike comfort

Impact of battery location of E-bike handling

In addition to the E-bike aesthetics, the location of the battery impacts the handling of the E-bike. Locating the battery higher in the E-bike shifts the center of gravity of the E-bike up, which reduces stability during usage. Locating the battery behind the seat tube results in a longer wheelbase. A longer wheelbase reduces the handling comfort and agility of the E-bike but enables better stability at higher speeds. Locating the battery in the downtube keeps the center of gravity of the E-bike low. It distributes the weight most even over the E-bike, which allows for optimal E-bike handling.

E-bike Geometry

Naturally, the E-bike must meet the E-bike comfort standards of the various user groups. The modular solutions should fit within the bike geometry standards required for user comfort. The company provided a general E-bike geometry shown in figure 12. The geometry bounds the solution space. The relative position between the saddle, handlebar, and bottom bracket decides the riders' positioning on the E-bike and constrains the design of the frame. The adjustability of the handlebar and the saddle position in the final design enables comfortable E-bike usage by user groups across different regions.

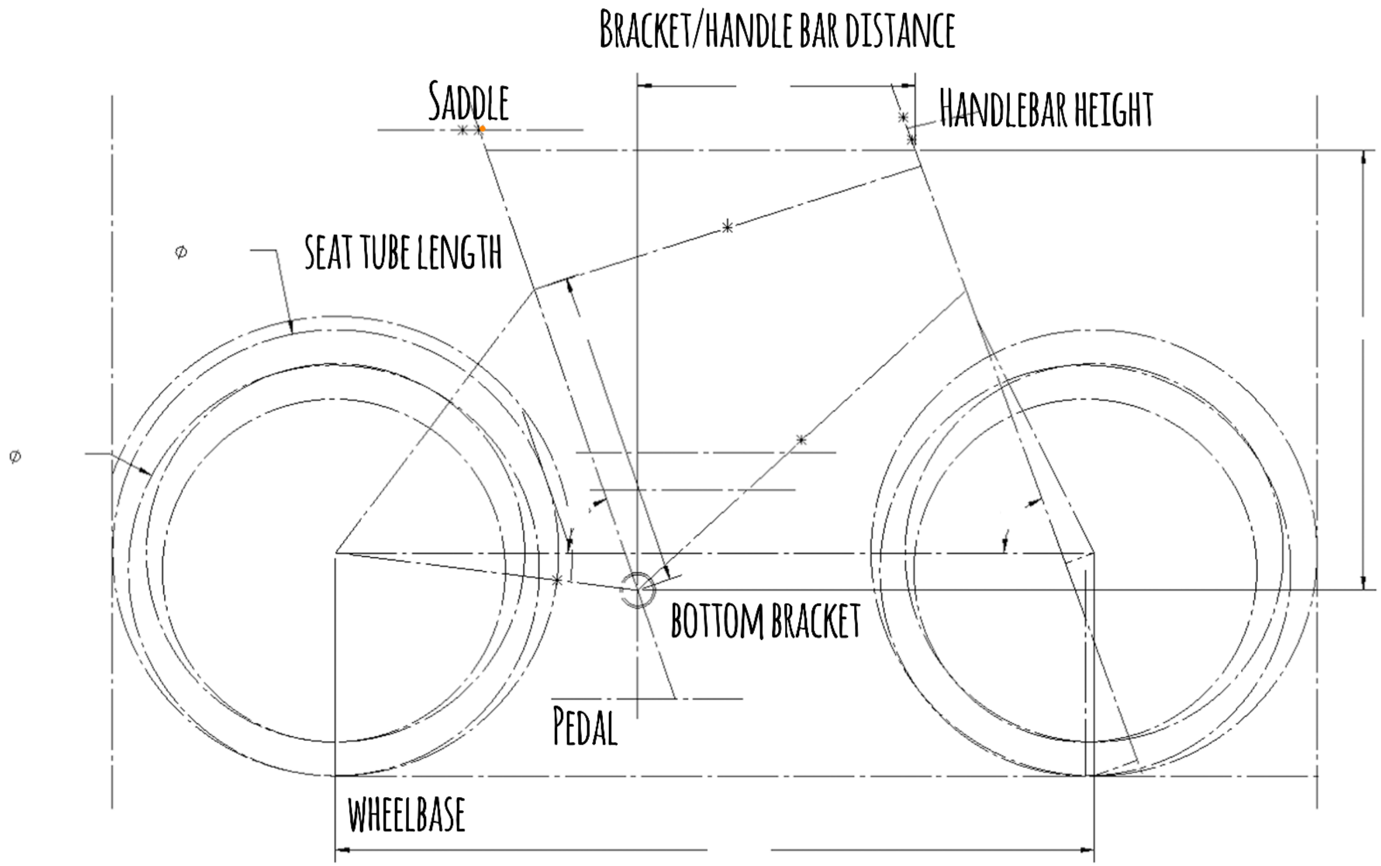

Figure 11 geometry for comfortable E-bike usage.

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In this chapter, we elaborate, visualize and discuss the design of the modular drivetrain system and the vast number of design decisions made throughout this project. We have chosen to specifically elaborate on the different concepts, the details, and the decisions to help the company in the further development of their concept.

4.1 The structure of the design chapter

The chapter is comprehensive. Therefore, we shortly describe the structure of the chapter. We briefly introduce every section in this chapter further on for quick rehearsals.

4.2: Design approach: We start the design chapter with a short elaboration of the design approach in the first section. The design approach explains the specific design sequence of the product architecture design followed by the interface design that leads to the desired concept principles and the final concept design.

4.3: Product architecture design: In this section, we elaborate on the product architecture design based on the modules that we implement in the modular system. The architecture design started from scratch. We have made many choices on the module positions to get to a feasible E-bike architecture in terms of module accessibility combined with the robustness and feasible aesthetics of the final E-bike design. We visualize the possibilities and shortly elaborate on the design decisions. The section concludes with a product architecture working principle.

4.4: Interface design: In this section, we elaborate on the interface design to achieve the product architecture working principle. We focus on the motor module and the display and Controller module interfaces.

4.5: Concept embodiment and iterations: In the concept embodiment we visualize and elaborate on the 2D and 3D embodiments of three different concepts that mostly rely on similar working principles, as decided in 4.2 and 4.3, but slightly but significantly differ in the manner in which modules are located within the system and removed from the system. We elaborate on all concepts since they all integrate working principles that we ultimately translated into the final design proposal. We elaborate on, and discuss, the first concept most comprehensive since it revolves around the main ideas that have to lead to the final design. Subsequently, we present the second iterated concept and discussion. After that, we present a final iterated concept and discussion. In the last section, we present the concept choice based on the durability and circular end-of-life requirements.

4.6: Final design: We have embodied the essential details on which the final concept choice revolves and present a final design. We walk through the most critical design features for durability and circular end-of-life and visualize their working principles.

4.7: Evaluation of the final design: In this final section of the design chapter, we evaluate the concept based on the full list of requirements revolving around durability and circular end-of-life of the final design. In the subsequent section, we elaborate on the missing design features in the final concept that are essential for the realization of the final concept into a viable E-bike solution.

4.2 The design approach

In this section, we explain the design approach we followed to achieve the final concept design.

In the design process, the company is responsible for the module design.
With the modules specified by the company, the design of the modular drivetrain system revolves around the product architecture and the modules. We visualized the design problem as a 3-variable equation in figure 13. Module design, product architecture design, and interface design are the variables that limit the solution options for the other variables. By defining them, we can realize a final product design. General module functions and forms are generally defined and allow for direct implementation in the process. We consider the modules to be a fixed variable. The product architecture and interface design limit each other in terms of possible design solutions.

A particular product architecture only allows for specific interface solutions that fit within the architecture. Vice versa, interface design requires a particular product architecture that enables the intended functionality.
The product architecture significantly decides on the performance and aesthetics of the final modular design. The individual characters of the modules restrict the freedom of positioning within the E-bike due to their functioning, e.g., we must locate the rear-brake near the rear-wheel. The limited possibilities of the module locations limit the number of different feasible product architectures.

We assume the interface possibilities to be much broader than the product architecture possibilities: the amount of different (separable) fastening methods is enormous, and any fastening method could potentially serve a function within the final modular E-bike design. We limit the interface possibilities by first deciding on a feasible product architecture based on the defined modules by the company in combination with the method of replacing them.

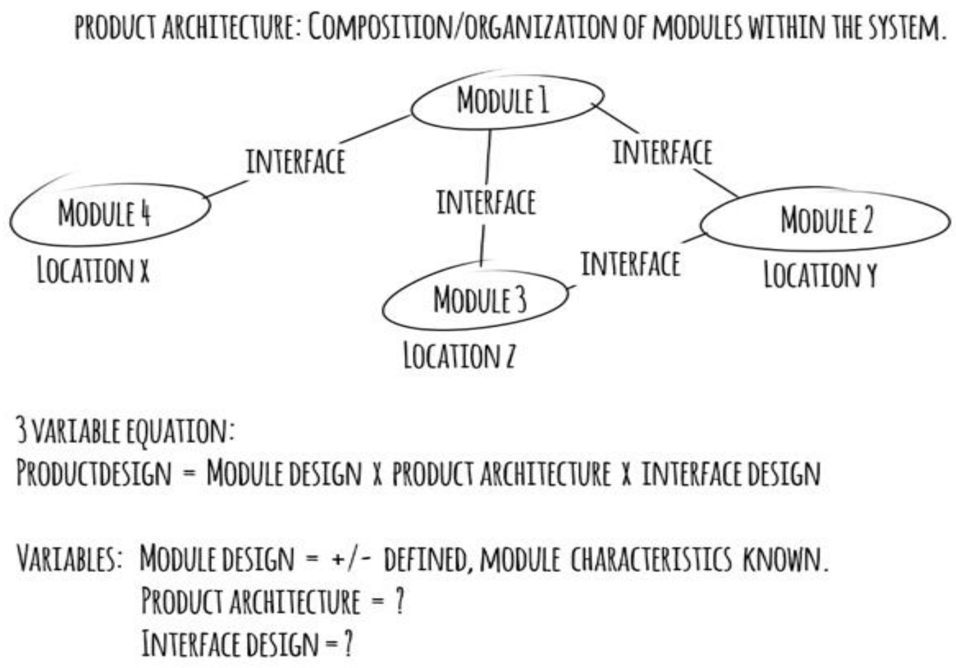


Figure 12: The 3 variable equation of the product architecture, the modules and the interfaces.

4.3 Product architecture design

In this section, we first elaborate on the product architecture design based on the modules that we integrate into the modular system and visualize the working principle of the product architecture in the second section.

4.3.1 Product architecture decisions

The E-bike platform, with its separate modular drivetrain, forms the starting point of the product architecture design. We envisioned the platform, consisting of the front frame, the rear frame, and the envisioned modular drivetrain, in a simplified manner in figure 14.

We made many concept choices throughout the design process of the modular system. If applicable to the design decision, we use durability and circular end-of-life as the main criteria for decision making. We created two morphological charts that show a variety of important design choices required for the final product architecture design. Subsequently, to each morphological chart, we shortly elaborate on the choices that we implement in the final concept design.

The first chart: major product architecture decisions

The first morphological chart shows the possibilities that we identify for battery position/removal, frame architecture, and display- and controller module positions/removal. The module position and manner of removal decide on how we have to locate the modules throughout the E-bike and where we need to create space for module access. The decisions have the most significant impact on the final E-bike design. The choices impact E-bike aesthetics (module volumes, frame cut-outs, visible connections), E-bike handling, and module accessibility. The decisions we make are mostly interdependent on earlier or other decisions. *We marked the design decisions with a blue X in the morphological chart, figure 15.*

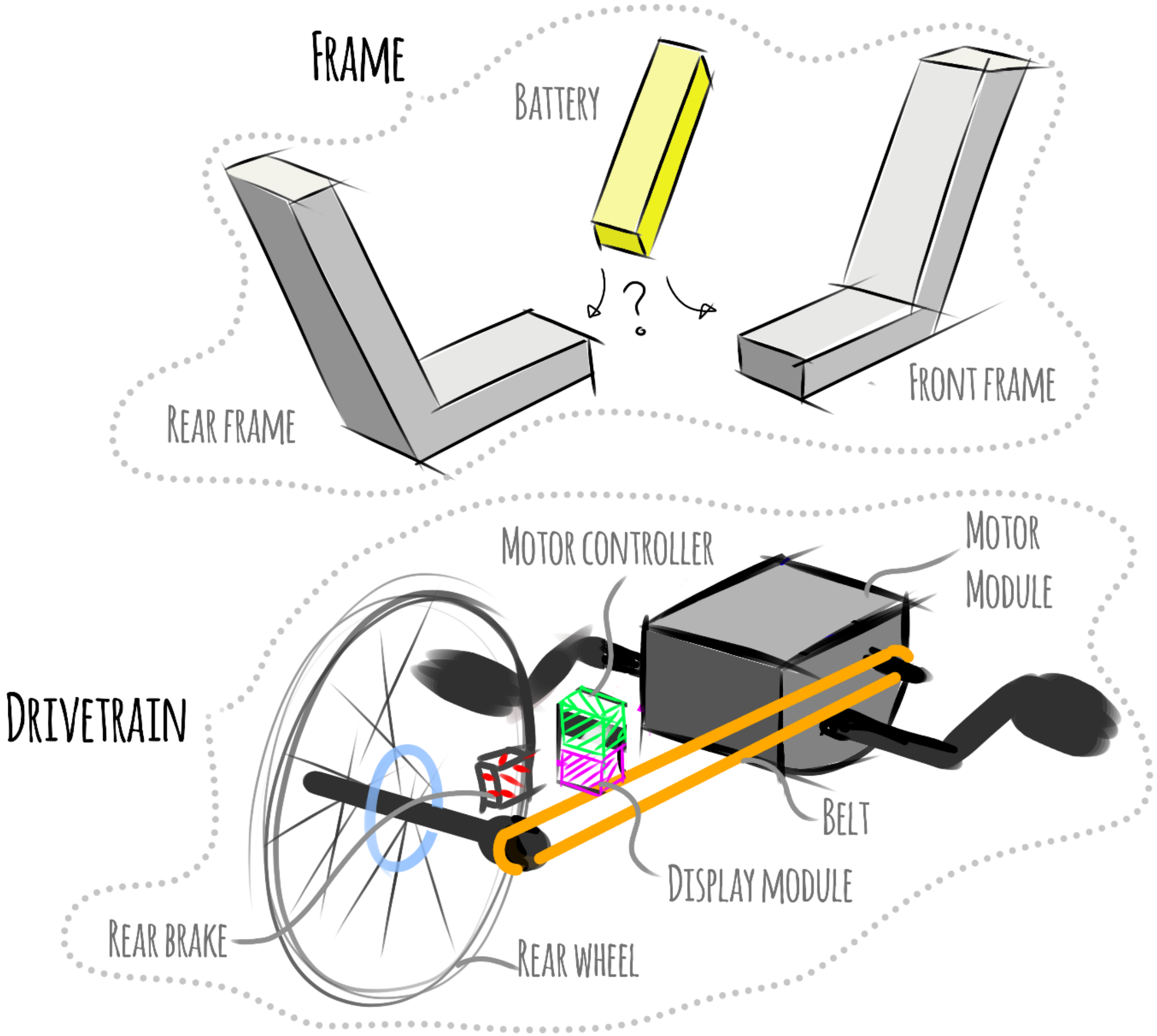
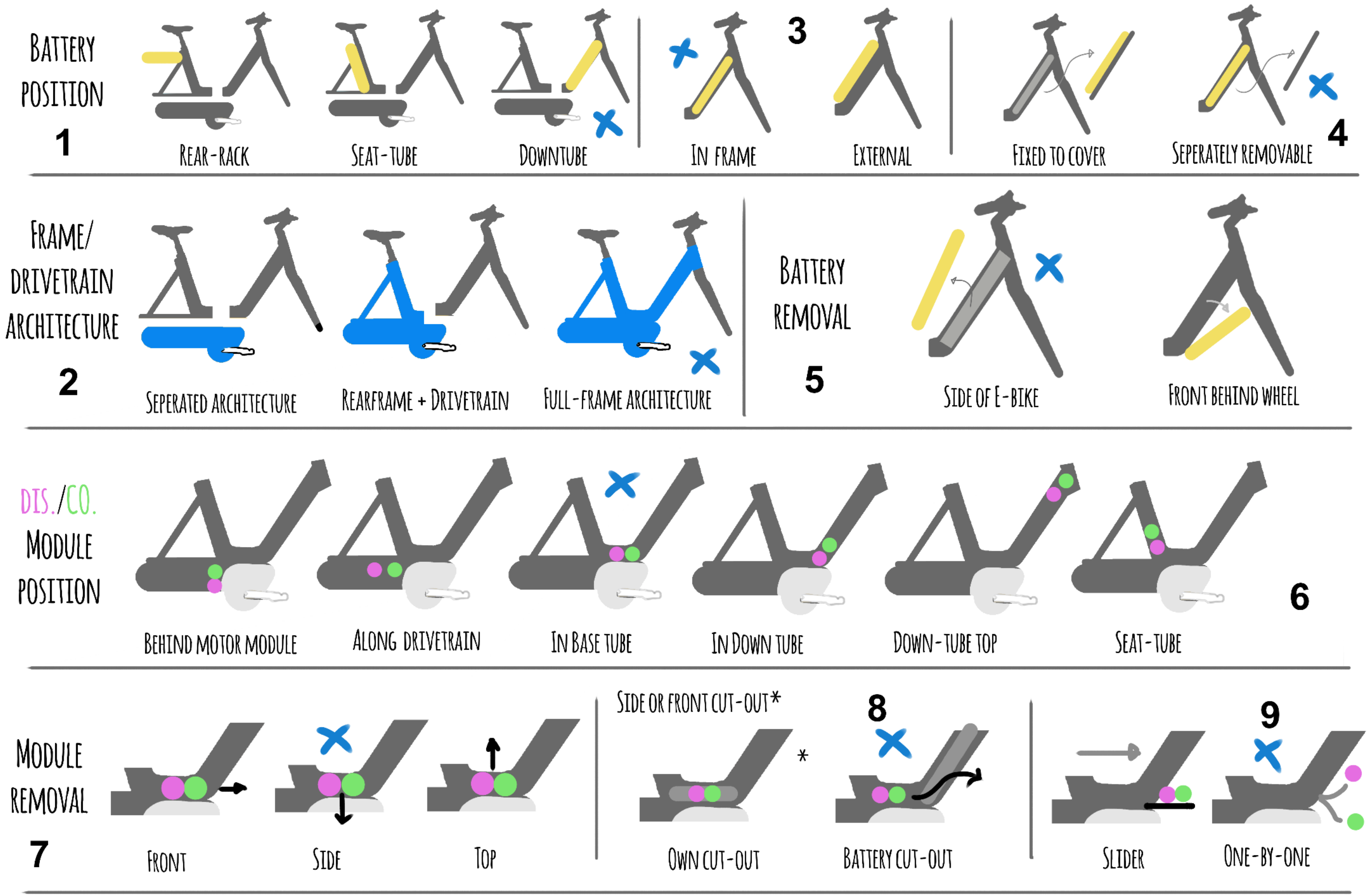


Figure 13: The modules that we implement in the product architecture, excl. the brake.

Figure 14: Morphological chart 1: the major product architecture decisions.



Elaboration of the choices within chart 1

We elaborate on the design decisions made in chart 1 in this sub-section.

1: Battery position

We locate the battery within the downtube. The design trend of integrating the battery in the downtube allows for the most natural and timeless E-bike look and feel. The timeless look results from its recognizable aesthetics to the traditional bicycle and the optimal weight distribution of components throughout the E-bike adds to a similar feel. We elaborated this in section 3.4.2, *E-bike aesthetics*.

2: Frame/drivetrain architecture

We choose for a full-frame architecture by considering the robustness, accessibility of frame re-use, and the need for minimal product complexity. Locating the battery in the downtube makes the frame split redundant due to similar rear frame structures of existing E-bikes, which translates the frame to a full-frame architecture. We refer to appendix 6.5, *E-bike aesthetics and structure,* and Appendix 6.6 *Product architecture design* for a more comprehensive elaboration.

3: Internal/external battery

We position the battery within the frame. The internal location of the battery allows for a sleek E-bike character as well as optimal battery protection. As seen in section 3.4.2, *E-bike aesthetics*.

4: Battery/cover integration

We can remove the battery from within the frame, including its cover, or removal of the separate cover. We choose to separate the battery from the cover.
The battery has to be separated from the cover to minimize the risk of an exposed system when a replacement-battery is unavailable. Also, the separated cover is the most optimal solution for aesthetical differentiation of E-bikes. A separated cover enables the usability of the same batteries by various aesthetically-differentiated E-bikes.

5: Battery removal

We choose to remove the battery from the side of the E-bike. The side-removal allows the most optimal combination of comfortable battery accessibility and protection from the weather: rain coming from above, dirt coming from the front wheel below. We further elaborate on this in Appendix 6.7, *Battery, and module removal.*

6: Display/Motor controller positioning

We locate the display- and the motor controller module within the base-tube. We define the base-tube as the horizontal frame component in the middle of the fame just above the bottom bracket. This module location allows for optimal usage of existing frame volume, optimal protection through frame integration, the concentration of electrical components and connectors as well as an open drivetrain character. We also elaborate on this in Appendix 6.7, *Battery, and module removal.*

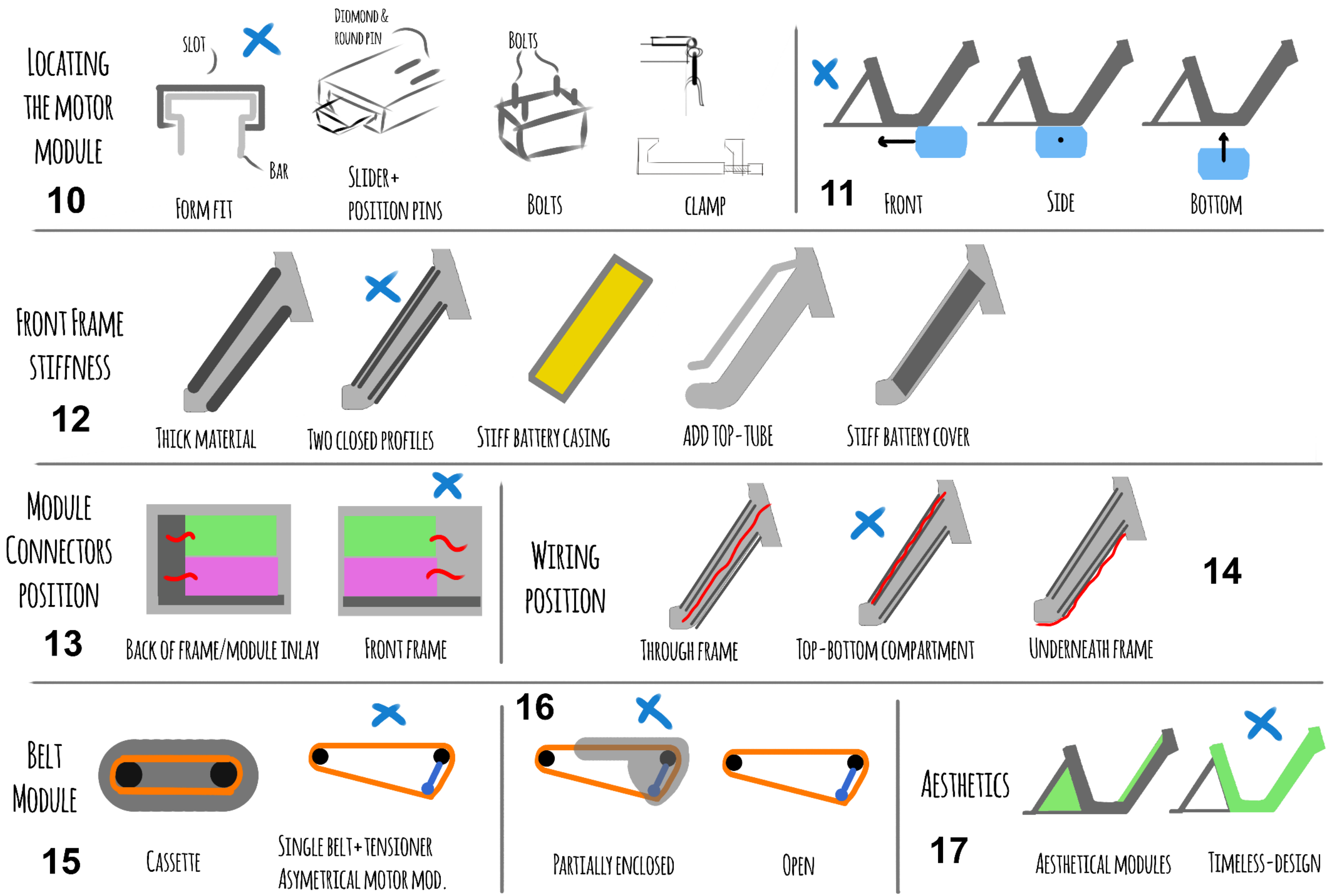
7/8/9: Display/Motor controller removal, frame cut-out, and removal method

We choose for module removal through the battery slot. Battery slot removal allows for a single cut-out in the frame, which helps in sustaining the frame integrity. Besides, the modules are protected by the battery cover that already has to be well sealed and well-locked in the future system. The large cut-out for the battery allows for plenty of space to remove the small modules and allows the modules to be internally locked. The limited free volume in the front of the frame results in a need for one-by-one module removal.

The second chart: Follow-up chart of more specific architecture decisions

The second morphological chart visualizes decisions that are constraint by the decisions made in the first chart on module positioning and resulting frame architecture. The motor module and the belt positions are fixed within the E-bike. Still, their manner of implementation within the modular E-bike system can be different. *Again, we marked the design decisions with a blue X in the morphological chart, figure 16.*

Figure 15: Chart 2: Follow-up chart of more specific architecture decisions.



Elaboration of the choices within chart 2

We elaborate on the design decisions made within chart 2 in this sub-section.

10: Motor module positioning

We choose to implement a flat form fit to locate the motor module underneath the frame. A form-fit allows the motor module to be intuitively positioned in the desired position every time it is removed and re-mounted. The form fit enables the motor to stay suspended above the ground when it is unlocked, which minimizes the risk of the motor module dropping to the ground and getting damaged during removal. The flat connection allows for repeated alteration of the motor module by either a smaller or larger module without compromising the pre-defined E-bike aesthetics. We elaborate further on the motor module connection in section 4.4.1, The motor *module interface principle.*

11: Positioning direction

We choose to slide the motor module in position from the front of the frame.
The positioning of the motor module from the front allows for frame symmetry on both frame-sides and locates the motor module connection in a non-eye catching position. Sliding the motor module in from the front of the frame distributes the force that is exerted on the motor module evenly over the surface of a form-fit that runs over the length of the bottom of the frame. Also, sliding in the motor module from the front allows the positioning of an internal lock below the battery that enables the locking and unlocking of the motor module from within the frame when the battery is removed. Sliding in the motor module from the front requires a flat motor module interface. The motor module must be electrically connected from within the E-bike after being slid into position. We also elaborated this further in section 4.4.1, The motor *module interface principle.*

12: Front frame stiffness

We integrate two closed profiles that run along the length of the downtube, both above and beneath the battery. The closed profiles compensate for the lost torsion stiffness resulting from the large cut-out in the side of the downtube. Usage of a double enclosed profile is a lightweight solution commonly used in existing E-bikes. We refer to Appendix 6.8*, frame integrity* for a short elaboration on frame stiffness.

13: Module connector positioning

We position the connectors in the front of the frame as close to the battery cut-out as possible. We concentrate the connectors in the said position to enable optimal access in case of E-bike maintenance. Positioning in the back of the E-bike is another possibility that we further elaborate in Appendix, 6.10, *influences of the original idea on the final embodied concept.*

14: Wiring and cable positioning

The brake cable and electrical wiring are to be routed through the volume of the enclosed tubes that create frame stiffness. Routing the cables through the free, un-used volume allows for maximum free volume for the battery and therewith for the largest battery capacity possible. Cables are to be easily routed from a top opening to the bottom opening and connected to the modules afterward.

15: The belt

We choose for a single clean belt solution combined with a tensioner.
The belt cassette, as envisioned by the company, is replaced by the chosen solution. We elaborate on this decision further in Appendix 6.9, *The belt.*

16: User/belt protection

We choose to fixate a small cover to either the motor module or the side of the frame that protects the belt from wear keeps the user safe. The belt needs partial enclosing by a cover to protect the E-bike user from getting stuck in the belt.
A carbon belt does not need protection against dirt or water like a traditional metal chain since this does not induce significant wear to the belt. We elaborate the belt more extensively in Appendix 6.9, *The belt.*

17: Aesthetics

We aim for a timeless base E-bike design and prefer to keep the number of aesthetical components, likely to be un-re-usable, at a minimum.
We add aesthetical modules for E-bike differentiation and is easily removable when a (different) fleet-owner requires alternative E-bike aesthetics.

The resulting concept

A concept is visualized based on the individual but interdependent design choices in the next section.

4.3.2 The working principle of the product architecture

We combined the design decisions into a 2D concept visualization of the modular system shown in figure 17. With the concept visualization, we show the working principles of a modular system that we envision implementable in a durable E-bike design with circular end-of-life purposes.

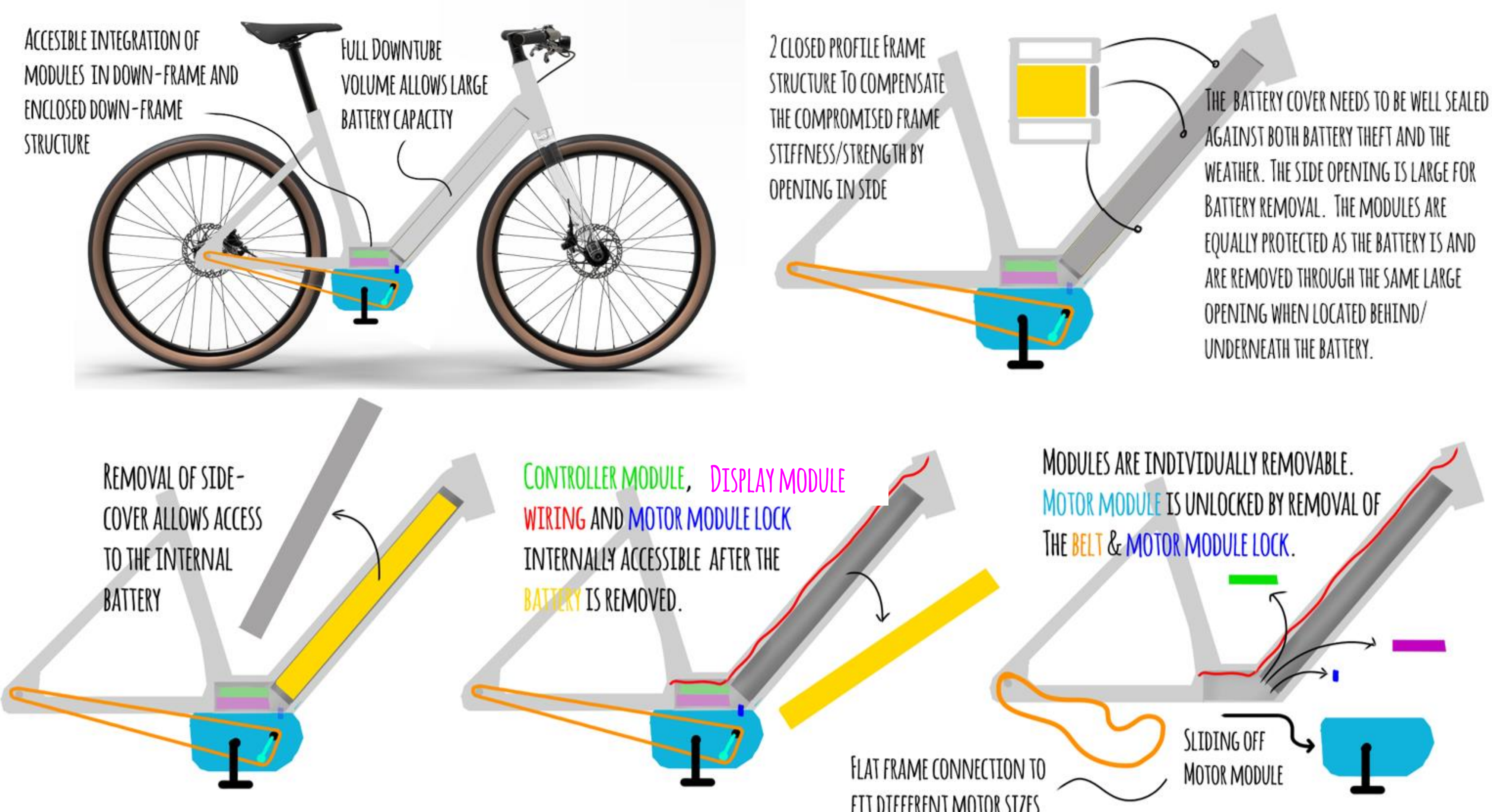


Figure 16: A combination of the design decisions translated in a working principle of module removal.

4.4 Interface design

The product architecture and its working principles require specific interface design for the concept function as intended. After the product architecture design in the previous section, we elaborate on the interface design in this section.
The illustrated concept in section 4.3 requires the design of the motor controller, display, motor module, and battery interfaces to perform as intended.
We prioritized the interface design of the motor-, display-, and controller module. Battery interfaces for removal of the battery from the side of the downtube are common. Proven battery solutions that fit the working principles can be copied from existing E-bike designs and integrated into the concept.

4.4.1 The motor module interface principle

We identified a flat, form-fitting, sliding connection between the motor module and frame that is both locked and electrically connected from the inside of the frame as feasible to connect the motor module to the frame.

The motor module is the only module that we position outside of the frame. A flat connection between the frame and the motor module is desirable for accessible and aesthetical coherent (future) motor module variation. The connection has to be able to resist the usage forces of the E-bike. It has to be located firmly underneath the frame in a way that fixates all degrees of freedom. There is a zero-play allowance of the motor module to the frame as we want to prevent undesired wear through play. The motor module is to be well secured to prevent theft; thus, we consider just the usage of external or visible connections of the motor module to the frame as undesirable. At the same time, the motor module should be removable from the frame with ease and without risk of being damaged by falling off the frame. The described set of requirements makes the motor module-frame connection the most critical connection within the system.

We designed an initial principle solution resulting from an interface exploration that meets the requirement. We visualized the principle solution in figures 18 and 19. We integrated this design solution in the first embodied concept in section 4.5.1 *module removal through the battery slot*. We further iterate upon this design solution in the iterated concepts, although the visualized principle remains mostly the same.

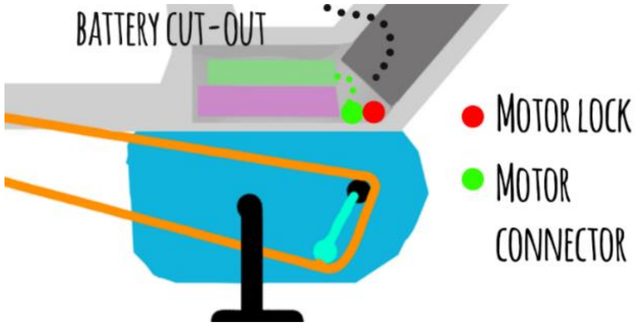


Figure 17: locking the motor module from within the frame.

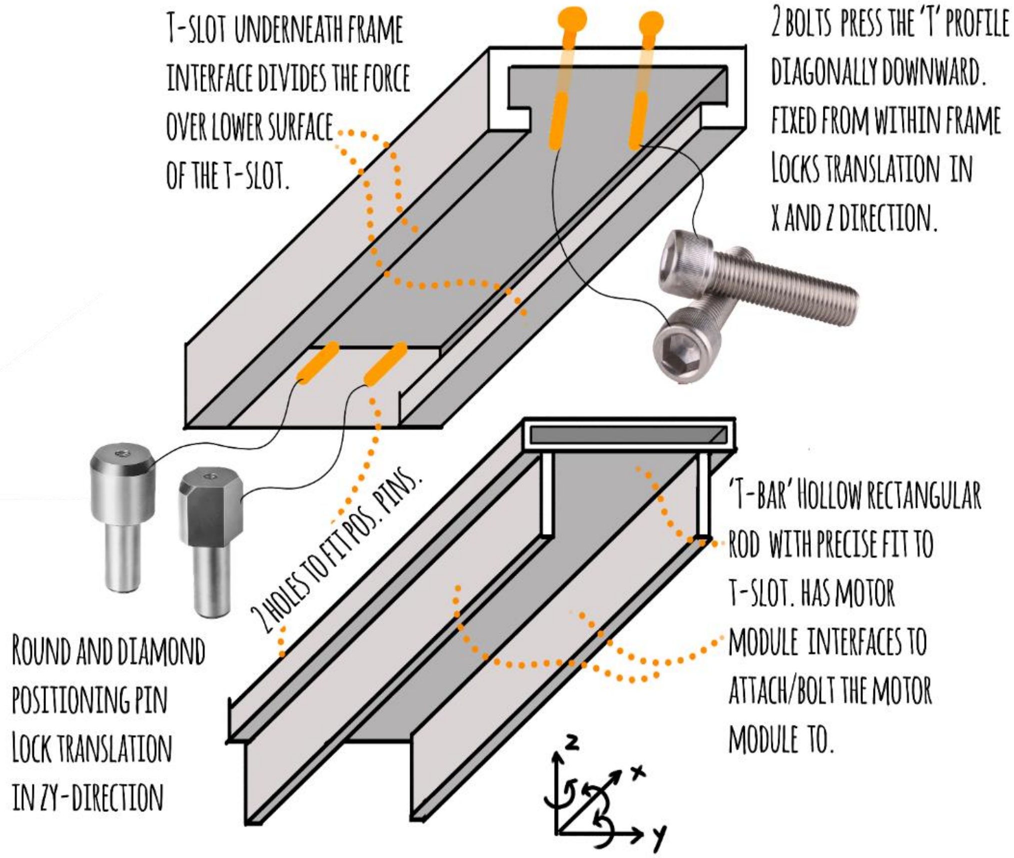


Figure 18: the motor module interface principle.

4.4.2 Display/Controller module interface principle

We fixate the display and controller module within the frame. In contrast to the motor module, there are no forces exerted onto the modules. The modules, however, do have to be fixed firmly into place to avoid damage from vibrations resulting from E-bike usage.
The fixation of the display and controller module must enable the interchangeability of the modules for alternative ones. Besides, the interface needs to allow easy removal of the modules from within the frame through the frame-cut-out.

We found an existing modular solution that can meet the stated requirements in the principle of upgrading server systems, which we visualized in figure 20. Server systems have designated slots that integrate 'trays' which in turn hold a variety of modules into place. The trays are shoved into the server system and locked via a click-lever system. The system allows for firm fixation of (electrical) modules into place and toolless removal and re-mounting of modules. The said components are commodities and can be purchased integrated into our modular system.

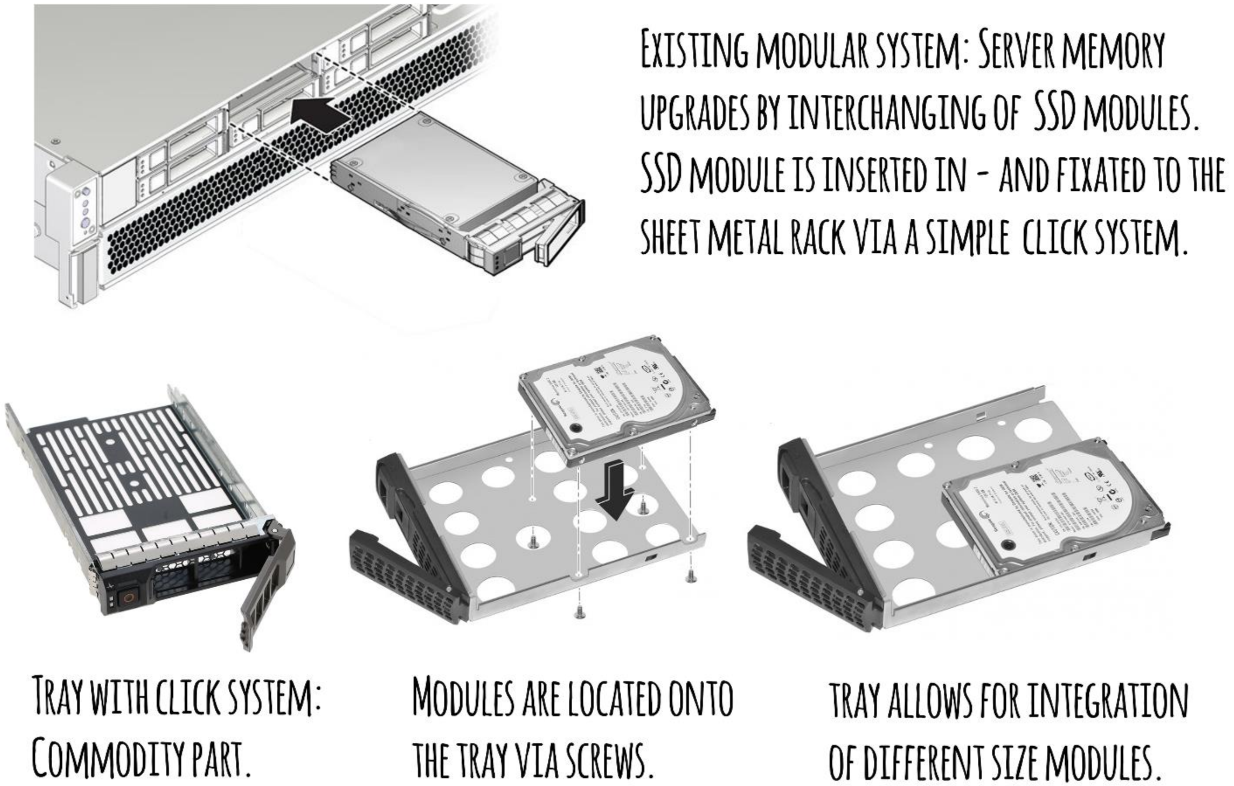


Figure 19: upgrade mechanism of servers.

4.5 Concept embodiment and iterations

In this section, we visualize and elaborate on the 2D and 3D embodiments of three different concepts. The concepts mostly rely on similar working principles. They differ slightly but significantly in the manner in which the modules are located within- and removed from the system.

We translated the conceptual architecture and the matching interface principles into a first concept which to which is iterated upon, resulting in two alternative concepts. The concepts differ in product architecture in terms of the controller and display module positioning and module removal from the frame as visualized in figure 21.

We explain, visualize, and discuss all three concepts individually in this chapter. The first concept is worked out most thoroughly and elaborated in section *4.5.1: Module removal through the battery slot.* We embodied the concept be able to grasp the solutions as well as their implications on the final E-bike aesthetics. The first concept is explained in depth to illustrate the working principles that remain mostly the same in the iterated concepts. We discuss the concept in a separate but subsequent section 4.5.2, *Discussion of concept 1.*

The following concepts are two alternative designs that incorporate slight alterations based on the discussion of the previous concept. The first iteration is is elaborated in section 4.5.3 and discussed in section 4.5.4. The second iteration is discussed in 4.5.5 and discussed in 4.5.6. We conclude the concept embodiment with a final concept evaluation and concept decision in section 4.5.7.

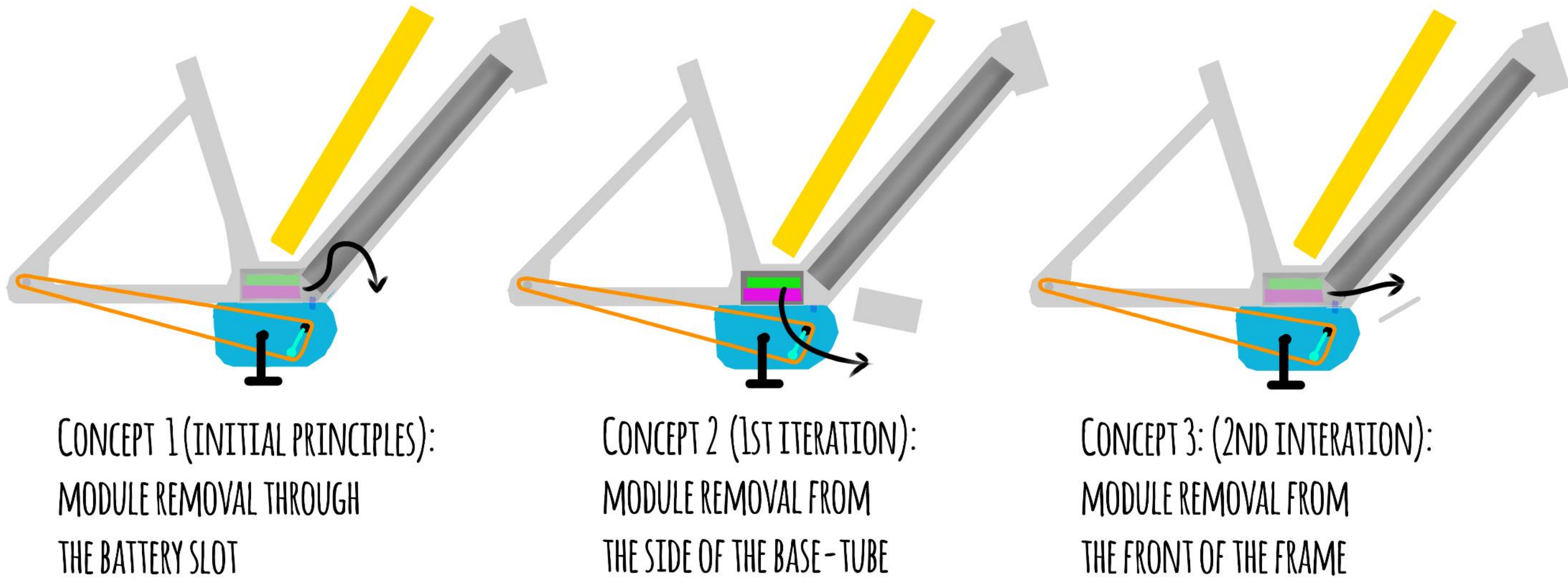


Figure 20: The three concepts that we present in this chapter.

4.5.1 Concept 1: Module removal through the battery slot

This section visualizes and describes the first modular E-bike concept distilled from the design choices in the morphological chart.

We embodied a complete E-bike to visualize the influence of the design decisions in combinations with the modules on the final E-bike aesthetics.
The embodied E-bike is shown in figure 22. It is robust and enables module exchangeability and interchangeability. We perceive the E-bikes design as simplistic, even though the large motor module integrated. The E-bike has a side cut-out in the downtube through which the battery is removable. Removing the battery allows for access to the modules that we integrated within the E-bikes' base-tube. We elaborate on the concept features and their working principles in the next sub-sections.

Figure 21: E-bike design based on the design decisions throughout the morphological charts.

Battery removal to expose the modules

Before we can access the modules in the base-tube, we have to remove the side cover and the battery. Removing the battery from the side exposes the protector. The protector is located underneath the battery and protects the internals of the E-bike against moisture and dirt. Removal of the protector grants access to the interconnected E-bike modules within the base-tube. We concentrated the connectors and wiring below the battery underneath the protector. The connectors are well visible from the outside, and the cut-out in the frame allows for sufficient space to be able to separate them by hand and then remove the modules through the cut-out. We visualized the described process in figure 23.

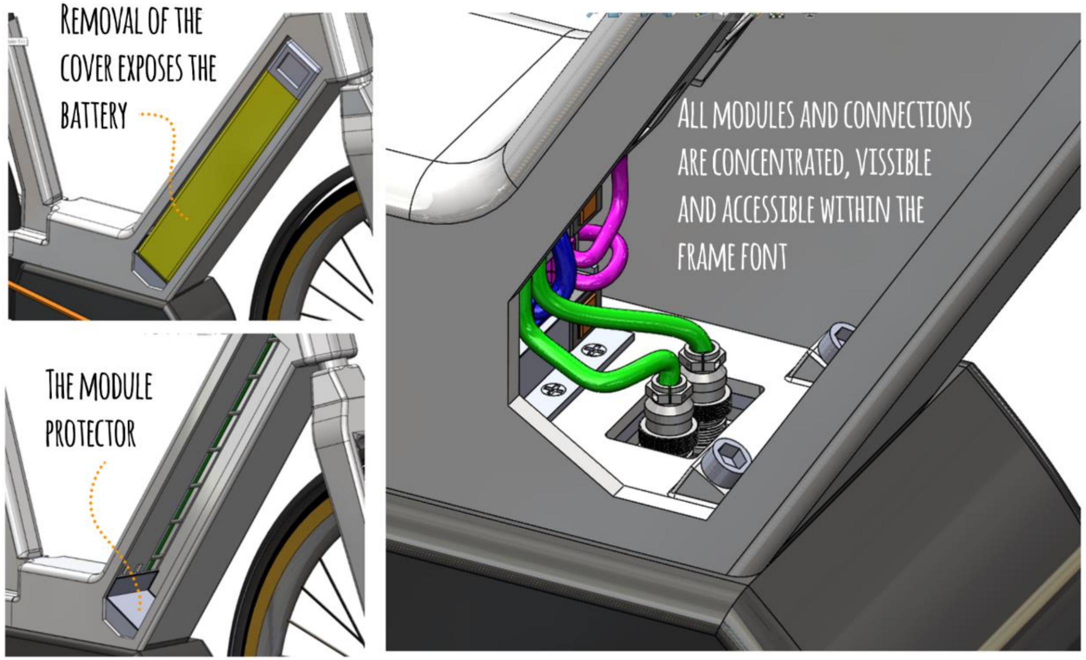


Figure 22: Exposal of the internal system after the battery and the protector are removed.

Fixation of the modules within the frame

We fixate the controller- and display module within the frame by the interface principle elaborated in section 4.4.2, *display/Controller module interface principle.* We fit the motor controller and the display module within separate, but equal trays. The trays lock the translation of the module in all directions by bolts integrated into the tray that clamp the modules down.

A large variety of different modules fit the tray due to the range of clamping by tightening and untightening the bolts. The trays can be re-used for new or alternative modules when needed. The tray is slid into the sheet metal module holder located within the base-tube and fits into positioning by two positioning pins. We fixate the module tray to the module holder through a small commodity click lever. We can fit the module holder itself through the battery cut-out and is fixate it underneath the frame through countersunk bolts.

Module removal

The modules are stacked on top of each other, and we interlink them by wires. We disconnect the motor controller module (green) from the other first. Then we open the click-lever and remove the motor controller together with its outgoing cables (The green cables to the motor module and the blue cable to the display module). The removal of the display module requires the removal of the motor controller and then follows the same principles. We visualized the fixation and removal of the modules in figure 24.

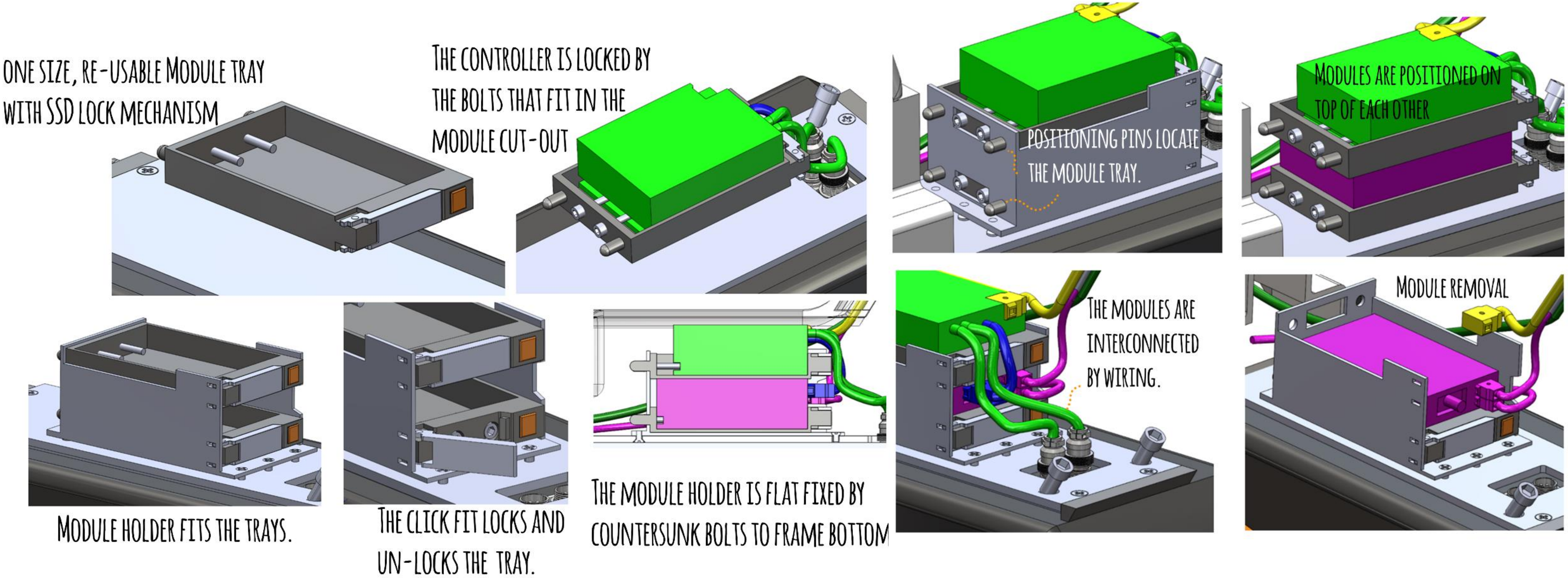


Figure 23: Module fixation within the frame and module removal from the frame.

The motor module connection (motor module interface design)

We fixate the motor module by a form-fitted slider, as described 4.4.1, *The motor module interface principle.* The embodied motor module interface design is shown in figure 25.
We make use of a T-profile that has a precise fit to a slot underneath the frame to locate the motor module underneath the frame. We connect the T- profile itself to the motor module by a standardized, yet unidentified interface connection, or we fully integrate the T-shape with the motor module housing. The first method enables the linking of the same T-extrusion to a variety of motor modules.
The T-profile has a connector-component that fits precisely onto the position pins that we fixate onto the frame, to block play vertically and sideways. The vertical forces exerted on the motor module are distributed over the surface of the T-slot. An aesthetical component is fixed to the front of the profile to create aesthetical coherence with the frame.

The T-profile is milled from the top to create a dented surface that is needed to lock the profile from within the frame through two diagonally positioned M8 bolts that run from within the frame to the bottom of the frame. The bolts can only be accessed from within the frame to prevent the motor module from being stolen.
The motor module is connected to the motor controller from within the frame after it has been positioned. Removal of the motor module requires the two connectors that run from the motor controller to the motor module (green cables) to be disconnected. Loosening the bolts enables the removal of the motor module. The motor module stays into place through the form fit, even when the bolts are not clamping it down. The sustained positioning of the motor allows for convenient removal and re-mounting of the motor module and minimizes potential motor module damage from falling off the frame.

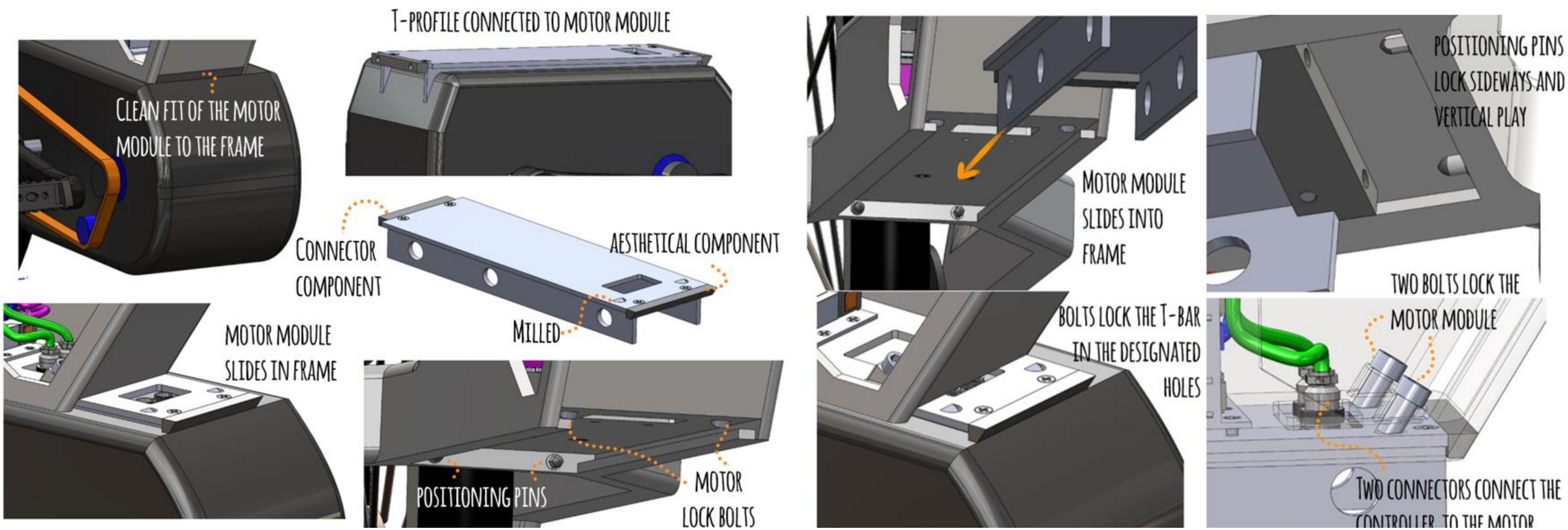


Figure 24: the motor module interface.

Double-walled frame and routing through of wiring

We weld two internal walls inside the frame to compensate for the loss of frame stiffness resulting from the battery cut-out. For more extensive product series, we can potentially use a double enclosed extrusion profile. We run a notch over the internal top wall through which the E-bike cables are routed neatly to optimize the free inner frame volume for a maximum capacity battery. The frame and cable routing are visualized in figure 26.

A belt solution

We have not been significantly focussing on a complete belt solution within this project due to the rear of the E-bike being a 'black' box. The ambiguity of the rear part of the E-bike un-ables the design of a complete solution.
In the shown concept, we run the belt over the pedals and tension it by a tensioner. The tensioner is fixated to the motor module.

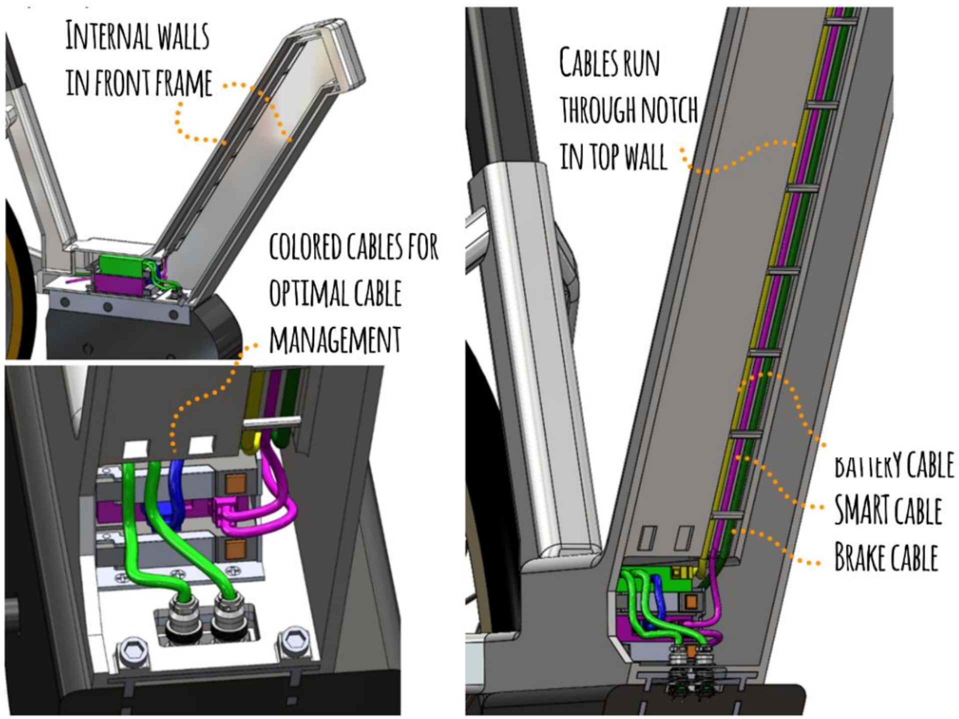


Figure 25: Double walled frame and cable routing through the notch.

The belt runs from the front-axle to the rear-axle. The location of the motor module in the middle of the frame, with the belt running over the pedals, compromises the even positioning of both pedals relative to the frame. We position the motor module asymmetrically underneath the frame allows the belt to run over the pedal while keeping the pedals in an exact position relative to the center of the E-bike. The high positioned chainstays enable the belt to run from the front to the rear axle without the need to run them through the belt, which enhances the removability of the belt. A small cover is likely to be added over the front of the belt and fixated to the motor module for the protection of both the belt and the rider. The belt solution is visualized in figure 27.

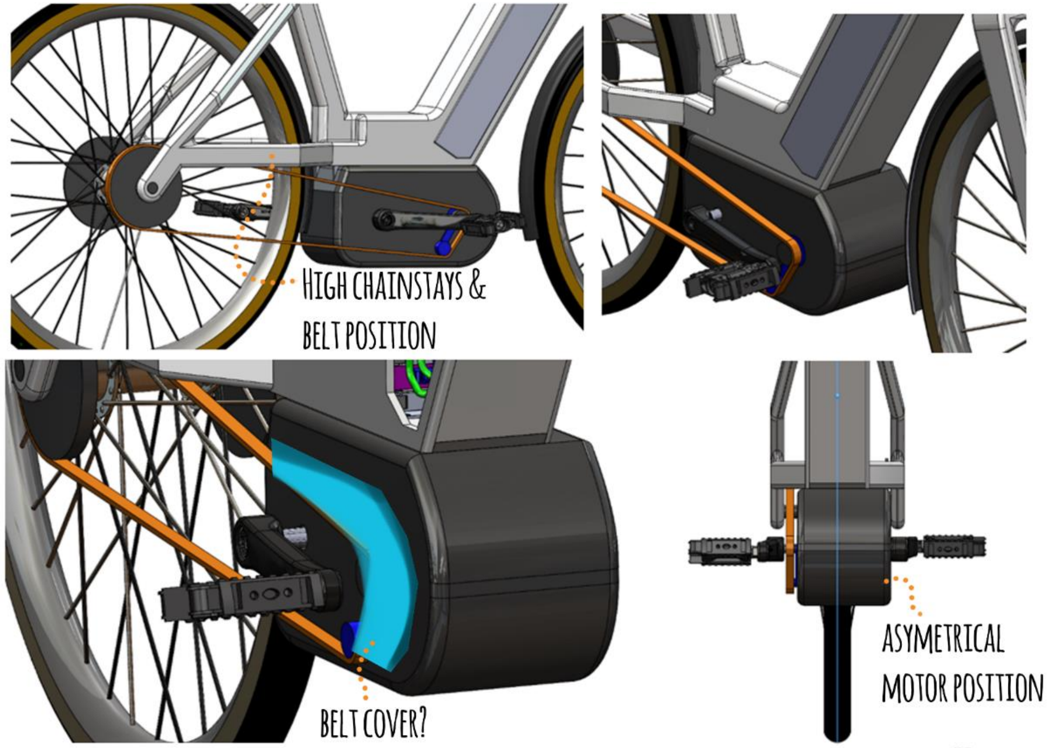


Figure 26: The belt solution

4.5.2 Discussion of concept 1

We designed this concept for the durability of the E-bike and the accessibility of module exchange. We designed product architecture design combined with the interfaces result in a clean final E-bike concept that is repeatably customizable in terms of functioning. We can repeatably exchange and interchange modules for the same and different sized modules. The frame integration of the modules protects the modules against theft and vandalism. The design requirements to reduce the total cost of ownership and to create a circular E-bike are therefore potentially met by a combination of the current concept solutions.

However, the initial concept design has pointed out un-foreseen and potentially undesired characteristics that make us doubt the effectiveness of some solutions. Some of the uncertain design characteristics result from the iterative design process explained and visualized in Appendix 6.10, *Influences of the original idea on the final embodied concept*. The slight concept alterations without complete adaptation of the entire system have had their implications on the embodied E-bike. We elaborate on the design characteristics of which we are uncertain in the next sections and visualized them in figure 28 and figure 29.

E-bike entry and empty volume in the back of the E-bike frame

The stacking the modules on top of each other results in a high entry of the E-bike. At the same time, the cable that runs from the display module to the back of the frame is difficult to access and position through the battery cut-out. Even when we reposition the wiring and connectors to the front of the E-bike frame, we create an un-used volume in the back of the frame. In this design, we do not allocate the frame volume optimally. The positioning of either the motor controller or the display module in the back of the frame allows for better use of the existing frame volume. It creates a lower E-bike entry for more user-friendly accessibility of the E-bike. We have to remove the rear module in an alternative manner from the frame if we decide to position it in the back of the frame.

Visibility of cables and connectors when performing repairs.

We positioned the cables and connectors in the front of the E-bike to allow for visibility and easy access. With this positioning, we aimed for optimal ease of repair. The large cut-out should enable access to the connections and wiring as well as simple module removal. Although the components are easily reachable through the cut-out, visibility of the performed actions that are needed to remove the modules is minimal due to the hand blocking the visibility of the components when we insert it into the frame. Enhancing visibility requires a larger cut-out, which compromises the frame stiffness.

Removal of the display module requires removal of the motor controller

The modules need to be interconnected. We must separate the module connections before we can remove modules. The display module is only removable by removing the controller module, which is located on top. This working mechanism un-ables the removal of the modules individually.

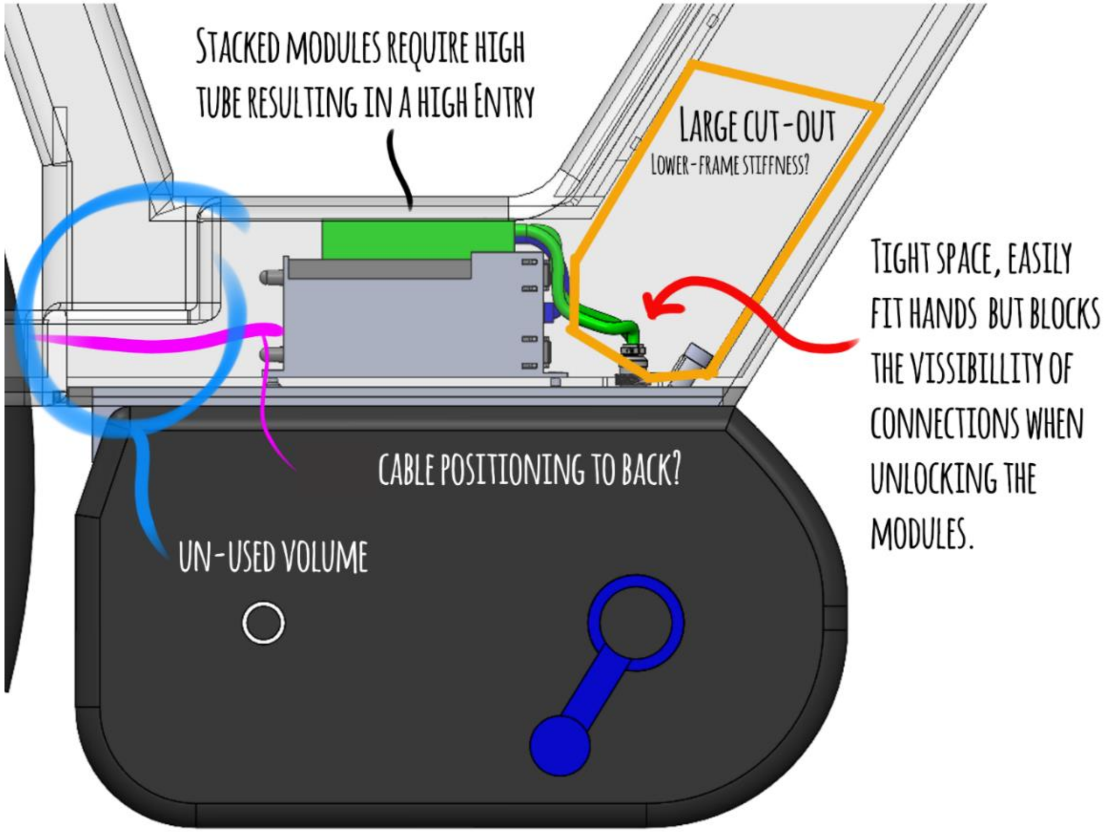


Figure 27: Undesired characteristics of the first concept: un-used volume, high-entry, visibility of cables, not possible to remove modules separately.

Positioning pins

We intend to the T-profile to be evenly supported by the flat T-slot surface underneath the frame. The position pins require tight tolerances in the vertical direction; otherwise, the T-profile could end up being supported by the pins in the back of the frame. Tight tolerancing of the visualized solution adds to the costs of the components. A different motor module interface solution is likely to be more feasible.

Cable notch complication

We designed a separate notch for routing the cables through, as shown. The separate notch feature adds frame complexity. The cables can run through the empty volume and make the cable notch redundant. Routing the cable through the hollow frame structure reduces the frame complexity and enhances the frame integrity.

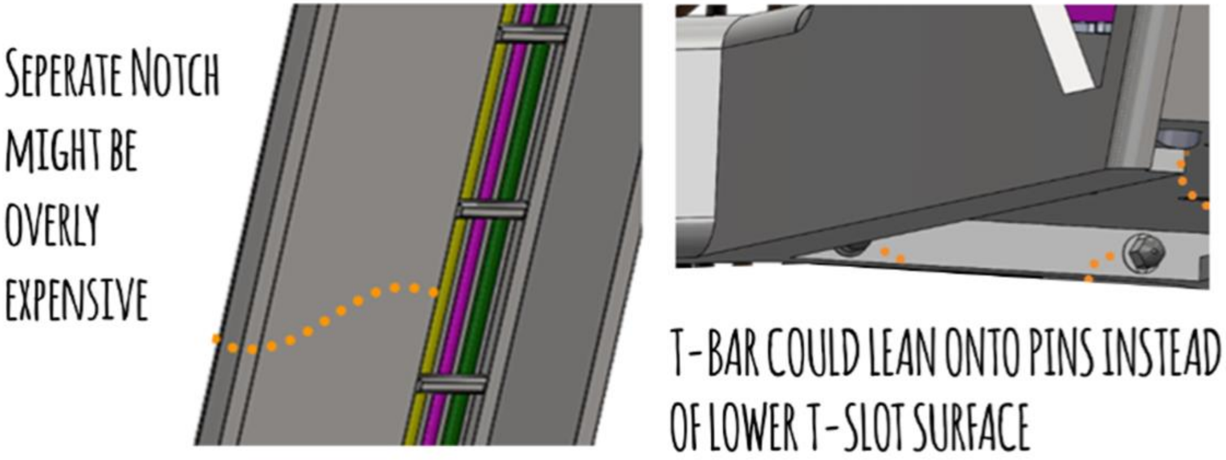


Figure 28: Redundant cable notch and T-bar leaning onto pins.

4.5.3 Concept 2: Module removal from the side of the base-tube

Our main doubts described in the discussion of the first concept revolve around cable management and module visibility during module exchange. This section elaborates on an alternative product architecture approach aimed to solve these problems. We visualized the altered product architecture decisions in figure 30. Most working principles remain much the same; however, slight alterations allow for better accessibility to the controller module and display module, more accessible cable management, and fixation of the motor module.

We can choose to remove the modules from a separate frame cut-out in the side of the base-tube, instead of the battery cut-out. This manner of removal allows for the removal of individual modules. It enables better accessibility to- and visibility of cable-management and enhances the ease of repair of the E-bike. Besides, this method allows for more efficient usage of the existing frame volume. We visualized the module removal from the side in figure 31.

In the alternative concept, we locate the display module behind the motor controller within the frame. The display module requires a connection to the back of the frame and is therefore located behind the motor controller. The said locations of the modules enable single removal of the display module without the need to remove the controller module. The module positioning also lowers the E-bike entry, which is a desirable characteristic for getting on the E-bike in the most accessible manner.

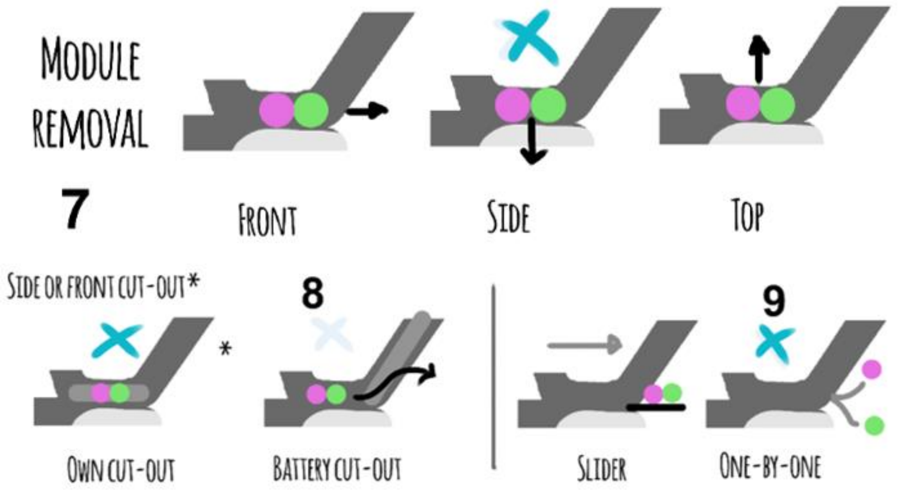


Figure 29: Alternative decisions in the morphological chart.

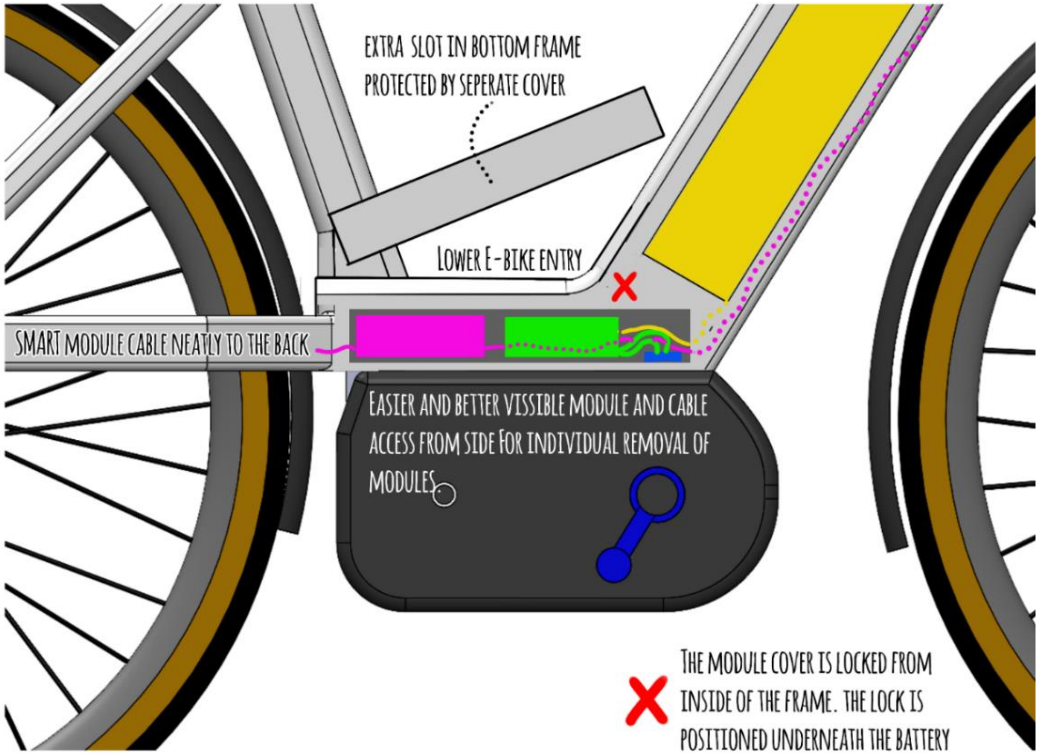


Figure 30: Concept 2, Removal of the modules from the side of the frame.

Module removal and decoupling of the cables

The frame structure and the fitting of the modules into trays that fit within a module-holder remain much the same. We rotate the module holder, so it faces the side-cut within the base-tube. The ‘click’ fit that we implement to secure the module trays within the module holder is directly accessible when we remove the cover. Unlocking the click-fit does not require the initial removal of the cable connectors as in the original concept. The module tray, with the module, can be removed from the side of the frame with its connectors still fixated. The cable length must be sufficient to do so. With this method, we enable the decoupling of the modules when the modules are already outside of the frame. We then only need to connect the new modules to the existing connectors and re-mount the tray in its designated slot. We visualized these principles in figure 32.

Frame integrity

We compensate for the lost stiffness of the base-tube, resulting from the cut-out, by extending the top of the double-walled downtube over the middle of the frame. Stiffness of the bottom of the base-tube is created by the combination of material thickness and is enhanced by the stiff T-profile that is fixated firmly underneath the frame.

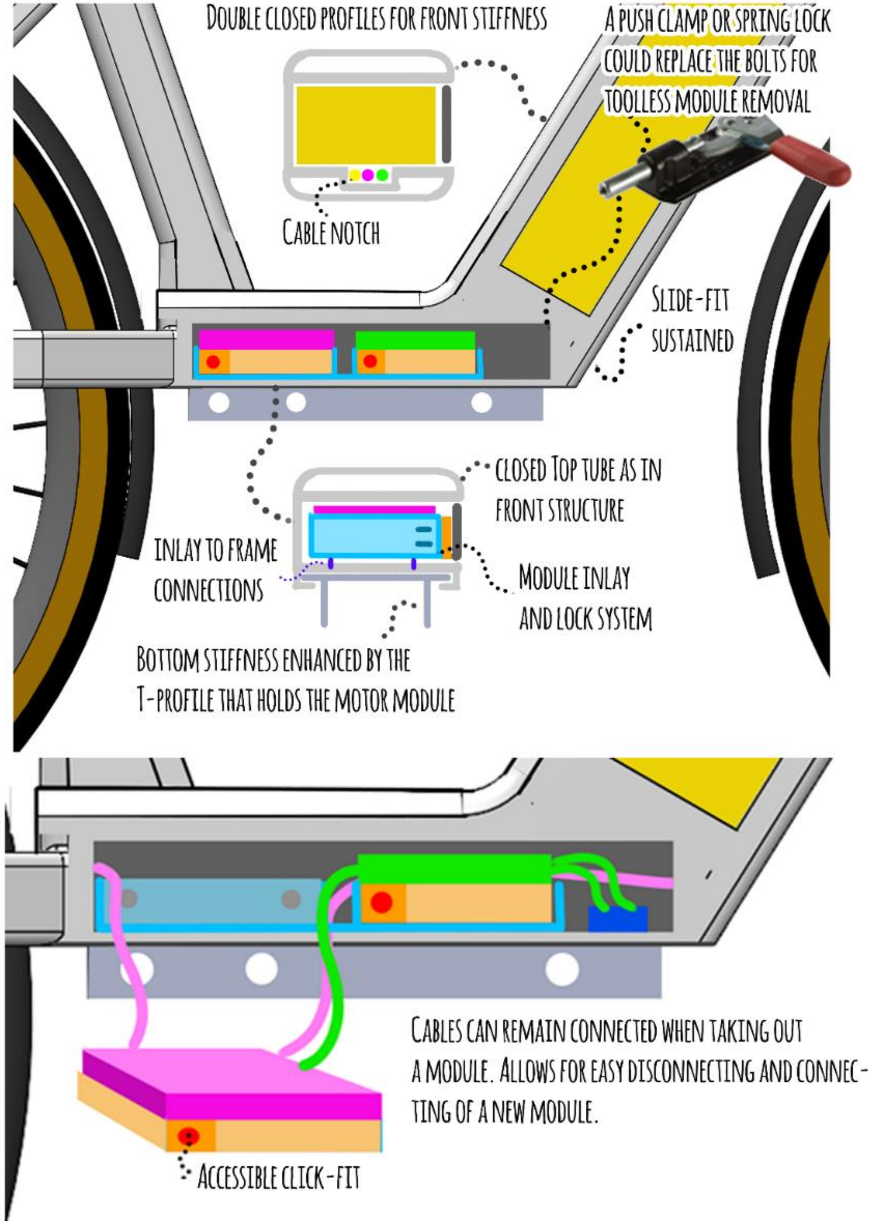


Figure 31: Module fixation and removal from the frame.

Module cover

We seal base tube cut-out by a removable cover. We envision a solution in which the cover fits precisely over the cut-out and is connected to the frame by a hinge on one side and locked by a retractable spring-loaded pin on the other side. When we retract the pin, from within the frame after we removed the battery, we unlock and remove the cover. We can make the cover a part of the frame structure to compromise for the lost frame-stiffness resulting from the cut-out. We visualized the module cover in figure 33.

The motor module interface

The slide fit principle for the motor module remains the same; however, we replace the two bolts by a push clamp or a spring clamp that pushes the motor module in position to enable tool-less removal of the motor module. We replace the double wedge clamp principle that locks the T-profile in place, within the T-slot, by a 2-directional wedge in the back of the frame. The wedge aligns the T-profile and presses the T-profile down. This method enables the even distribution of the forces exerted onto the motor module. The wedge is either formed directly with the frame or welded onto the frame. The wedge removes the complexity of the precise positioning of the position pins. We visualized this solution in figure 34.

4.5.4 Discussion of concept 2

The second concept proposal allows for better accessibility to- and visibility of the modules relative to the first concept. Even considering the provided solutions to compensate for lost frame stiffness, the full-length cut-out in the base-tube, leads to doubts on the final frame integrity. The base tube has to endure high pedal forces. The large cut-out on the side is not ideal in terms of frame integrity. A structural module cover could partially compromise for the lost frame integrity but requires a sturdy connection to the frame to function as desired.
Also, the wedge clamp might not be ideal either. The wedge clamp on T-profile could result in the profile getting stuck, which compromises the ease of removing the motor module from the frame.

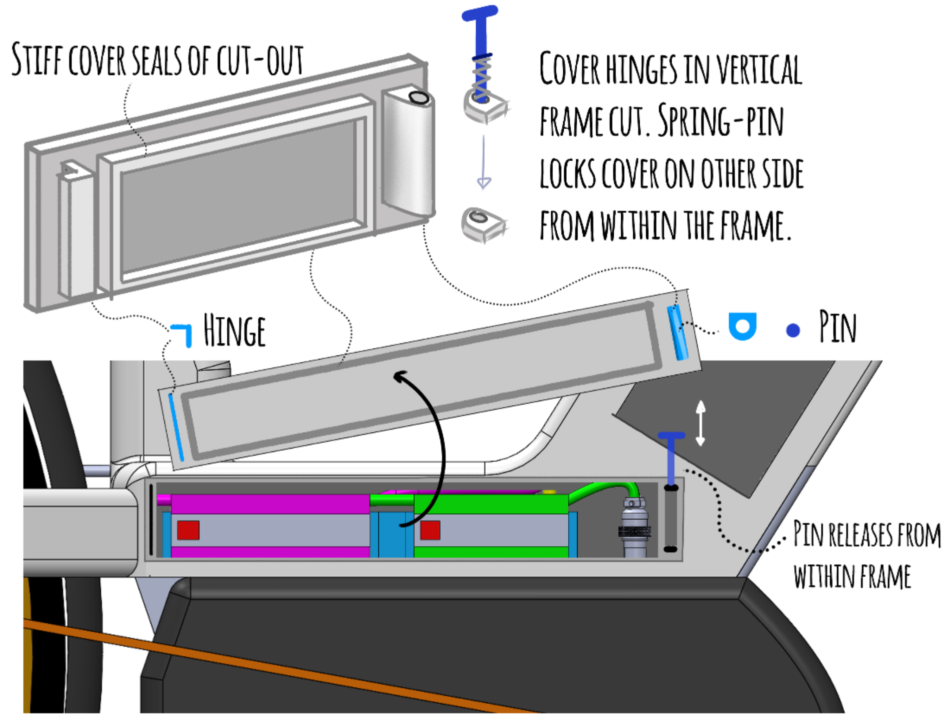


Figure 32: Cover of the side cut-out.

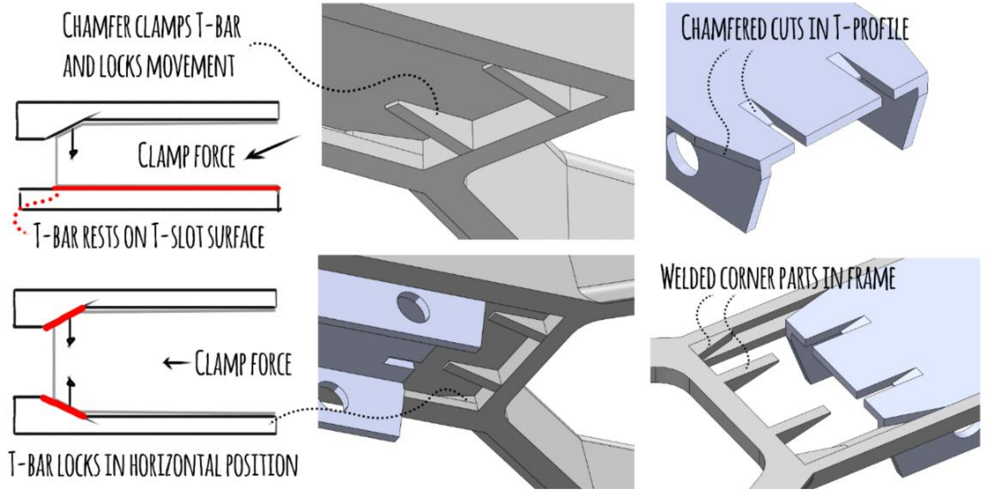


Figure 33: The wedge clamp principle.

4.5.5 Alternative concept direction 3: module removal from the front

The main doubts of the second concept result from the compromised frame stiffness that results from the cut-out in the side of the base-tube. In this section, we elaborate on an alternative product architecture approach that sustains both the frame integrity, through incorporating only a small cut-out in the frames' front, and module accessibility and visibility. We visualize alternative product architecture decisions in figure 35. We identify the removal of the modules from a separate frame cut-out in the front of the base-tube while implementing a sliding inlay as another manner to remove the modules individually. We position the modules onto an inlay that slides out of the front of the frame. Sliding out the inlay enables a well accessible and visible manner for both module and cable management. With this principle, we can sustain the frame integrity.

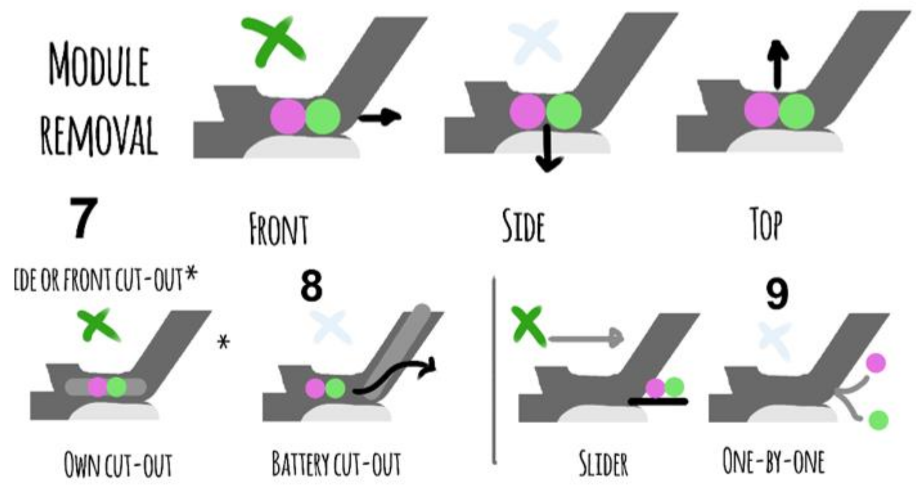


Figure 34: Module removal from the front.

We identify two sliding principles usable to remove the internal system from the E-bike frame. We can expand the motor module inlay and integrate the motor controller and display module onto the T-profile. This method enables the removal of all the modules from the system at once. We elaborate upon this principle in sub-concept 1. Expanding the motor module interface.

The other option we identified is positioning the controller and display module onto a separate sliding-inlay. This method enables the separate removal of the motor module as well as the display and controller module. We elaborate upon this principle in sub-concept 2. Separate display/Controller inlay.

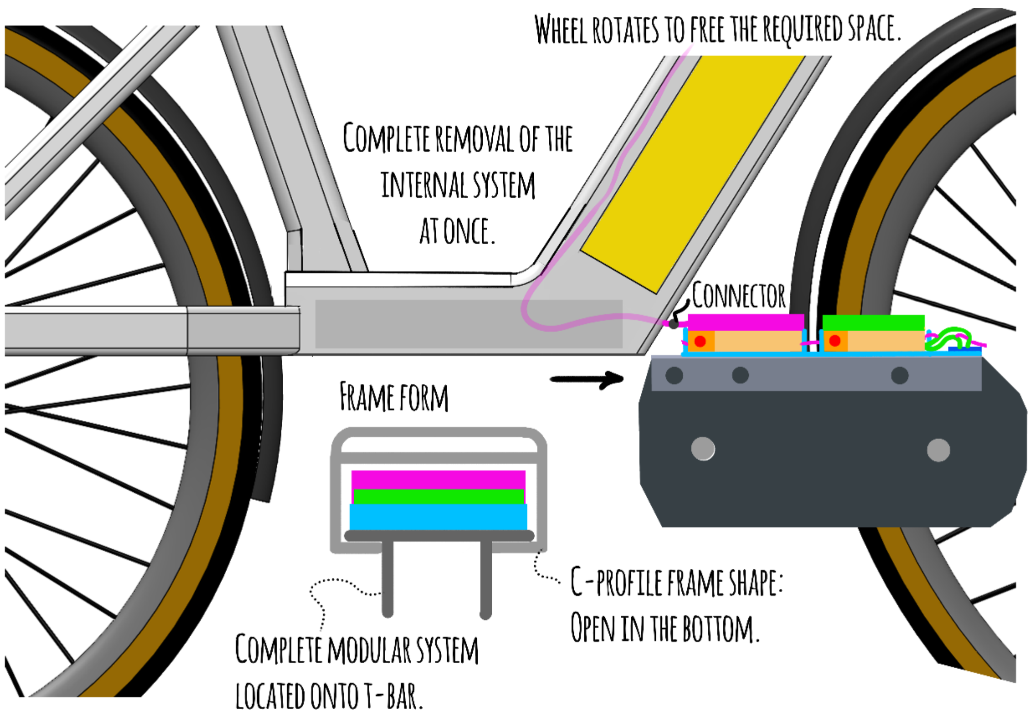


Figure 35: Removal from the complete internal system from the frame.

Sub-concept 1: Expanding the motor module interface

We can position the display and controller module onto the T-profile that connects to the motor module. The T-profile still slides into the T-slot underneath the frame and enables complete removal of the internal system at once. This method enables optimal accessibility to the modules, the implemented wiring, and their connections. It also makes the disconnecting of cable connectors between modules within the frame before removal redundant. We require excessive cable length within the frame. This excessive length enables disconnection from the internal electrical scheme after we removed the modular system from the frame.

The bottom of the frame needs to be open to be able to remove the internal system as described. The open structure of the frame compromises the frames' integrity. The integrity is to be compensated by the usage of thick frame walls, which is not ideal in terms of final E-bike weight and raw material usage. We visualized the conceptual solution in figure 36.

Sub-concept 2: Separate display/Controller inlay

We can position the display and controller module on a separate slide-able inlay to enable separate removal of the said modules and the motor module. The module inlay positions the modules in the same manner. It uses the same click-fit fixation principles as elaborated in the second concept. However, the inlay can slide out from the front frame to remove the modules. Similar to the first sub-concept, sliding out the inlay allows for accessible and well visible removal and cable management outside of the frame. The difference from sub-concept one is that the connectors from the controller to the motor module are to be disconnected within the frame first before we can slide out the inlay with the motor module sustaining its position (or vice versa). We visualized this idea in figure 37.

The separate removal of both the T-profile and the module inlay requires individual sliding slots for both. The original T-slot we used in concept one can remain the same, sustaining the bottom of the base-tube. We keep the base tube structure enclosed, and thus the frame integrity can be maintained without the need for overly thick frame walls. The enclosed profile keeps the wall thickness and, therefore, the frame weight and raw material usage down. We can rout the cables through the frame in various manners.

1. We locate Excessive length cables within the rear frame volume. This method allows the removal of the inlay and then disconnecting it from the outside the frame. 2.
2. We locate the cables within the top frame volume. We disconnect the inlay from within the frame before sliding the inlay out.
3. We rout the cables through the bottom of the frame volume.

The modules need a connection to the E-bikes' handlebar, and we inevitably rout electrical wiring upwards. The second option is the most logical and least invasive solution in terms of accessibility to the front cover (which we elaborate in the next section) and the inlay connections. We visualized the concept idea and the routing of the cables in figure 38. The cable section is also applicable to sub-concept 1.

Ultimately, within this third concept, sub-concept two is most interesting in terms of separate removal of the modules and frame integrity relative to the final frame weight and is therefore discussed in the next sections.

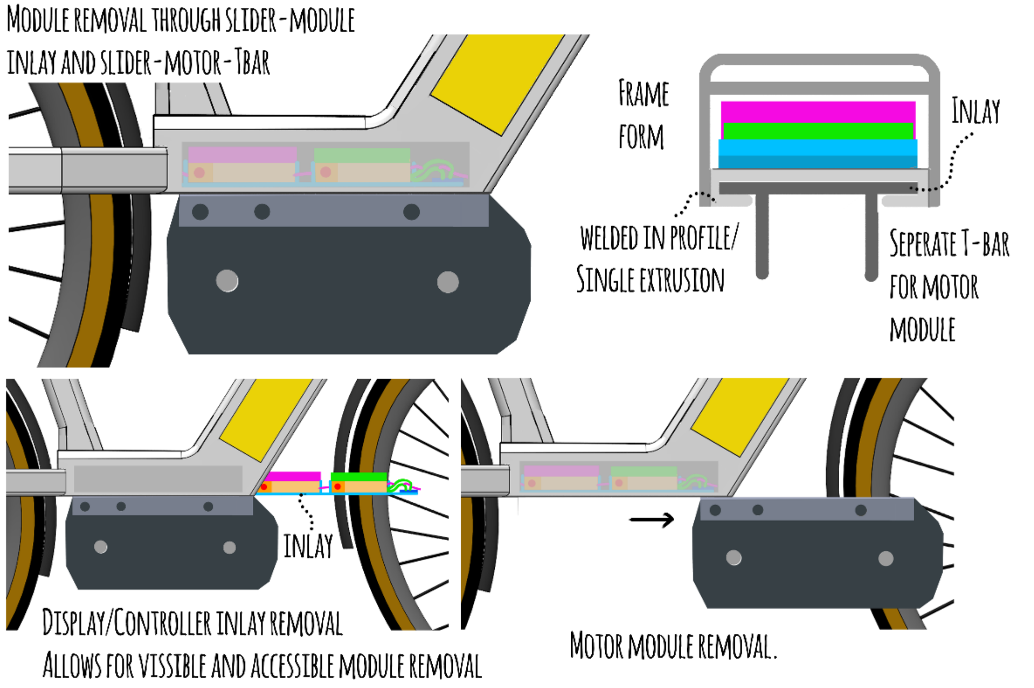


Figure 36: Removal of te full system from the front.

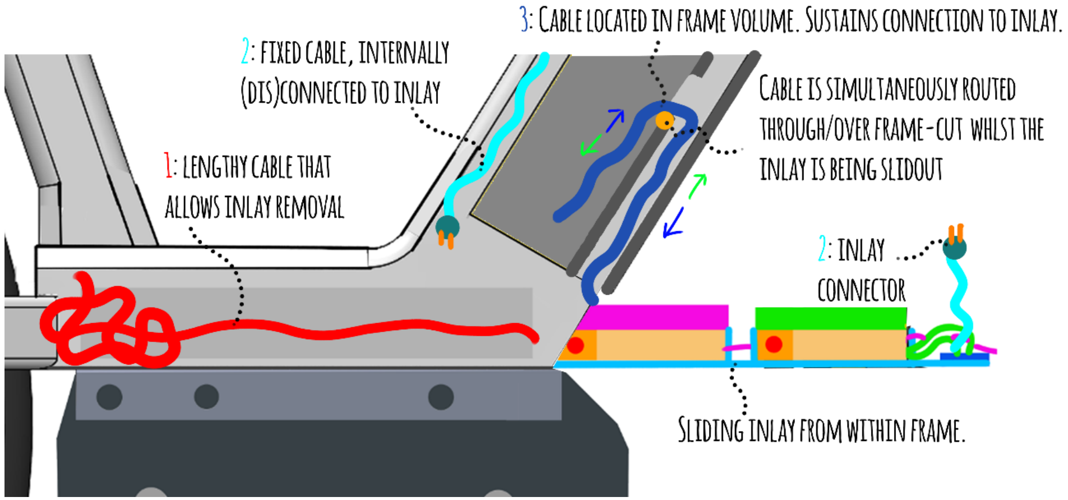


Figure 37: Cable management options.

Clean front cover

Naturally, the front cut-out is to sealed to protect the internal system against the weather, debris, and theft. We envisioned a spring-locked cover to seal the frame cut-out. The cover follows the shape of the frame and, together with the cut-out position, forms a clean, barely visible frame closure. The cover fits over the cut-out to block moisture and dirt splashing of the front wheel from entering the frame. A rubber seal in the opening could enhance the sealing ability of the cover.
We can unlock the cover from within the frame after battery removal. The cover integrates four spring-locked pins that are pushed outwards by springs. The pins fit designated slots within the frame and allow for firm fixation of the cover onto the frame. Squeezing the pins towards each other, retracts the pins, and allows for the removal of the cover. We visualized the cover solution in figure 39.

Motor module interface iteration

The motor module fixation is re-defined into a grub-screw fixation. Four grub screws lock the T-profile in the T-slot underneath the frame: two screws form within the frame; two short screws in the front from within the frame and two long screws in the back on each side of the seat tube. The grub screws press the T-profile down vertically in the four designated chamfered holes on its top face of the T-profile. The chamfered ends of the grub screws slightly adjust the T-profile position and lock horizontal movement in all directions. The downwards force of the screws onto the T-profile presses it evenly over the T-slot surface and evenly distributes the forces exerted onto the motor module over the T-slot. The system requires precise tolerancing of the holes in both frame and T-profile over the width for proper screw fixation. We compensate for the tolerances over the length adding two slots in the back of the T-profile slots. The front screws are countersunk within the frame to enable the module-inlay to slide over them. We visualized this principle in figure 40.

4.5.6 Discussion of concept 3

We identified some surmountable problems in concept 3, which we shortly elaborate on in this section. The inlay within the frame is to be fixated to prevent excessive vibration of the modules. The screws are not tool-less however enable a firm fixation for the motor module. A single hex tool allows for easy disconnecting of modules. We might need to seal the external screws in the back of the frame to prevent leaks. We can cover them by a cap fit a rubber between the screws and the frame.

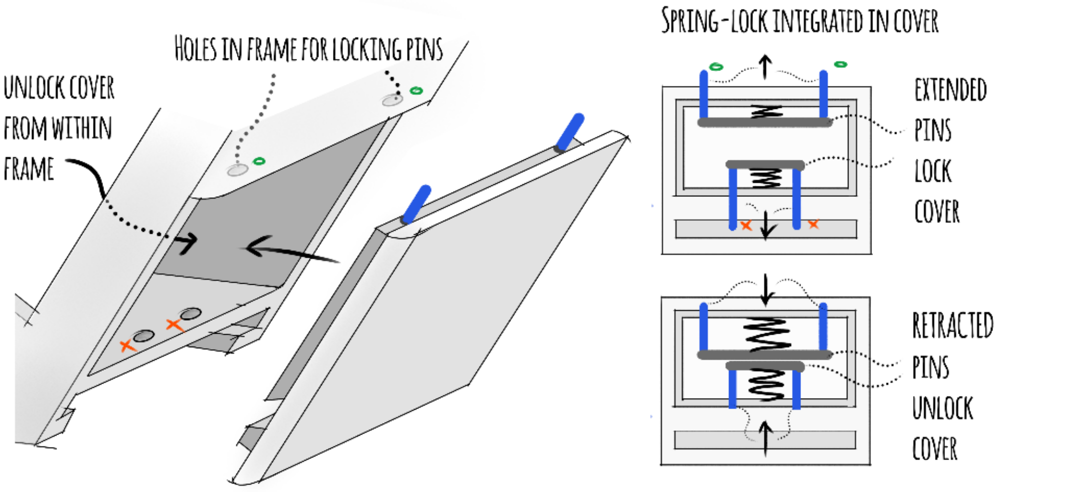


Figure 38: The cover of the front frame cut-out.

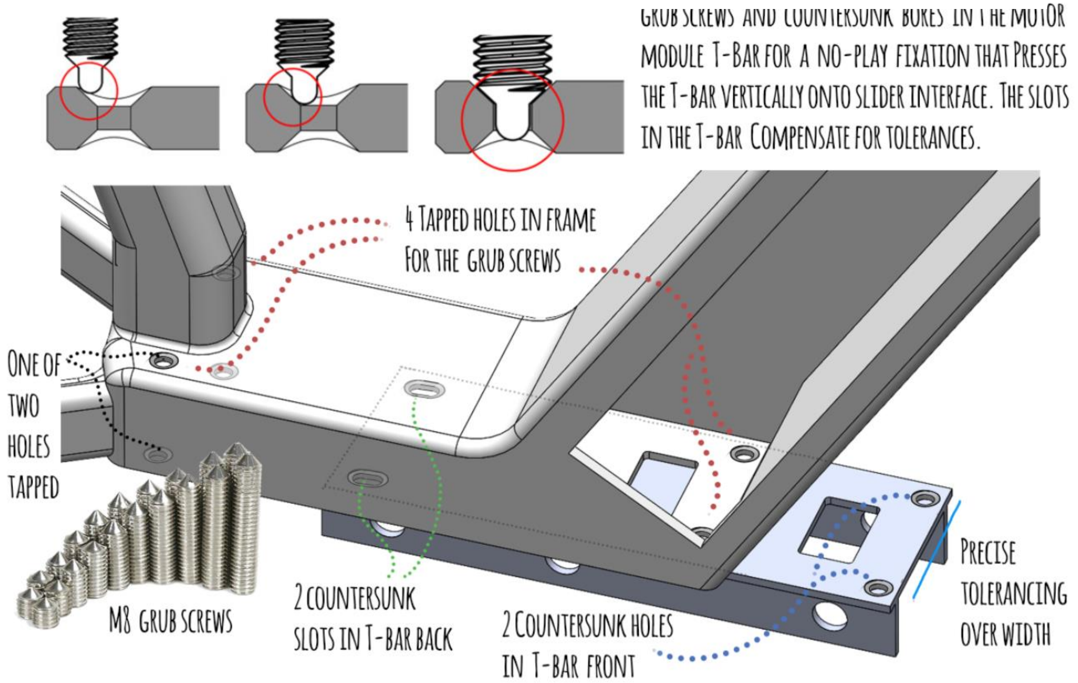


Figure 39: Motor module interface, grub screws to lock the motor module.

4.5.7 Concept choice: Module removal from the front

The main requirements of the circular E-bike are durability and end-of-life, which require a combination of robust E-bike design and module accessibility. Concept three, sub-concept two: module removal from the front by a separate offers a combination of accessible and individual module exchange for module repair while sustaining frame robustness required for E-bike longevity. Although we perceived concept three as a separate concept, it is an iteration of many concepts designed for durability and module accessibility. Logically, we consider it most feasible. We visualized the decision in figure 41. We present a final embodiment in the next section.

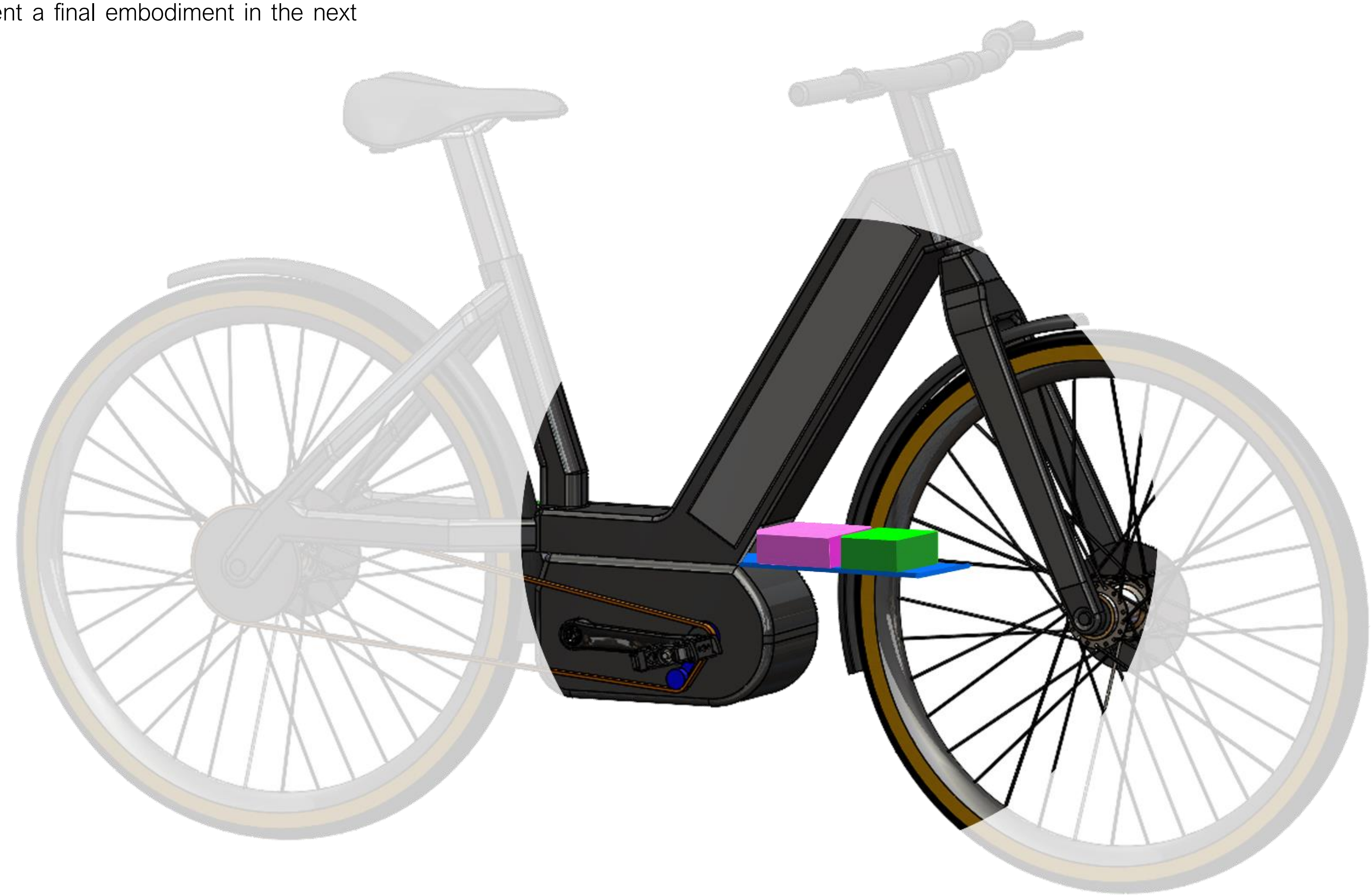


Figure 40: Module removal from the front of the frame.

4.6 Final design

In his section, the concept that we embodied based on the decision to remove the modules from the front. We show the final E-bike designed around our modular system in figure 42. We consider the E-bike design as simplistic and clean. We created a durable E-bike around the recognizable aesthetics of the traditional bicycle to achieve a future-robust timeless design. We present a robust E-bike in a retro-blue color and a set of retro wheels to fit both the classic character. The basic bike is further customizable by adding features such as a rear rack or a front rack.

Figure 41: The final E-bike design revolved around the modular system.

The bus-modular system

We initially envisioned a modular drivetrain system design that incorporates the described modules in section 1.3.1, *The E-bike as a platform*. The drivetrain took a different shape in the form of a frame module consisting of the downtube and base-tube. We visualized the bus-module in figure 43. We call this module the front-frame module. This front frame incorporates all modules in a minimal interdependent manner. Thereby, we consider the front frame module is as the bus-modular solution that we identified as the most feasible product architecture in 2.2.2*, durable modularity with an end-of-life purpose*. *We can offer the bus-modular frame as a separate offer to fleet owners or as part of a complete E-bike offering. We elaborate on this in the recommendations to the company in chapter 5 evaluation, section 5.2.3, Recommendations for the company.*

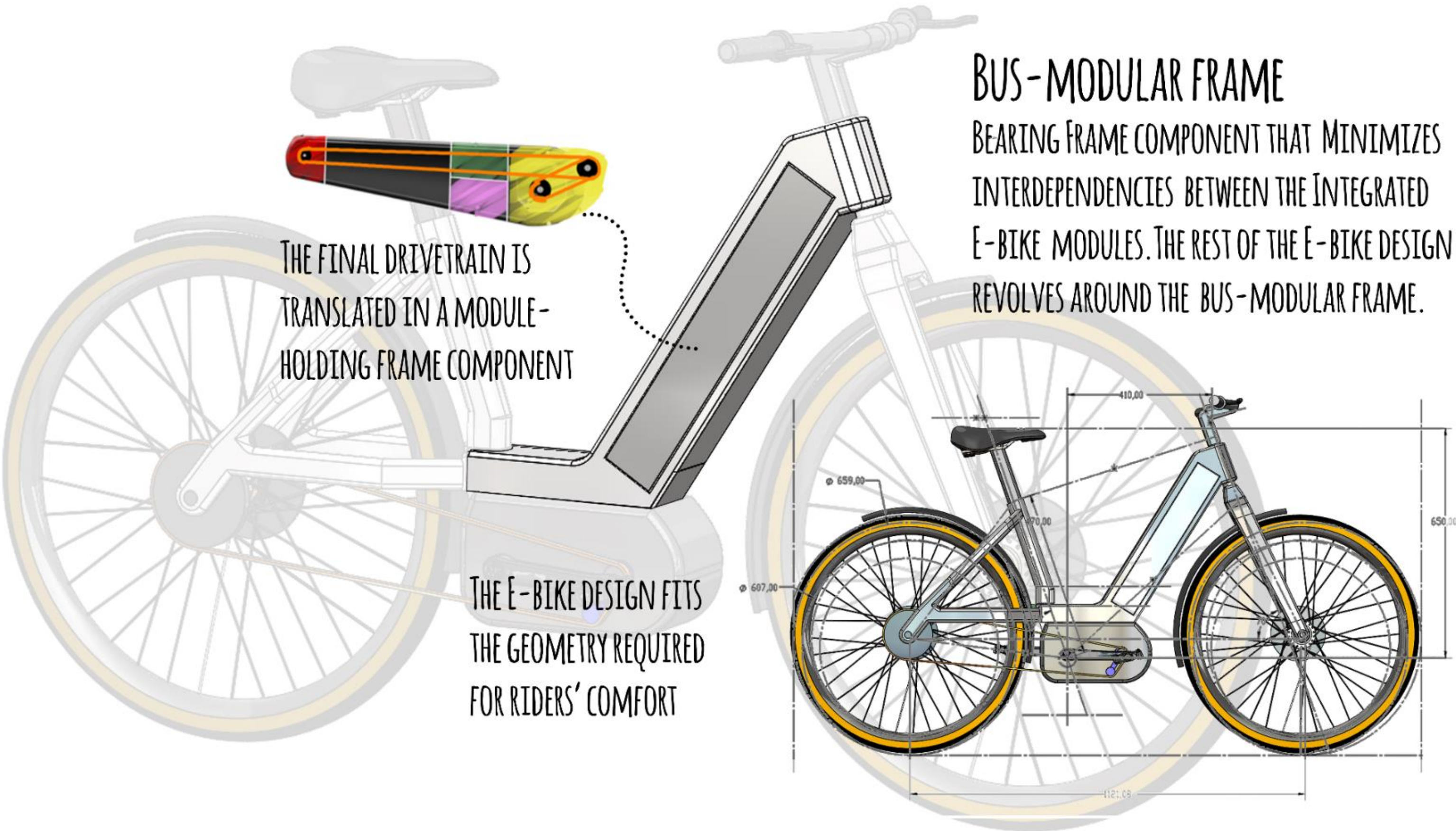


Figure 42: The bus-module.

Specific E-bike characteristics

We implemented a series of design characteristics in the E-bike. We describe the main design characteristics of the E-bike in figure 44.

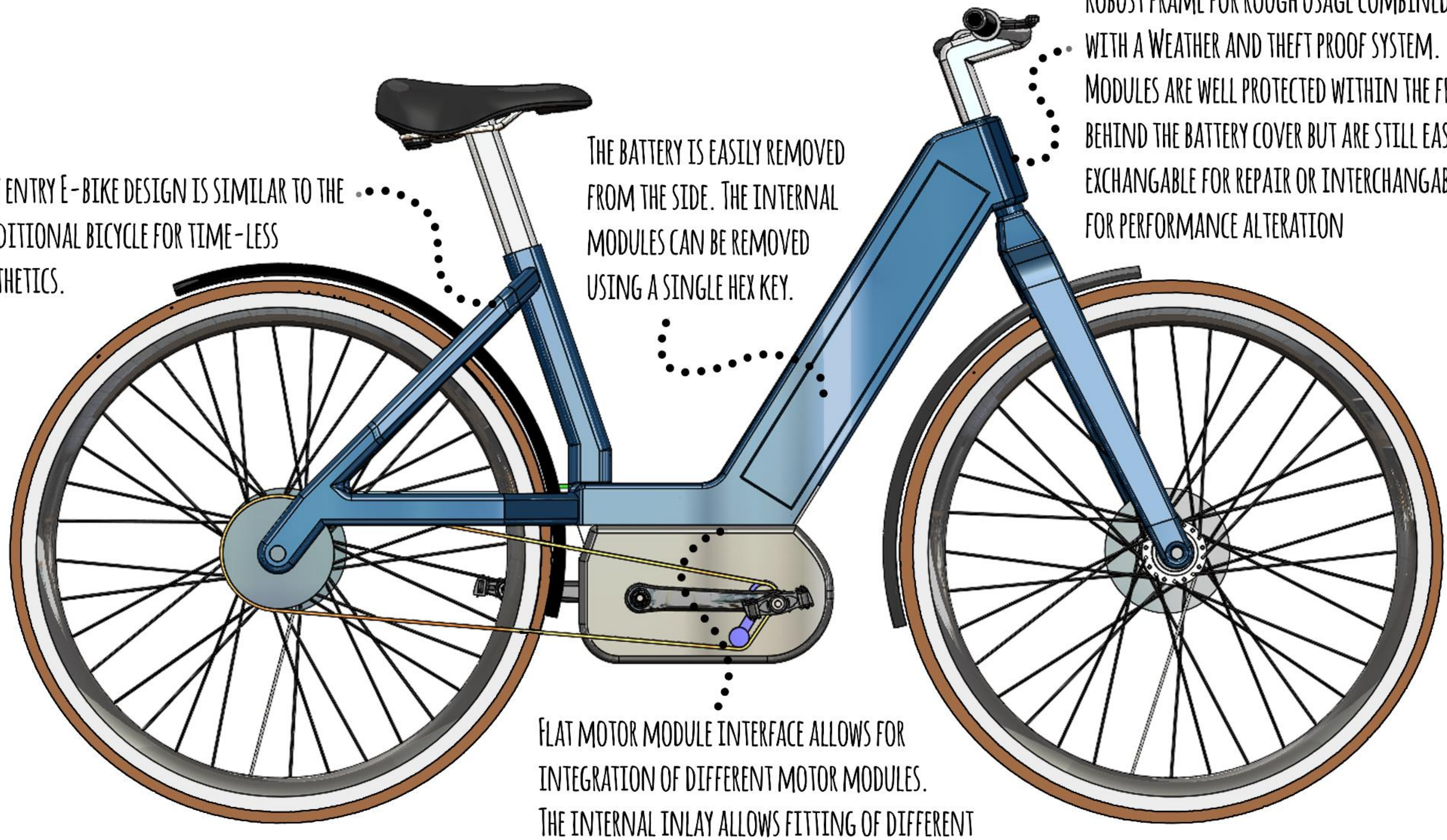
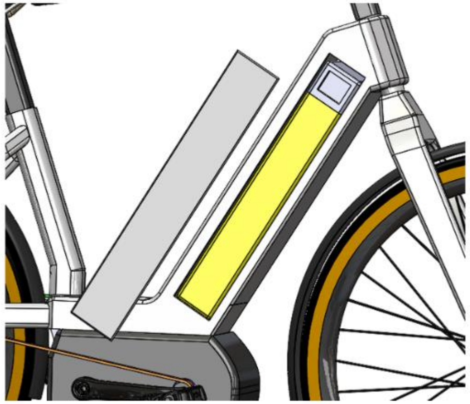


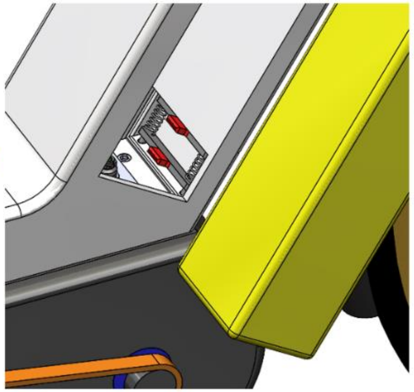
Figure 43: the most important E-bike characteristics.

The working principles: access to the internal system

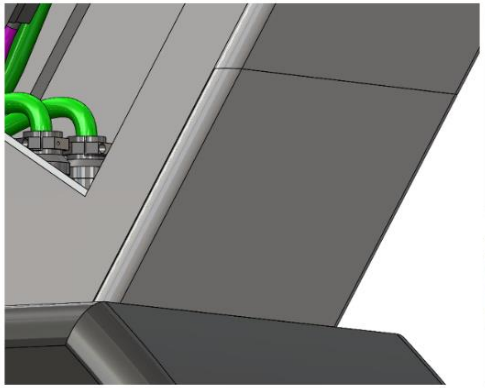
In figure 45, we show the sequence of steps to be performed to access the internal system of the E-bike.



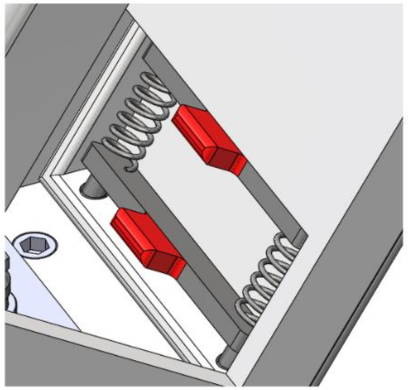
1. Removal of the battery cover from the side exposes the battery.



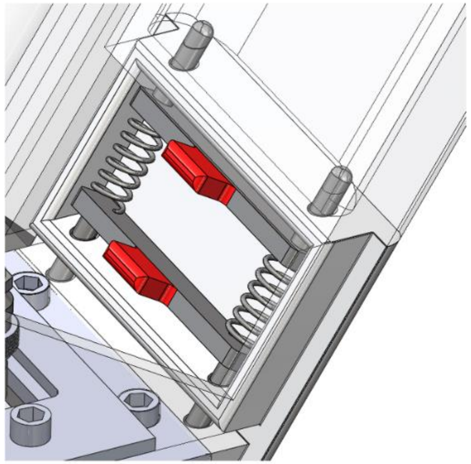
2. Battery removal enables acces to the internal E-bike system.



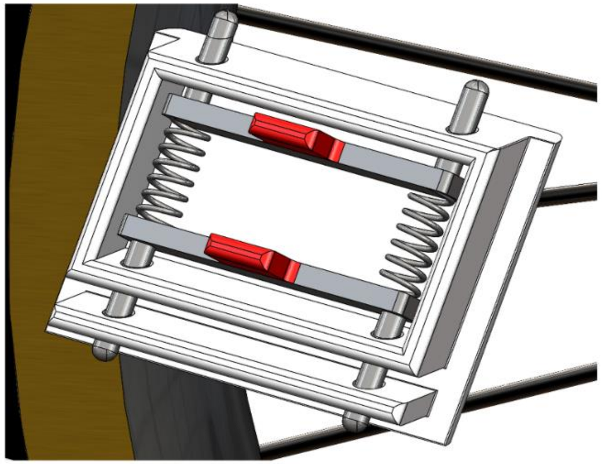
3. The front cover cleanly seals of the frame and is to be unlocked to access the internal system.



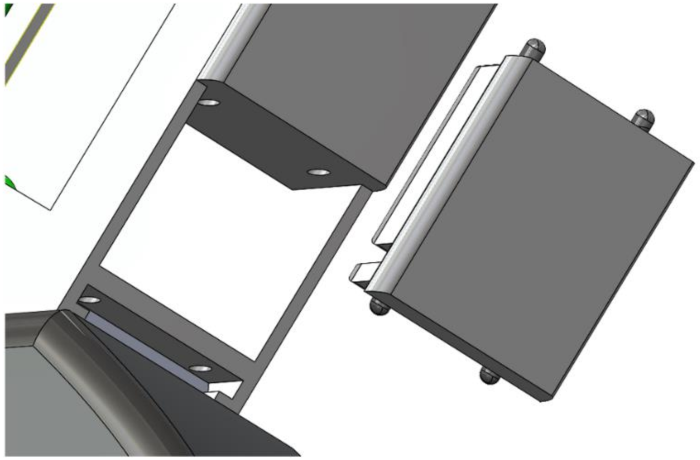
4. The cover is (tool-less) unlocked from within the frame by squeezing the red tabs together.



5. The cover has 4 outward pressing pins, the frame has 4 designated slots to fit the pins.



6. The system is spring-loaded for self clamping of the cover to the frame.

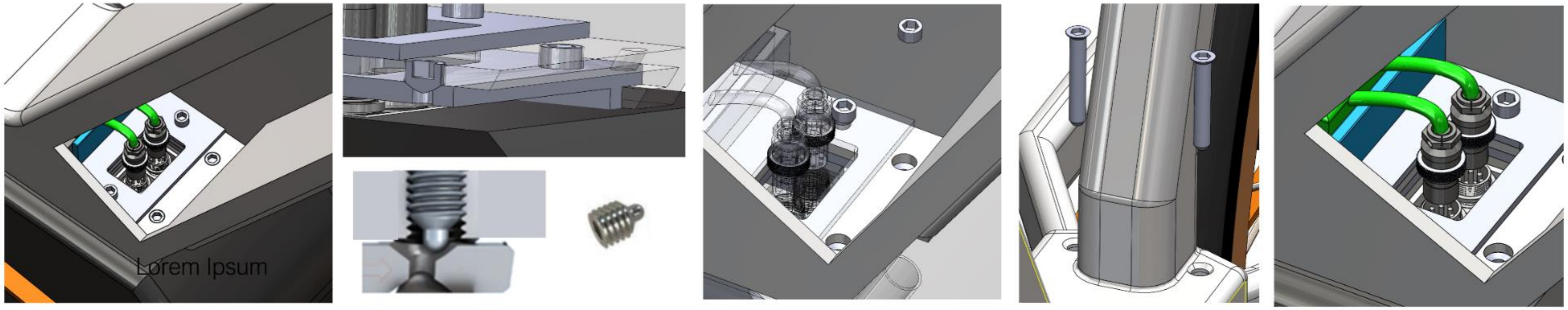


7. The cover is removed and enables the removal of the motor module and the module inlay as explained in the next vizuals.

Figure 44: Removal of the battery and front cover to access the internal system.

The working principles: motor module removal

In figure 46, we show the sequence of steps to be performed to remove the motor module from the E-bike after we have access to the internal system by the sequence visualized in figure 45.



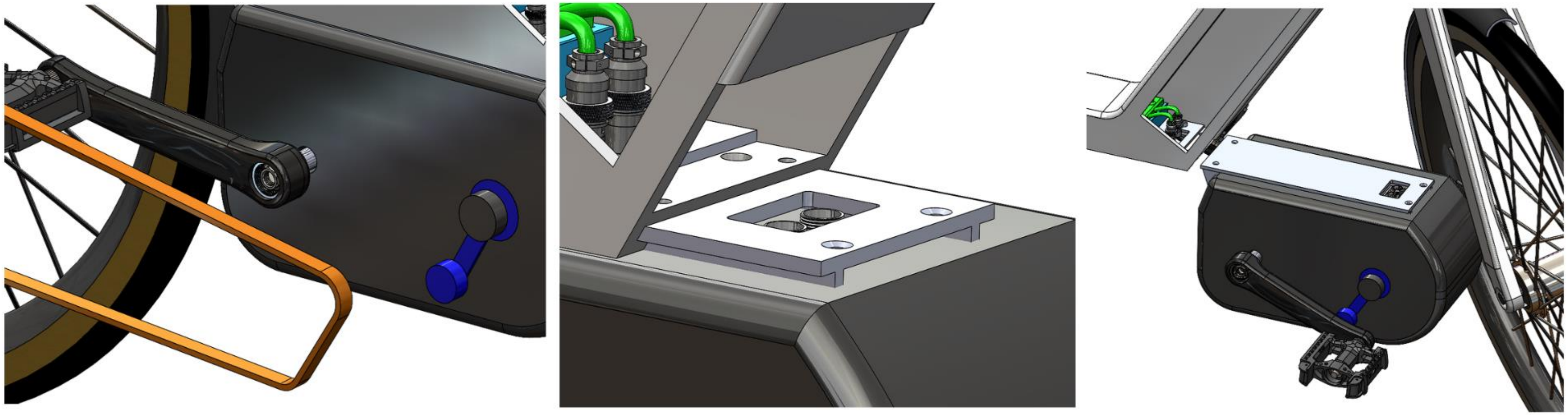
1. The motor module is firmly fixated within the frame T-slot by four bolts of which two bolts are safely located within the frame.

2. Two short grub screws both position and fixate the inlay in the front by pressing onto the countersunk holes in the inlay.

3. The front grubs are removed from within the frame with a hex key.

4. Two long grub screws position and fixate the inlay in the back. Removed with the same hex key.

5. The motor connectors are removed from within the frame before shoving out/in the motor module.



5. The belt is removed by unlocking the tensioner, fixated to the motor module, before removing the motor module.

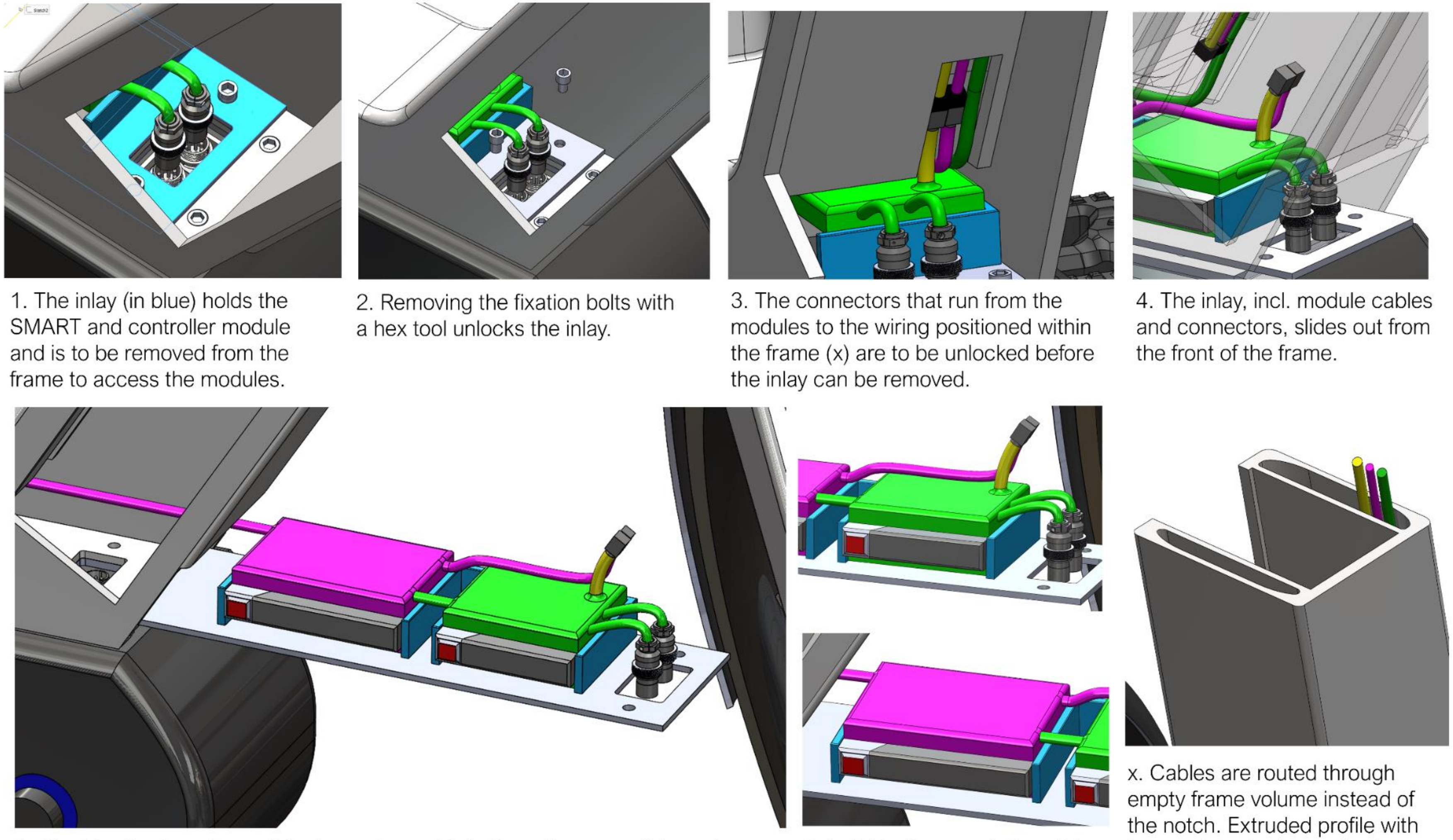
6. The metal form fit, integrated to the motor module, sustains the motor position to the frame even when it is not fixated and allows the motor to be shoved from/in the frame.

7. The front wheel needs to be rotated enable full removal of the motor module.

Figure 45: Removal of the motor module, the sequence is rotated for re-mounting of the motor module.

The working principles: display and controller module removal

In figure 47, we show the sequence of steps to be performed to remove the controller and display module from the E-bike after we have access to the internal system by the sequence visualized in figure 45.



1. The inlay (in blue) holds the SMART and controller module and is to be removed from the frame to access the modules.

2. Removing the fixation bolts with a hex tool unlocks the inlay.

3. The connectors that run from the modules to the wiring positioned within the frame (x) are to be unlocked before the inlay can be removed.

4. The inlay, incl. module cables and connectors, slides out from the front of the frame.

5. The inlay is shoved out of the frame front which allows for accessible and vissible module removal. The modules are fixated to the inlay by a click-fit in a similar manner describedin the controller/SMART interface design section.

6. Individual removal of modules is possible by the described inlay removing principle.

x. Cables are routed through empty frame volume instead of the notch. Extruded profile with two enclosed volumes for frame stiffness

Figure 46: Removal of the module inlay, the sequence is rotated for re-mounting the module inlay.

4.7 Evaluation of the final concept

The final concept is evaluated based on the requirements and followed by a section that describes missing but essential design solutions for the final realization of the concept.

4.7.1 Working principles within the concept

We presented a series of working principles in the final concept embodiment that offer a combination of durability and circular end-of-life purpose to the E-bike. We made the working principles clear. However, more specific decisions are necessary to achieve a final E-bike design that revolves around the principles. These specifications include component characteristics that are to be decided by the final intended usage of the E-bike, e.g., the final E-bike dimensions and component dimensions such as wall thickness of the frame depend on the required comfort and robustness of the final design. We have to define these dimensions based on a more specific user scenario of the E-bike to realize a viable E-bike solution.

4.7.2 Evaluation based on the requirements

The final design implements many design solutions but is still in a conceptual stage. We significantly focussed on existing E-bike architectures as well as existing technical principles and solutions throughout the design process. The proposed working principles visualized in the final concept embodiment do need to be further detailed. Their working principles, however, are considered to be free of significant flaws that unable their effective final integration in the E-bike concept. Ultimately, we need to embody and test the proposed principles to be able to verify their effectiveness.

The primary requirements of the circular E-bike design are durability and enhanced End-of-life by accessible exchange- and interchangeability for reuse, repair, and recycle. The concepts' fit to the defined requirements in section 3.3, *Design requirements of the modular E-bike system* is evaluated.

Durability

The proposed E-bike design solutions result in a robust modular E-bike in terms of frame integrity as well as the durability of the interfaces. The internal integration of components seals of the modules against its usage environment and safe-keeps the modules from theft. We minimize the futures to the E-bike's functioning, and we integrated a minimal number of components to reduce the risk of breakdowns. The final component quality further decides on the final E-bikes' durability but is bounded by the allowable E-bike costs, which are unknown and depend on the targeted fleet owner.

End-of-life

The proposed concept allows for timeless functioning as well as aesthetics and thus for future-robustness required for long-term re-usability of the E-bike within the circular system. The E-bike design is limited to serving a practical and timeless function without incorporating unnecessary features. We enable time-less E-bike performance by the final product architecture, that reserves space for alternative modules, combined with standardized interfaces that allow for continuous upgradeability and backward compatibility of functional modules.
We combined the functional E-bike alteration possibilities with a basic but traditional looking design of which the aesthetics are further customizable through (re)applying the aesthetical modules. The full-frame E-bike design enables accessible re-use of the full E-bike by the same or different fleet-owners.

We enabled optimal repairability by minimizing the module interdependencies through the design of bus-modular product architecture. The minimal interdependencies between modules result in easy decomposability of the modular system. The modules located within the frame are adequately protected but well accessible after we have removed the battery. The removal and remounting of modules from the E-bike system through the integrated sliding principles allow for the simple and well visible exchange of faulty modules. Module removal only requires a single standard hex tool. The standardized positions of modules, cables, and their connectors within the product architecture allow for intuitive maintenance.

The re-use and repair of the proposed modular system rely on the availability of spare parts and the workforce to perform the required repairs. Recyclability is the last resort option when the means for repair are unavailable, or the product is worn beyond and form of salvaging. The decomposability of the E-bike ultimately enables the effective recycling of separated materials.

Concept feasibility and consideration

The proposed E-bike concept consists of realistic solutions and working principles. It is, therefore, when detailed further, assumed to perform as intended to reduce the total cost of E-bike ownership and to allow for sustainable business operations for fleet-owners when realized. In the requirement evaluation, however, the final effectiveness of the concept could not be assumed with a hundred percent certainty due to the current lack of verification.

4.7.3 Additional design solutions essential for concept realization.

The general product architecture of the E-bike, as well as the motor module interface, the display module interface, and the motor controller interface, were non-existent in the first place. These E-bike features significantly add to the differentiated character of the circular E-bike relative to existing E-bikes. Therefore, we have been explicitly focussing on the said architecture and module interfaces throughout the design process resulting in the proposed solutions and working principles in concept 3. The final design, however, does still miss some essential features for the final realization. We visualized these features in figure 48.

The proposed concept direction in which we locate the modules and their connections safely within the frame relies on a properly sealed and well-locked cover over the side-frame cut-out. Accessibility of the modules depends upon the removal of the downtube integrated battery from the side of the frame. Battery integration and removal from the side of the downtube is common practice in existing E-bike designs (appendix). Therewith, a multitude of (combined) cover and battery solutions exist. An existing solution that allows for firm locking and sealing of the frame and removal of the battery combined with accessibility to the lower frame internals can be copied and implemented in the E-bike design to ease the design process and ensure the effectiveness of the final design.

The battery is to be intuitively (dis)connectable to the wiring routed through the empty frame volume above to allow for ease of battery removal. In addition, the internal system is to be protected from debris, rain, and potential moisture from the battery. A sealing plate, e.g., as visualized in 4.5.1, *Concept 1: Module removal through the battery slot* is to be located underneath the battery to seal off the base-tube volume from the downtube volume.

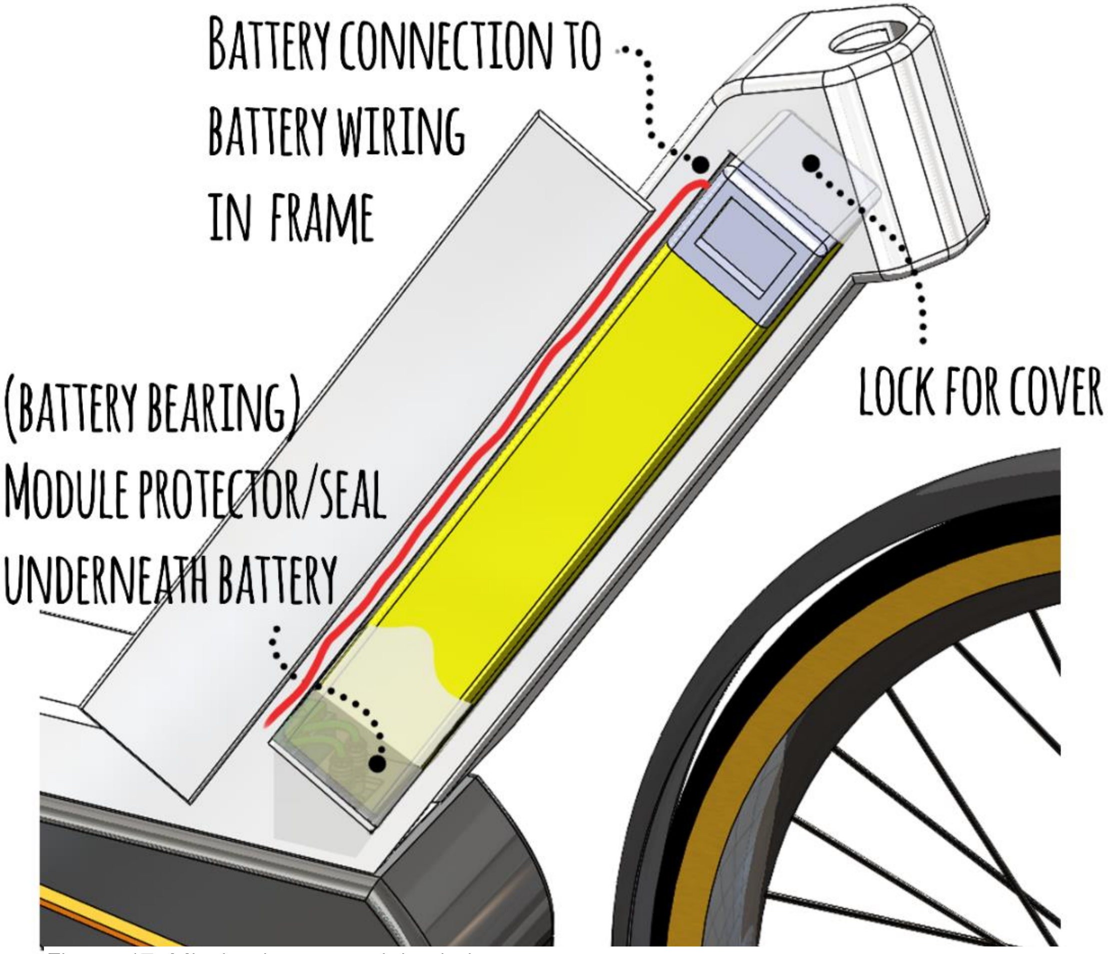


Figure 47: Missing but essential solutions.

5 Evaluation

Discussion
Conclusion
Recommendations
Reflection

In this chapter, we discuss the project results concerning the initial project brief. We conclude on the project and formulate a set of recommendations to help the company realize a feasible final E-bike design.

5.1 Discussion of the project

The initial design brief revolves around the design of modular interfaces to realize their circular E-bike platform envisioned to be usable by all fleet-owners.
From the analyses, we concluded that the E-bikes' problem-solving ability is vital for inducing common fleet-owners' interest in the circular E-bike platform in the first place. Therefore, we revolved the design specifically around modular solutions that solve common critical problems for fleet-owners. We discuss the implications of the proposed final modular concept design on the E-bike platform that the company envisions. We discuss the single-frame design, and the specific focus on modularity.

The single full-frame E-bike design

The proposed E-bike concept enables the total cost of E-bike ownership reduction and sustainable business practice for fleet-owners. However, it dissociates from the modular the company platform as envisioned by the company by its implementation of a full-frame in the final E-bike design.

The implication of the full-frame design is the lost option to customize the front and rear frames separately. The full-frame results in the lost ability to radically alter the E-bikes' functionality, e.g., alteration into the envisioned cargo bike. The described loss of function alteration is perceived to be an acceptable trade-off. A specific functioning bike, such as the cargo bike, is likely to serve only a small percentage of the total E-bike needs. At the same time, the cargo-bike requires alternative frame characteristics such as a significantly more robust base frame to endure high carrying loads. The cargo-bike option could, therefore, have an undesired impact on the more-widely usable frame design in terms of mechanical requirements, frame robustness, weight, and ultimately costs. At the same time, the customized frame halves have low, to no, end of life value relative to a simple, robust, and timeless E-bike full frame.

The proposed full-frame E-bike design has implications on the usability of the concept by different fleet-owners. Just like the Mo-bike does not serve all users of different regions equally, the single E-bike concept is likely not to be able to serve all different fleet-owners equally.

A typical quote used in bike design: "Light, strong, cheap – pick any two" Keith Bontrager – bike designer and former president of Trek Bicycles, implies that bike design decisions always come with trade-offs. The robustness of components often goes at the costs of user-comfort, e.g., airless rubber Mo-bike tires reduce riding comfort, and a heavy frame reduces acceleration. A heavy E-bike requires better performing E-bike components to sustain speed and achieve the same range as a lightweight bike.

The required E-bike characteristics differ per fleet-owner based on their targeted end-users of their bike and their market strategy. Shared bike companies, in the current micro-mobility market, rely on consumer-accessibility of their bikes and are used for last-mile transport. The fleet-owners employ as many bikes as cheap as possible to win market share. In contrast, personal owned lease bikes are used to everyday long-distance commuting. They are subject to a relatively enhanced feeling of ownership in relation to a full-shared bike. The personal lease bikes can likely be less robust, are to be more comfortable, and can be more costly relative to the shared E-bike.

We incorporate many general solutions within the final E-bike concept that can be adjusted to the final specific fleet-owners' needs. Alteration of individual components implemented within E-bike, such as better quality tires or a more ergonomic saddle and handlebar, can further enhance the bikes comfort whereas needed to fit particular fleet owner's desires. Therefore, in theory, the concept can be optimized and employed by a wide variety of different fleet-owners. A single final E-bike frame designed for common usage, however, is likely to not be usable at equal satisfaction by all different fleet-owners.

Modularity as a panacea

We present modularity as the main driver to reduce the total cost of ownership. Besides, we present modularity throughout this project as 'the' solution to enable a circular end-of-life purpose. Therewith, we present modularity almost as a panacea to tackle all identified profitability and sustainability issues of fleet-owners. We must consider that modularity can have negative implications on the final product as well. We must consider these potential implications when we implement modularity is in the final design. We identify the Rigidity and costs of a modular system as potentially harmful to the future viability of the final concept.

The rigidity of the modular system

We must take the considerable rigidity of a modular system into account when implementing modularity in the final E-bike design. The rigidity of the modular system is, ultimately, the biggest downside to product innovation. Once a modular system is deployed, interface standards are difficult or impossible to adjust without a complete alteration of the system. Pre-determined aesthetics and standard interfaces may imply that changes are only possible on module level, which means that the entire product architecture becomes very static. This forces designers to conform to the standardized interfaces and usage of existing modules. Usage of existing modules limits creativity and results in reliance on existing modules, leading to an overperforming system (Ulrich & Tung, 1991). An essential interface alteration, e.g., a new connector required for the functioning of future modules that are critical to the E-bikes' function or a need for architectural innovation, could mean that the modular structure becomes obsolete.

The rigidity of the modular system may result in companies not being able to react quickly to continuously changing demands, which decreases strategic flexibility as it reduces the company's ability to respond to continuously changing standards (Boer & Hansen, 2013). If we introduce the modular system in the wrong market stage, the product could end up completely obsolete, which is precisely the opposite of what we try to achieve within this project. The modular system should, therefore, be designed around a substantiated forward-looking perspective in terms of modular architectures and technological advances of modules (Arnheiter & Harren, 2006). We should significantly focus on predicting the advances in the market before employing the final design to reduce the risk of an obsolete system.

Unexpected costs of the modular system

We have to consider that trade-offs potentially accompany the modular system that we envision in terms of unexpected product costs and even unexpected environmental impact. The repair method of entirely replacing complete modules when only a single component fails requires complete spare modules that individually integrate many components. Therewith, a large number of duplicated components are needed to complete the spare modules that sit idle on the shelve, waiting to relieve the used faulty modules from the E-bikes. The required number of duplicate components enhance the required total number of components within the system dramatically. Also, whereas we can locate all components in an integral system within a single housing, e.g., the E-bike frame, all modules in a modular system require separate sealed housing for protection during transport and to sustain the positioning of their internal component. The separate module housings add to the total number of components within the E-bike product-service system. The need to produce duplicate components to be integrated within spare-modules goes at the costs of raw material and energy and adds costs for the fleet-owner.

A final unexpected implication of modular upgradability is its potential to increase the environmental impact. This impact is a result of the accelerated obsolescence arising from the more frequent introduction and replacement of modules (Agrawal & Ülkü, 2013).

Take-away from the discussion

We have to substantiate a target group and market for future concept development and for final implementation of modularity in the E-bike to ensure its viability. We need to minimize the risk of future obsolescence of the complete modular system and minimize the costs of the product-service system.

5.2 Conclusion of the project

With this project, we aimed to design a modular system to help the company realize a viable circular E-bike concept. We followed a top-down design approach. We started with the design of durable and aesthetically feasible E-bike architectures based on specified modules that enable optimal module accessibility. Subsequently, we designed interfaces to fit product architecture concepts. The design process resulted in a final concept vision and design of a modular system. This modular system can be integrated within the E-bike design to reduce the total cost of E-bike ownership for fleet-owners.
Moreover, the modular system, in combination with the product service-system, enables fleet-owners to run sustainable business operations. We incorporate a variety of design principles that solve common critical problems for different fleet owners. We, therefore, consider the proposed modular system as the key selling point of the final E-bike concept. We envision the proposed modular system to be the fundament of the final circular E-bike design and recommend that the company revolves the rest of their E-bike development around it.

In this final chapter, we shortly review the main insights from the analyses of the fleet-owner problems and modularity and conclude on the final design solutions. We conclude this section with recommendations for the company to realize a viable and profitable circular E-bike concept for fleet owners and the company in a manner that reduces the end-of-life waste of shared E-bikes.

5.2.1 Analysis

In the problem analysis, we identified that the key-problems of fleet-owners lack of profitability and the unsustainable character of their shared E-bike operations. In the modularity analysis, we identified the manner of implementing modularity to solve the fleet owners' problems. We elaborate on the main-insights of both analyses.

Insights distilled from the fleet owner problem

Many different fleet owners are competing within the shared E-bike market, and they employ similar business models. The fleet owners commonly suffer from high operating costs and require sustainable E-bike solutions to be able to meet regulations and to establish a positive brand image. The fleet that can ultimately achieve low-cost operations and establish a positive brand image are the ones that could outperform their competition, which pleads for the employment of the circular E-bike. The micro-mobility market is growing fast, and shared E-bike mobility is destined to stay, which makes reducing the total cost of E-bike ownership and enabling sustainable business operations for fleet-owners of significant importance. A durable E-bike design with a circular end-of-life purpose is required to solve the common critical problems of the fleet owners.

Modularity insights

A durable and future robust modular E-bike design could sustain value in a circular system and enables sustainable business practice for fleet owners.
E-bike durability reduces upkeep frequency. Durable design is achievable by the quality of the component and interfaces. Modularity enables the exchange- and interchangeability of modules, which are critical enablers for re-usability and repairability of the E-bike. Accessibility of modules and decomposability are key necessities for the degree repairability of the modular system. We could enhance the repairability by minimizing the number of interdependencies between the modules combined with accessible, easy separable interfaces.
The boundary condition for long term circularity is a future robust design. Future robust design ensures the desirability of the product over time. It is a precursor for re-use of the E-bike. Future robust design results from practical function combined with timeless performance and aesthetics of the E-bike. The aesthetics and functionalities of the modular E-bike are to be kept at a base level, and module exchange is to allow for repeatable functional and aesthetical customization of the final E-bike over time.

5.2.2 Design

We have designed a modular system to reduce the total cost of fleet-owner E-bike ownership, and that enables fleet-owners to run sustainable business operations in combination with the product service-system. We can integrate the modular system within the circular the company E-bike concept. With the modular system, we propose solutions for the circular E-bikes' architecture in combination with interfaces that allow for a durable E-bike that enables feasible long-term re-use and repair. The modular system design is in a highly conceptual stage but provides the working principles needed to solve common critical fleet owners' problems. The proposed principles tackle the most significant common problems for fleet owners. However, they require more specific decisions and design efforts for effective implementation in the final E-bike design, and to achieve a realistic final E-bike design revolved around the modular system.

5.2.3 Recommendations for the company

We distilled a set of recommendations from the project that could help the company in realizing its circular E-bike. The recommendations focus on the concept target group, future concept directions, and the scale of the project.

A specific target group

In this project, we propose a full-frame bike design that comes at the expense of the platform that the company originally envisioned. The platform, as envisioned initially, might be better able to serve a wider variety of fleet-owners through its extensive customization options. We decided on a modular E-bike with fewer customization options to reduce product complexity, costs, and enhance the accessibility re-use through single full-frame design.

The further development of a single frame E-bike usable by all fleet owners must be (re)considered by the company. Different fleet-owners serve a variety of purposes and end-users. They likely do not want to compromise on the characteristics of their employed E-bikes. A single E-bike design revolving around the proposed working principles is likely to result in an E-bike design that could serve the variety of fleet owners at a satisfactory level but serve none of them optimally. We recommend that the company defines a specific end-user before starting to develop a single circular E-bike to avoid a common inadequate fit of the final design to all fleet-owners.

If the company decides to develop a single-frame E-bike usable by all different fleet-owners, the critical question they need to answer is whether there is a viable business case within the current or future market. Generally, if a single product solution that solves all problems exists, often there are individual solutions that perform the separate functions more effectively. In this market, a one-E-bike-fits-all approach will inevitably lead to fleet owners having to compromise on their desired E-bike characteristics when deploying the single E-bike solution. Ultimately, a design focus on what is specifically needed by the individual fleet owners is of primary importance for the successful employment of the E-bike. The company can validate whether the project has potential in its current form by identifying the needs of the Fleet-owners and by assessing if the circular bike can realistically serve those needs.

A better fitting final design is achievable by deciding on a more specific target group. In the end, the strength of design is about emphasizing with the target group to find the right solutions. By identifying the fleet-owners that benefit the most from the modular E-bike, the company can focus the design efforts in the right direction and create a more viable business case for its concept.

The business case around the circular E-bike should be the first step to steer and optimize the potential of future design efforts. The final business case should incorporate a clear vision as well as design requirements that fit the target group. The identified fleet owner(s) that best fit the concept should be involved in the circular E-bike design to ensure the realization of fitting E-bike solutions. We consider optimal fitting E-bike solutions essential important for the long-term viability of the final concept design and, thus, for the profitability of the company and their desired waste reduction.

Future concept directions

We consider a sustained focus on the problem-solving ability of its E-bike concept for its intended target group as most important for the company throughout the further development of their circular E-bike concept is. The rigidity and the costs of the modular system, as explained in the discussion, should be considered. Naturally, the concept should be verified and iterated upon by real-life testing with the final user group. Further development of the modular system can take two shapes for market introduction: as part of a complete E-bike or as a separate offered E-bike module.

- The modular system as part of a complete E-bike offering

We focused on the integration of the bus-modular frame into a single E-bike offering throughout this project. A full E-bike solution allows for a minimally complex and re-usable E-bike. Still, it limits the E-bike customization options for individual fleet owners. A full E-bike solution requires the company to focus the E-bike design on a specific target group to enable the right fit. The offering of a complete E-bike as envisioned in the concept vision helps the company to optimally sustain the control over the circularity of both the basic E-bike and the modules.

- The modular system as a separate module offering

the company can also offer the bus-modular frame as a separate E-bike platform component. The separate offering allows integration of the modular system in an E-bike platform, as the company originally envisioned. The bus-modular frame can also be sold separately as one of the frame components to be incorporated within

the E-bike designs of other E-bike companies. Separate selling of the system enables full E-bike customization combined with the benefits of the modular system.
Usage of the bus-modular frame within both the platform as well as by other companies in their E-bike designs allows for wide-scale use of the same functional modules among different fleet-owners. This practice enhances the scale of economies of the complete modular system and while sustaining the circularity of the modules. It could, however, compromise the re-usability of the frame due to the risk of specific non-future robust frame designs.
The biggest perk of offering only the modular system is that it allows the company to concentrate the design focus on the problem-solving-ability of its concept for fleet owners. Narrowing down the focus helps the company in the optimal allocation of their limited resources and allows the company to achieve a sophisticated product as soon as possible.

The single module could result in broader usability by many different fleet owners and a more sophisticated product in the short-term. It could, however, lead to reduced re-usability of E-bikes, which in turn compromises the circularity which the company strives to achieve. The full E-bike solution allows for better re-usability. Still, it must target specific fleet owners, which, in turn, reduces the broad employment options of the concept. Both paths could ultimately enable waste reduction, which the company aims to achieve. The business case is to be leading.

With the company and the current stage of both the concept and the market in mind, minimum viable product (MVP) could be an interesting development technique for the company. MVP is defined by Eric Ries -writer of the lean startup, as *a product which allows a team to collect the maximum amount of validated learning about customers with the least amount of effort.* In MVP, a new product is developed with sufficient features to satisfy early adopters. The final, complete set of features is only designed and developed after considering feedback from the product's initial users. With MVP, the company will not waste any time on anything beyond the bare minimum and build every other feature over time as they assess the customers' wishes and preferences as they start using the product. (*What Is a Minimum Viable Product (MVP)? - Definition from Techopedia, 2020*)

The project scale

It is easy to underestimate the vast scale of this project. It is not merely designing an E-bike based on the incorporation of existing components offered by other companies. Although the company aims to incorporate commodity parts, the frame, as well as the main modules incorporated in the companies' circular E-bike, have to be specifically designed from scratch. The individual modules are perceivable as products by themselves. This project should not be taken lightly given the number of required and interdependent sub-solutions combined with the design of the multitude of complex modules.
The described project scale, combined with limited time and resources of the company, is likely to become a challenge in making their original envisioned circular E-bike platform a reality. A focus on a specific target group and the problem-solving ability of the concept narrows the focus down to only the needed E-bike features, which helps in the optimal allocation of the design efforts.

We would suggest that the company forms a clear concept vision that revolved around a well-defined target group to guide the future development of the concept. After that, we would recommend partnering up, especially if 'purpose over profit' is the most crucial aspect of what the company is trying to achieve.
There is a lot of target group exploration and design work to be done for the viable realization of the concept. This exploration requires a great deal of emphasis with the right target group, and the company has the resources to do so. Partnering up allows the company to focus on the design of an optimal E-bike to fit fleet owners' needs and achieve their goal of waste reduction. The engineering of the designed modules could be outsourced to the partner to help realize the concept sooner.
Partnering up could speed up the market introduction. The sooner the concept becomes a reality, the sooner it can start shaking up the existing market and begin to reduce E-bike waste.

5.3 Reflection

In this section, we reflect on the project. We split the reflection into two parts: a project reflection and a personal reflection.

5.3.1 Project reflection

The project has been a really interesting challenge. Designing for circularity is something that got my interest, and I am happy that I finished my studies on this subject. I am glad that I have been able to combine this interest with the design of a relevant product. I have always enjoyed cycling but was not familiar with E-bikes. I always perceived an E-bike as a product that is mainly made for older people to help them get around. This, however, is definitely not the case. I much enjoyed riding around on an E-bike, and I see how it can change the future of mobility in an extremely positive manner. Personally, I would love to get around on an E-bike in the future, and I believe this inevitably will happen. I might just be my own E-bike design, who knows?

Overall, The project itself has proven more complicated than I initially expected. There have been various reasons for which, for me, the most important one is the fact that this project is individual. Throughout my studies, I have always been working on group projects, which I did really enjoy. Executing a design project alone could work for some people, but for me, it seems not to work so well. zl-n the end, I think good design is a team effort, and working together makes a significant difference in making decisions more effectively. I like the energy of a group project, the mutual interaction, the great ideas that suddenly pop up, and the satisfaction of delivering together. Luckily, most design projects are team efforts, as I cannot wait to start designing in a team again.

Throughout the project, I did feel like I was on my own. I did not expect this initially. I feel like the 'social distance' from the TU Delft, and the company really got me. The TU Delft had to cope with the corona hectic, which made direct contact with my supervisors difficult and compromised my typical working structure. I have always been studying at the university, working from 9-5, after which I could close my laptop and leave my work behind. For questions, most often, I always just passed by the person I needed to talk to. Having to work from home stopped me from being able to let my studies go, which resulted in pretty hauling study days and negatively impacted my assertiveness. Everyone had to cope with the sudden social distance and corona fuss, which makes communication errors understandable. Still, I feel like my team helped me throughout my project and supported me much when needed. Looking back on the project, this is something I am grateful for.

Throughout this project, I have mostly been struggling with finding a suitable project focus. The project brief from the company has been extremely focused explicitly on designing interfaces for their circular concept. I wanted to revolve my design as much as possible around this project brief to be able to help the company realizing their idea. I tried to help the company with their concept and create realistic and well us-able results. I had a difficult time making it into a good university project since TU Delft does not allow for an 'embodiment' project. It would have been too much of an AED project. For me, AED was my favorite course, and I did not expect an AED type of project to not fit a graduation project. Generally speaking, I found it a bit difficult to define the right link between the requirements of the TU Delft and what the company was expecting from me.

I wanted to start designing as soon as possible since designing is what I really like. However, I am kind of a perfectionist. This Perfectionism made me research in all areas and writing down everything I found consciously. In the end, I have been writing at least another report, of which none is in this final report since it just was not relevant. However, I have been learning a lot about good report writing. I have been rewriting my report structure multiple times. I think this is because I really like designing and that I have been focussing on creating instead of writing most of the time during the group projects. In the end, I should have made a better plan before I started to do research and write down only the relevant findings. This would have saved me a considerable amount of time. In the end, I put more research into how to properly structure a report and how to write more consciously. I do feel satisfied with my progress in writing. I do, however, want to emphasize my extreme appreciation for Ruud for helping me and being so involved with everything throughout this project. I learned a lot from the critical remarks, and I do think it helped me with the structure, clarity, and consciousness of my writing. Ultimately, this is something I will benefit from for the rest of my life.

Looking back, I should have gotten more familiar with graduation in general, so I could have been better prepared for what I was getting myself into. I just stepped into the blue and went with it, which resulted in a lot of uncertainties throughout the project. My project was not without its hurdles, but looking back from where I started, I am content with the results of both my final report and the design process. My design solutions, however, do feel generic relative to what I have been capable of throughout my studies. On the other hand, the focus on a more conceptual design does feel fitting to the company and the current stage of their project. I have learned enormously on how to approach a design project, learned a lot in terms of visualizations and necessary design steps. In the final stage of my project, I got to the point where I was actually happy with the results and motivated to finish my project.

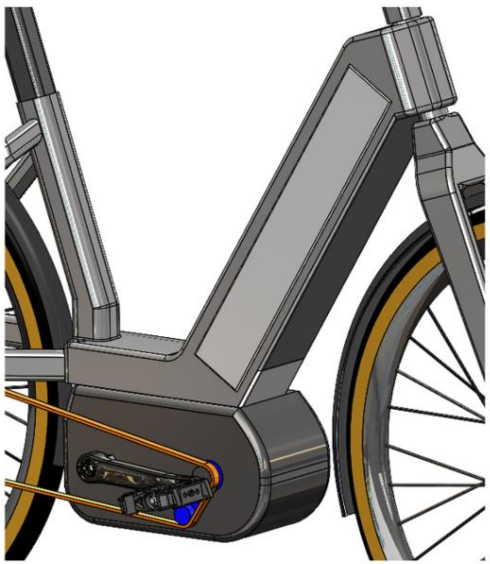
5.3.2 Personal reflection

I have been reflecting a lot throughout my project. I wrote a really extensive reflection before the mid-term. I keep this one short. This project has been a rough but mostly an extremely educational ride for me. I did my studies well, I completed my bachelor with honors, my master went right as well, and I had a great time designing at npk. Still, this project seemed to be more difficult than I would expect it to be. I have been working extremely hard, but I felt like I was not getting the results I was working for. This feeling of un-achievement made me look in different manners, which got me to the solutions I needed. I had some bumps, and I had some doubts about persevering in this project; however, I am glad I put through. This project has been the most learn full and probably the most valuable experience of my studies.

The things I have been good at throughout my studies were always the more technical parts, simulations, and the materialization involved with design. This project was of a different kind. This project turned out more conceptual, but as my primary focus was on providing the right direction for the company, I feel like the project is not missing the board.
The good thing is that even though I did not use my more comfortable skillset, I did not lose that skillset either. The best thing is that I actually learned to work on a project in a different way and became better at designing head to tail. In the end, failing made me always learn from the most. When I could do this project over, I would take a completely different approach. This, in the end, is applicable for all my future projects.

Therewith, I got a lot out of this project. All in all, I think my project can really contribute to the development of the circular E-bike that the company is working on. I could not say this for many projects that I have been working on during my studies, but I am really confident about the future feasibility and viability of this project. I hope from all my heart that the company achieves its goal and puts this bike on the market.





Appendix

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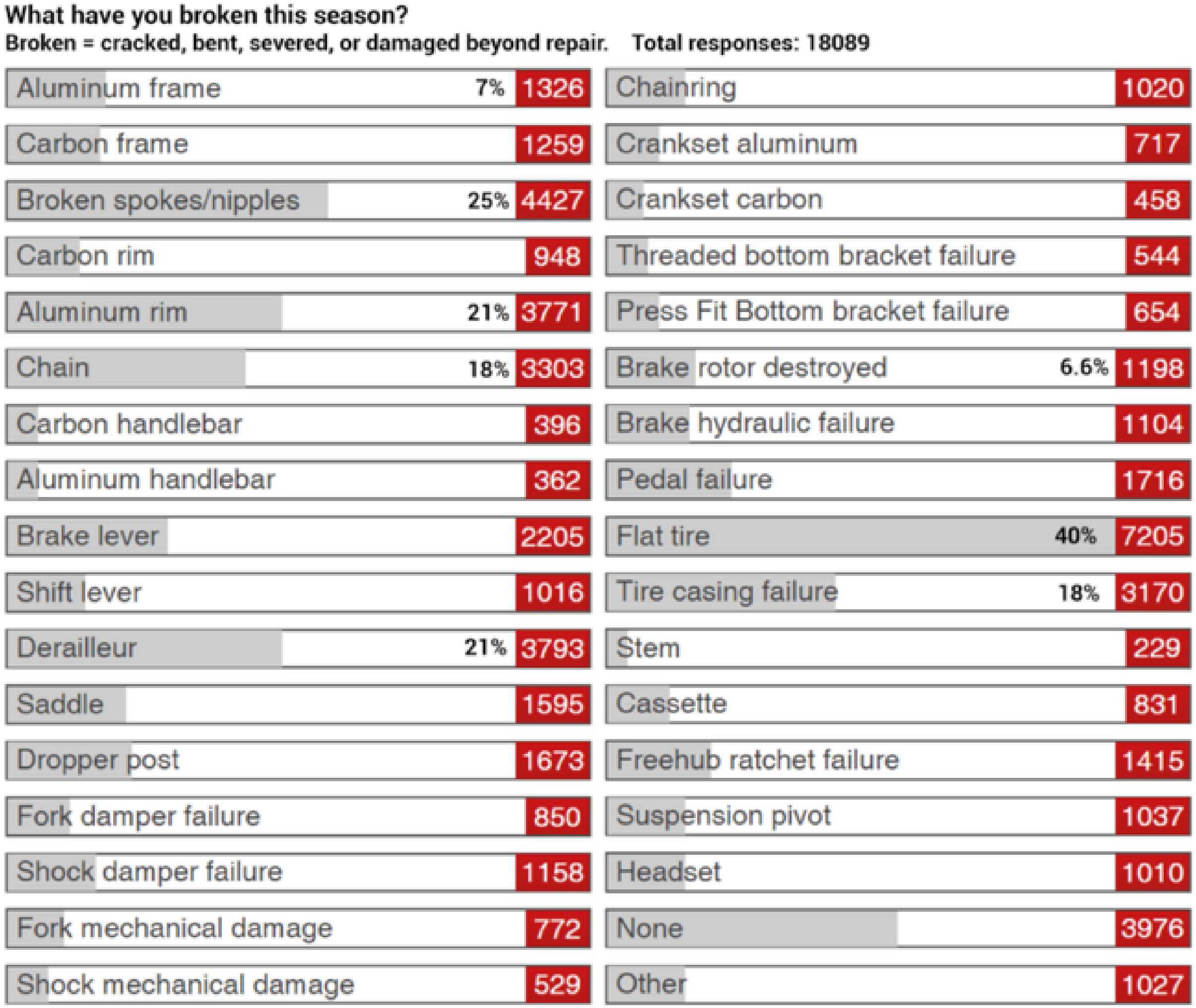
6.2 (E)bike Component failure and the module requirements.

Traditional bike component failure

A statistic on mountain bike failures has been found on the Pinkbike bicycle forum. Mountain Bikes differ from urban bikes in usage: they are built to endure rough use on off-road and downhill trails and must resist high usage forces. The functional components implemented in mountain bikes are no different than urban bike components. Still, they differ in product characteristics such as enhanced robustness and performance needed for more challenging off-road purposes.

It is interesting to identify which traditional bike parts are most likely to fail under extreme usage conditions. Even though the mountain bike is composed to endure heavy usage, it is still expected to fail at some point during usage. Even though the urban E-bike is not likely to be used in off-road scenarios, similar failures as identified with mountain bikes are assumed possible with E-bikes when used near the limits of their functional capacity since it incorporates the same traditional bike components.

Tires seem to be the most significant problems: broken spokes (25%), broken aluminum rim (21%) flat tires (40%), and tire casing failure (18%) are highest-scoring faults and are all sub-parts of the tires. The chain is also scoring relatively high on the breakdown, and so does the derailleur and the brake lever of the mountain bike. Replacing a chain and brake lever both requires servicing/adjustment and testing of the brake system and drive system after re-mounting.



Mountain bike component failure poll (*EndlessSphere*, *2018*).

E-bike component failure

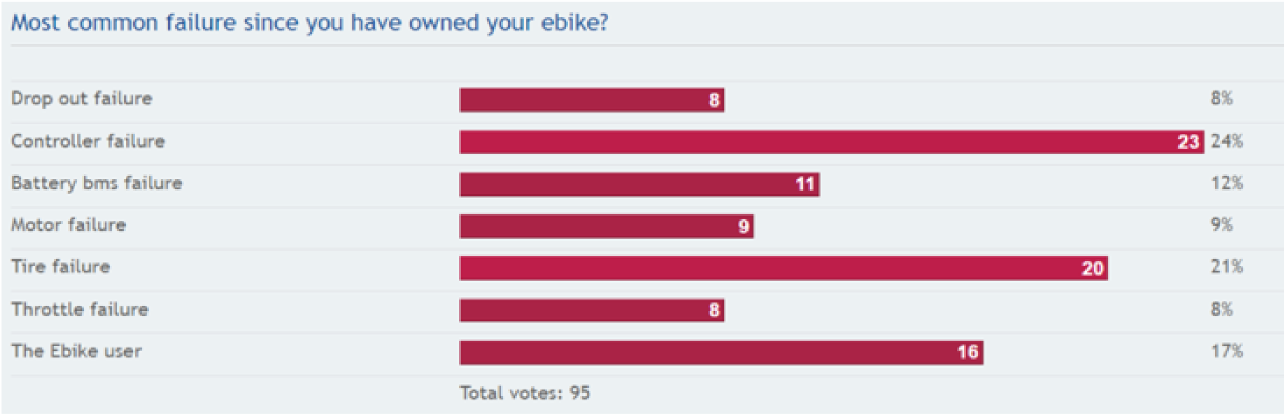
Statistics on E-bike failures and the least reliable component perceived have been found on the endless sphere electric vehicle forum. The primary and most critical E-bike components are listed.

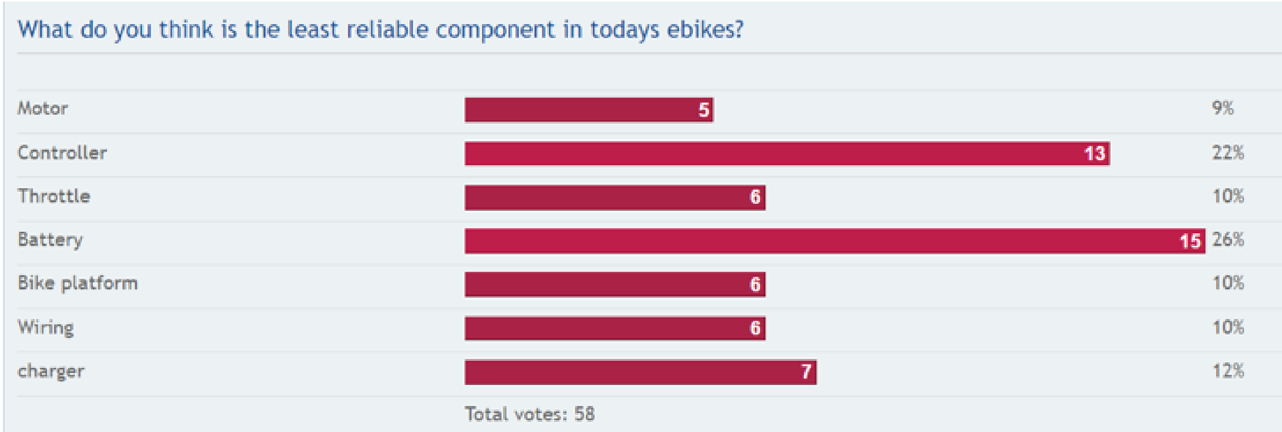
Both statistics show the motor controller as the most critical component in the E-bike system. Tire failures are, like in the mountain bike, common problems for E-Bikes as well. Batteries are perceived as unreliable. From the E-bike, separable Li-on battery packs require incorporation of a bms (battery management system) that manages the charging and discharging of a li-ion battery. The bms and protects the battery and prolongs the battery life however when it fails, the battery is not usable anymore, which poses another risk to battery failure together with deterioration over time and resulting battery capacity reduction.

Failing of both the frame (drop out failure means frame breakdown/bike platform) and the motor occurs less often but are assumed to be high impact problems due to their initial purchase costs, the importance of function to the E-bike and their repair costs.

Other failures occurring are throttle failures and wiring reliabilities. The throttle is connected to the motor controller through electrical wiring thus, problems could go hand in hand. The E-bike users driving behavior, or a faulty charger are external problems that could lead to breakdown or un-usability of the E-bike.

E-bike component failure poll on endless-sphere (electric vehicle forum) E-bike component reliability on endless-sphere (electric vehicle forum) via (*Pinkbike Poll: Who's Breaking Bikes These Days? - Pinkbike*, *2019*)





6.3 The modules

The modular E-bike is separated two subsystems: the (modular) frame and modular drivetrain. Both sub-systems consist of multiple modules that have been pre-determined by the company.

The modules are currently being designed by the company and are based on identified problems with their own E-bikes offer, their experiences with the practice of refurbishment of bike fleets, and their interviews with fleet-owners. Modules are basically defined by their separated specific functions.
Separating functions in modules allows optimized ease of exchange/interchange of single parts to ease maintenance/repair and to enable the upgradability of the system through replacing individual modules. The modules are assumed to be a defined variable based on their current state. *With the initial design of the modular system, the modules are likely to be (minimally) adapted to the final interface design to be able to fit within the modular system design. Naturally, the modular system should allow for adaptation to the final module design as well.*

The final module design is currently being defined by the company. Some details on the module design have been decided on in the current stage. The modules and the characteristics that have been decided on are described in this section. The product architecture is top-down designed around the general characteristics of the modules that have been defined by the company.
The location of modules within the drivetrain is not fixed within the drivetrain product architecture yet. Still, their locations are restricted by specific module functioning, e.g., the brake will be positioned near the rear axle. Additionally, external forces exerted onto the modules and need for electrical connectivity depends on the modules functioning as well and define the main interface requirements.

Module variation

The present and future variation possibilities of modules are necessary to understand when designing a future robust modular system. It is important to analyze how modules can vary and will change due to technological progress to develop a realistic and future proof modular structure, including interfaces and aesthetics, that complements future module variations.

With the main modules not being defined, the module variation is assumed to be of similar character to the modules which the company is currently working on even though their performance will be different. Design of the product architecture without modules and module variation being fully specified will lay restrictions on the design possibilities of future modules.

Subsystem and modules	Function	Main reason for modular separation	Character/Requirements of module
Frame Front Frame/rear frame or single frame contains battery, brake/gear cable, electrical wiring.	Bearing structure Facilitates addition of other parts/modules, function differentiation of bike.	Functional differentiation of the E-bike	Stiff/strong, robust, Space reservations for attached parts Connections for to be fitted parts
Modular drivetrain *Bus modular structure that contains motor, module controller module, SMART module, brake module, rear wheel module*	Manages E-bike functionality Provides forward inducing power	Contains complex parts, forms the base of optimised product life cycle by allowing optimal and minimal assembly/disassembly whilst maximizing the long-term value of parts within the sub-system.	Enclosed, theft/vandalism proof, Aesthetically coherent to frame decomposable, hierarchical composition, standardized interfaces, fits bike geometry/comfort standards, able to endure usage forces

Overview of modules within the scope

The modules incorporated within the drivetrain, their function, reason for the modular split, and their character/requirements are described in table x. the company focuses on the specific rear-design of the E-bike; thus, the brake and rear wheel module are left out of the project scope. The display module is of similar character as the motor controller module.

The company is developing the rear wheel and brake solutions and this. Their solution will be directly implemented into the modular system thus there is no individual focus on the brake and rear wheel module throughout this project. Rear of the drivetrain system is currently a 'black-box'.

FMEA to define the critical components/modules

Module	Function	Main reason for modular separation	Character/Requirements of module	Module shape / connection focus
Frame Wiring, connections.	Structure and shape of the E-bike	Customizability for different user groups	Stiff, strong, customisable in terms of aesthetics.	Shape: Undefined Mechanically connected
Battery	Providing power to the E bike	Separate function and ease of exchangeability.	Well protected against theft, accessible for the E bike user, connected to energy needing modules.	Shape: Rectangle block 300x60x60. Electrically connected
Bus-module Platform, wiring, connections.	Facilitates single independent connections of parts/modules within drivetrain. Possible bearing/supporting structure of rear wheel/motor module	The base structure modular system. Allows enhanced performance of assembly/disassembly by offering the possibility of connecting of the modules through single connections.	Supporting, Provides fitting of modules, Electrical connectivity. Properly fixated to frame.	Shape: Undefined Mechanically connected Electrically connected
Motor-module motor, gear-hub, bottom bracket, bike pedals/crank?, housing	Provides propulsion power aid to user.	Complexity and high value of internal parts, the 'drive' function of part combination, similar stiffness/strength requirements of module housing.	Fixated to endure max. force, Electrical connectivity. Stiff/strong housing, connection to Frame/drivetrain platform, enclosed	Shape: Block with a two sided outgoing axle (bottom bracket) and a one side outgoing axle (gear hub) 310x160x150 Mechanically connected Electrically connected
Controller-module Controller, housing, wiring	Controls the motor module	High risk module: breaks down often. Allows easy replacement without replacing the motor module.	Directly connected to motor Enclosed	Shape: Block 90x60x30mm Electrically connected
Belt· Belt	Translates energy from bottom bracket to rear wheel axle.	Chain/belt maintenance requires fine tuning. The belt module allows for optimal ease of repair/maintenance	pre-tensioning possibilities Stiff/strong housing	Shape: Single belt Mechanically connected
Aesthetical modules Various	Differentiation of looks, match to E-bike look to frame	Has to be adaptable to different fleet owners needs/preferences.	Clean fit, stiff/strong enough to endure forces wherever needed.	Shape: Undefined Mechanically connected

Optimal longevity of the modular system within the envisioned circular product-service system is what the company aspires. Sustaining the value of the modules and materials within the circular system is the goal.
It is interesting to define the risk of breakdown, impact of the breakdown of individual modules on the performance of the rest of the system and whether users or fleet-owners can identify faults that could result in breakage in time either during usage or during preventive maintenance. It is important to identify the part(s) that induce the highest risk to both part specific devaluation and the extended devaluation potential of the full system. The critical parts require more intensive monitoring, servicing, and/or protection than other parts whilst being most easy examinable, reachable, and/or replaceable within the system. The initial design focus should be on integrating the critical modules in a risk-minimizing manner that fits in terms of desired reachability based on the needed frequency of maintenance and replacement. A method to identify the high-risk modules is a failure mode and effect analysis (FMEA). The FMEA identifies the severity of a failing component, the frequency in occurrence, and the risk of not detecting the failure in time. Multiplying the scores in each segment per module translates in a hierarchy of critical modules of which the highest-scoring module is the most critical in inducing breakdown risk of the system.

Breakdown risk of components within the system.
The breakdown risk of the modules within the system has initially been provided by the company and has been verified through the statistics. The breakdown risk is traced back to a variety of different problems, faults or breakdowns that can occur during usage of modules and can be results of natural wear or resulting of bad design, lack of maintenance, wrongly installed and/or badly adjusted modules. The greater the number of components, interdependencies, and the (human performed) steps required to assemble and/or adjust the module, the higher the risk of missteps in the process and the higher the chance of failure of the module generally becomes. The scores range is set on: *1: relatively low chance of breakdown.2: Breakdown may occur. 3. Breakdown occurs almost certainly.*

Effect of the component failing on system performance
The severity of the failing component is assessed by the effect on the performance of the E-bike system. Performance goes together with E-bike value and user-comfort and is there with an interesting scale to measure with. Failing parts that significantly compromise the systems' performance must be addressed asap and with sufficient ease. It must be noted that all modules that are implemented in the drivetrain are critical for the system to function, which results in high average scores per module on severity. The score range is set on: *1: No significant effect on system performance. 2: Degraded system performance. 3: Critical/heavy reduced system performance, alters the function of the system. 4: Catastrophic degradation of system performance, loss of the full system or linked component.*

The risk of not detecting a failure of fault in time
In time detection of faults within the system combined with preventive maintenance/replacement could reduce the risk of full breakdown of components due to normal wear, a wrongly composed system or bad adjustment of modules. A condition for in-time action is in-time detection of faults combined with discontinued usage of the E-bike to reduce chances of full break down of components. The E-bike should be serviced as soon as possible when slight performance alterations (even when not significantly impacting the riding experience) occur for optimal longevity of the implemented components. When the bike starts to perform or behave significantly different during usage, wear or breakdown could already have had its impact and it might be already too late for the components to be saved.

Faults could be detected by experienced mechanics or even the E-bike user (worst case scenario); however, faults within complex and enclosed modules are still difficult to detect/discover.
The risk of not-detecting faults (by humans) ranges from: *1: Easily able to detect faults. 2: High chance of fault detection. 3: Unlikely/Difficult to detect faults. 4: (Almost impossible) to detect faults without specialized tools.*

Subsystem	Breakdown risk of component	Severity of breakdown: Effect of the component failing on system performance	Open/enclosed module and complexity of module	Risk of not detecting faults based on occasional physical check.	Risk of not detecting fault with SMART module implemented in system.	FMEA score Bd x Sev x De. Wi - wo Smart
*Battery (benchmark) ** *	*3*	*2. E-Bike will still perform by heavy pedalling.*	*Enclosed and complex*	*4: Impossible without test equipment*	*1: Detects capacity/charging etc.*	*24/48 - 6/48*
Frame	**1**	**4.** E-Bike can not be driven anymore.	Open / simple	**1:** Faults are easily visible on frame	**1:** Detects vibrations/breakdowns	**4/48 - 4/48**
(hypothetical) Drivetrain Platform/base unit	**1**	**4.** E-Bike can not be driven anymore.	Open / Complex	**2:** Faults are detectable even though modules needs to be removed.	**1:** Detects vibrations/breakdowns	**8/48 - 4/48**
Motor-module	**2**	**3/4.** Depending on severity of breakdown. Less if its a small efficiency issue eg. gearing.	Enclosed and complex	**3:** Small (sudden) differences in sound and performance could result in detection.	**1:** Detects even the slightest performance change	**24/48 - 8/48**
Motor-controller-module	**3**	**3.** E-Bike motor is not functioning as desired/at all	Enclosed and complex	**4:** Impossible without test equipment	**1:** Detects performance issues	**36/48 - 9/48**
Belt-module	**1**	**4.** E-Bike can not be driven at all	Open / simple	**1/2:** wear possibly visible on belt/wear along other parts touched by belt	**1:** Detects efficiency/tension	**8/48 - 4/48**
Brake-module	**1**	**4.** E-Bike can not be safely driven	Open / simple	**1:** Wear is visible on brake pads	**1:** Detects mileage → wear down	**4/48 - 4/48**
Rear Wheel-module (air)	**3**	**3/4.** Depending on severity of breakdown.	Open / simple	**1:** worn/soft tires/bent spokes easily visible.	**1:** Detects efficiency/tire pressure	**12/48 - 12/48**
Aesthetical modules	**1**	**1.** No influence on E-bike performance	Open / simple	**1:** wear/breakdowns easily visible	No sensor need	**1/48 - 1/48**
Sensor module	**1**	**1.** No influence on E-bike performance	Enclosed / complex	**4:** Impossible without test equipment	**1:** No data transfer means broken	**4/48 - 1/48**
-module	**2**	**1.** No influence on E-bike performance	Enclosed /complex	**4:** Impossible without test equipment	**1:** No data transfer means broken	**8/48 - 2/48**
Cables/wiring	**2**	**3.** E-Bike motor is not functioning as desired (gear/elektrical) or is not safe to drive (brake)	Open/covered/ Visible / concealed	**2:** Wear and breakdown could be detected by inspecting the cables and connectors.	**1:** non-functioning modules could result from wire/cable breaks.	**12/48 - 6/48**

***: Battery is not incorporated in modular drivetrain but is choses as component to relate other scores to when needed.* *Highlighted are the most critical modules*

Non-enclosed mechanical parts could be checked on wear and performance alterations relatively easily compared to enclosed and/or complex electrical parts however the check still need to be performed. When not implementing a display module that keeps track of module performance and condition: the motor controller, motor-module, battery, rear tire and wiring (in that order) are highest scoring within the FMEA and are therewith most critical in reduced- or failing of E-bike performance.

the company wants to ensure optimal longevity of modules thus, the display module will be an integral part of the system. The display module, logically, reduces the FMEA score per module and, again, logically, induces the biggest reduction in FMEA score for the more complex modules of which physical fault detection was most difficult. When implementing a display module that keeps track of module performance and condition: the rear wheel, the motor controller module, the motor module, the battery and wiring (in that order) are highest scoring within the FMEA and are therewith most critical in reduced- or failing of E-bike performance. display detection is to be implemented for optimal tracking of module conditions thus there's no potential here. The modules have been differentiated in terms of specific functioning thus the severity of breakdown is difficult to reduce. The critical modules however should be the first in line for a redesign that reduces breakdown risk when better E-bike reliability is desired.

(Re)-design of module(s), emphasizing on internal structure/components is what the company is currently working on. The scope of this project lies on implementing the modules into a feasible and realistic product architecture. Low cost of servicing and long-term module value is what is aimed for and can be achieved through modular design with a focus on the appropriate module accessibility and protection.

Accessibility and protection of modules

Apart from risk and severity of module breakdown, modules can be defined by other specific characteristics such as (relative) value, maintenance frequency, theft and vandalism risk. These characteristics define the way the individual components should be located throughout the system so that they can be adequately reached, maintained, replaced or protected in order to minimize servicing costs and maximize long-term sustainability of module value. The frequency of required maintenance and risk of breakdown decides the level of accessibility per module. *Breakdown risk is reduced, and maintenance frequency is provided by the company and assessed on usage-wear, breakdown risk on the failures earlier described and used in the FMEA analysis.*

The (relative) value, theft risk and vandalism risk decide whether the part should be in a well-protected, difficult to access, manner in the system. Accessibility the module and safekeeping of the module thus oppose each other: an expensive module might need to be covered and well protected/connected in multiple ways which results in multiple steps required to reach the module
when needed. Protection thus compromises accessibility. The opposing needs could result in difficulties to optimize the modular architecture for both.

Need for accessibility and protection/robustness against thievery and vandalism are identified below to define parts with critically opposing requirements within the modular architecture. *Relative value, theft and vandalism risk are provided by the company.*

Whilst all modules require a base level of protection to not be stolen and to minimize 'occasional theft'. Modules that should be best protected against theft are the battery and the motor module (score of 2 >). The frame, motor module, rear wheel module and the cables/wiring are to be well protected against vandalism (score of 2 >). Modules that should be optimally accessible are the battery, the rear-wheel, the motor controller module, the brake module and the rear wheel module (score of 4 >). Based on the scores: the brake module and rear wheel should be best accessible for servicing whilst the battery, motor controller and, again, the rear wheel should be easiest to completely exchange due to high breakdown risk. the company aims to replace servicing by switching old modules for 'fresh' modules, whilst refurbishing old ones, in this case all modules that require relative frequent servicing are to be designed as easily exchangeable.

Drivetrain Subsystem	**Functional decomposition**	**Maintenance freq. *A***	**Breakdown risk. *B***	**A+B Easy to reach. 2 = min 6 = max**	**(relative) Value. C**	**Theft risk D**	**Vandalism risk. E**	**C+D+E Need for protection 3 = min 9 = max**	**Verdict**
Battery (benchmark)	*Providing energy to system*	*3 (charging)*	*3*	*6/6*	*3*	*3*	*3*	*9/9*	*Most critical module in terms of reachability and protection*
(modular) Frame	Added functionality, competitive differentiation	**1**	**1**	**2/6**	**1**	**1**	**3**	**5/9**	Not critical in terms of reachability however requires to be robust against vandalism.
Motor-module	High valued, complexity, altering performance	**1**	**2**	**3/6**	**3**	**2**	**2**	**7/9**	Critical in terms of protection
Motor-controller-module	Breakdown risk	**2**	**3**	**5/6**	**2**	**1**	**1**	**4/9**	Critical in terms of reachability
e	Maintenance frequency	**1/2*****	**1**	**2/6**	**2**	**1**	**1**	**4/9**	Not critical in terms of reachability and protection
Brake-module	Maintenance frequency	**3**	**1**	**4/6**	**2**	**1**	**1**	**4/9**	Critical in terms of reachability
Rear Wheel-module (air)	Maintenance frequency, breakdown risk	**3**	**3**	**6/6**	**2**	**1**	**3**	**6/9**	Critical in terms of reachability and requires robustness against vandalism.
Aesthetical modules	Competitive differentiation	**1**	**1**	**2/6**	**1**	**1**	**1**	**3/9**	Not critical in terms of reachability and protection
Sensor module	Added functionality	**1**	**1**	**2/6**	**1**	**1**	**1**	**3/9**	Not critical in terms of reachability and protection

Critical parts in the system

The FMEA analysis shows that the motor module, motor controller module and rear wheel are the most critical within the system in terms of failure risk. The protection/maintenance analysis shows that the motor controller, brake module, rear wheel module requires most maintenance (thus easy accessibility) whilst the motor and rear wheel need to be optimally located within the system in terms of protection.

Modular product architecture design

The initial focus lies on optimal implementation of the critical modules within a well working system that allows for the minimized repair and maintenance effort of these modules. The motor module, rear wheel (connected with the belt) and the brake module are subject to high interdependent forces. A stiff and strong base structure could be designed which optimally fits the said components in terms of function, mechanical endurance and cable/belt connections. The base structure should allow for ease of exchangeability of the critical modules at the same time.
The electronic components, of which the motor controller is the most critical, require electrical connections throughout the system. Their positioning is less critical within the system compared to the mechanical parts due to their functionality and not having to endure forces.
The mechanical system must reserve space for the electronic components to be located within the system and should locate interdependent components as close to each other as possible to reduce in between wiring length.

Design goal

The critical modules in reduction of maintenance/repair costs, and thus cost of ownership, are the motor module, motor controller module, rear wheel module and brake module. the company is focusing on the rear modules (the wheel and the brake) and has envisioned a solution already. These modules will therefore not be the focus of this project. The company's solution is considered to be a 'black-box' waiting to be integrated within the modular system which I will design.

The design goal is to mechanically design the base structure of the modular architecture that properly fits all the identified critical parts. The structure is to be stiff and strong enough to endure the resulting kinetic forces of E-bike usage, whilst allowing optimal exchangeability of the critical modules.
Aesthetics of the design are to be considered and the design needs to reserve space/allocate the electrical modules within the system.

Subsystem	Breakdown risk of component	Risk of not detecting faults based on occasional physical check.	Risk of not detecting fault with SMART module implemented in system.	FMEA score Bd x Sev x De. Wi - wo Smart
Motor-module	**2**	**3**: Small (sudden) differences in sound and performance could result in detection.	**1**: Detects even the slightest performance change	**24/48 - 8/48**
Motor-controller module	**3**	**4**: Impossible without test equipment	**1**: Detects performance issues	**36/48 - 9/48**
Rear Wheel-module (air)	**3**	**1**: worn/soft tires/bent spokes easily visible.	**1**: Detects efficiency/tire pressure	**12/48 - 12/48**

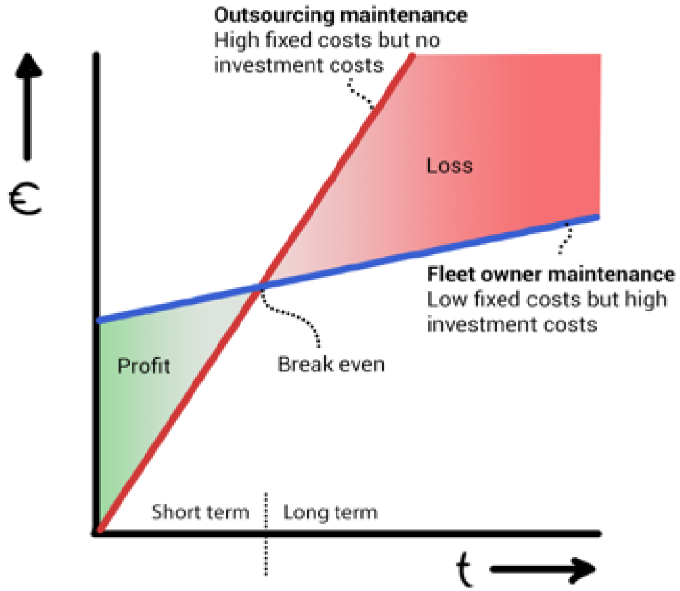
Drivetrain Subsystem	Functional decomposition	Maintenance freq. *A*	Breakdown risk. *B*	A+B Easy to reach. 2 = min 6 = max	(relative) Value. C	Theft risk D	Vandalism risk. E	C+D+E Need for protection 3 = min 9 = max
Motor-module	High valued, complexity, altering performance	1	2	3/6	3	2	2	7/9
Motor-controller-module	Breakdown risk	2	3	5/6	2	1	1	4/9
Brake-module	Maintenance frequency	3	1	4/6	2	1	1	4/9
Rear Wheel-module (air)	Maintenance frequency, breakdown risk	3	3	6/6	2	1	3	6/9

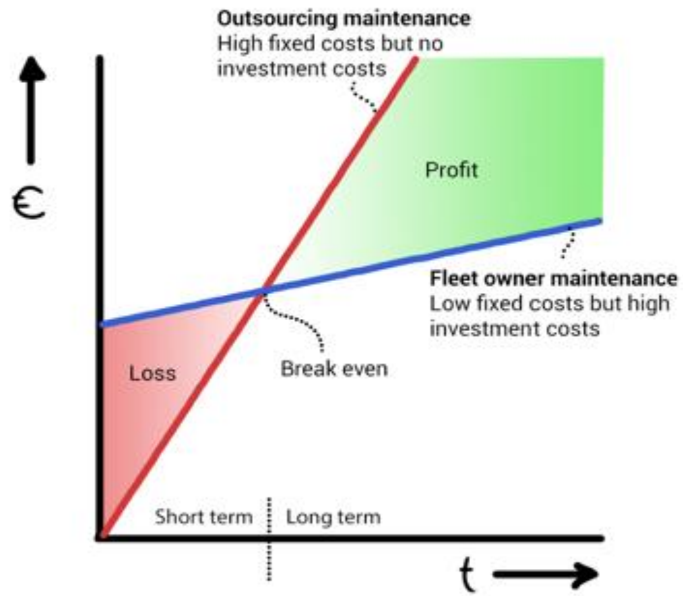
6.4 Benchmark for and ease of maintenance

the company has hinted that the conceptual E-bikes makes maintenance easy enough so that 3rd party services e.g. PostNL install servicing can interchange modules and thus maintain the E-bikes. This allows a fleet-owner to minimize its workforce size whilst sustaining the needed optimal bike performance.

Whether completely outsourcing maintenance is realistic is questioned. For a short- term solution, it might be feasible. It would allow the fleet-owner to maintain its E-bikes without the need to invest in transport e.g. trucks or tools which initially saves costs. In addition, a free-floating shared E-bike operator requires frequent rebalancing of its bike throughout its service area. This could again be outsourced. It is however important to note that every third party that is added in the system adds substantial costs. A 3rd party service is to make a healthy profit and pay taxes just like the fleet-owner thus the 3rd party service will add significant cost posts into the system. This adds to cost of E-bike ownership.

On the long run, it will be better for fleet-owners to invest in own equipment and workforce. The (on-time) equipment investments will pay off due to the (monthly) reduced maintenance costs if used for long enough. The fleet-owner operating its own maintenance is perceived as most realistic cost-wise as the envisioned product service-system is a long-term model.

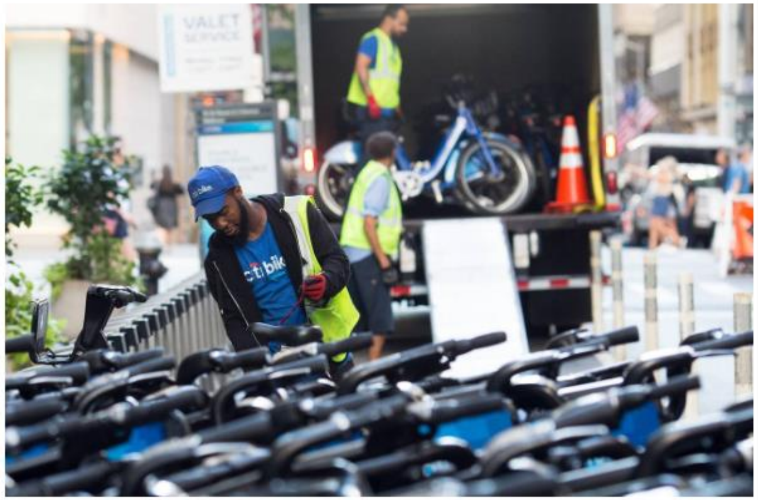




The operator workforce

Even without technical talent or initial skill, a fixed workforce is able to become familiar with certain tasks which ultimately enhances efficiency in performance of tasks to be performed. This slightly eases maintenance/repair requirements. It allows the maintenance/repair performance to be slightly more complicated in comparison to maintenance that is to be performed by random unskilled persons. A (slightly) more experienced person is likely to be able to perform a more complicated task in the same time that is needed for a completely inexperienced person to perform a simple task. This does not make the requirement for ease-of-maintenance redundant.
It is important to note that the potential scarcity of mechanics is putting pressure on the repair capacity of fleet-owners. Fleet-owners being forced to hire unskilled personal and/or high flow of workforce emphasizes the need for optimal ease of maintenance and repair.

The company workforce
When going back to the company employing a less ordinary workforce and being a social enterprise by heart, it becomes even more interesting to design for optimal ease of maintenance of the both the E-bikes itself and of individual modules. Maximum ease of maintenance would allow the company to further extend its social business by enabling more people with a distance to the regular labor market to be able to be involved in the final realization of the circular E bike concept and the involved product-service system.



Maintenance and repair is performed by fleet operator workforce.	
Character	Technically un-skilled (worst case scenario) However will performs same tasks often, able to become experienced at simple to slightly complex tasks
Equipment	Fleet owner transport: truck, cargo bike Able to bring along spare modules/parts Able to bring along simple tools
Task character	As simple as possible. Slightly more technical tasks allowed when the task has to be performed frequent due to ability to gain experience

6.5 E-bike aesthetics and structure

Open drivetrain

When looking at the illustrated E-bikes, it is noticeable that most E-bikes that integrate the battery within the frame also have an available drivetrain. No or minimal chain guards are implemented in these E-bikes. The trend of integrating the E-bike battery seems to go hand in hand with an open drivetrain character. Frame sleekness and minimal drivetrain design make for a logical combination in terms of aesthetical minimalism/simplicity.

The JUMP and Swapfiets have a similar open drivetrain. The recently designed Mo-bike uses the drivetrain as a bearing structure but still implements openness of the drivetrain, which advocates for an open drive-train design.

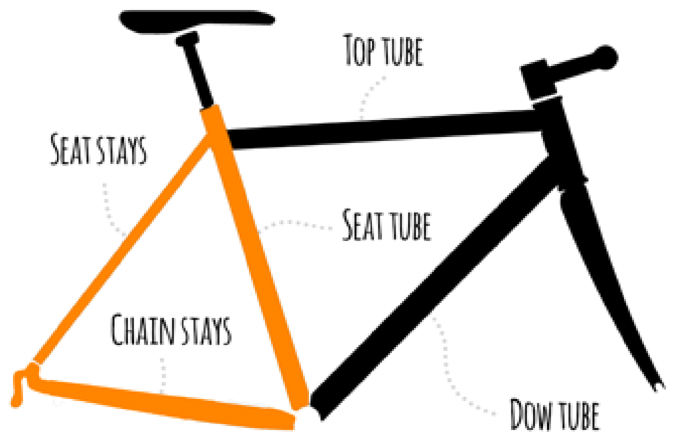
The battery is integrated into the frame, and the chain guard can be either small or completely removed to create a sportier design, as seen in the visualization on the right.

Regular city bikes E-bike incl. chainguard and external battery Sports bike E-bike with integrated battery, without chain guards.

Rear frame structure

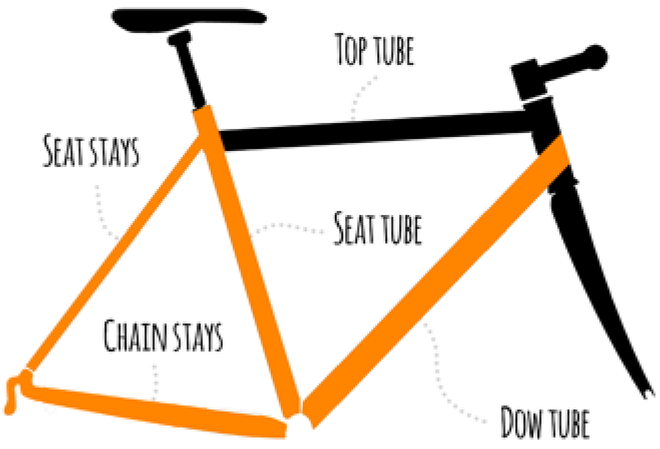
Apart from some of the rarer exotic E-bikes, all E-bikes make use of a similar triangular structure as described on the first page of this chapter. The triangles are visualized in orange in the bottom visualization. The triangles are not entirely equal, but the working principle of achieving frame stiffness through the implementation of the triangle in the frame design is the same for each E-bike. The tube sizing used to create the triangle (seat tube, chainstays, and seat stay) is similar in size for the shown E-bikes. The specific E-bike characters are resulting in the differences in the front frames, visualized in blue.

The triangular structure is the same for every E-bike allows for limiting the rear frame customization options for fleet-owners to a single aesthetically desirable rear frame while allowing fleet-owners to customize their E-bike specifically through front frame customization.



Front frame structure

Similarities in frame design between E-bikes could be taken a step further by identifying the down tubes incorporated within the front frames of E-bikes to be similar as well. All E-bikes make use of a similar downtube that runs from the bottom bracket to the steering post. The position angle of the down tube is broadly similar per E-bike; however, the tubing thickness differs per E-bike. Differences in thickness of the downtube are mostly due to the integration of the E-bike batteries being integrated within the downtube of which automatically leads to a more voluminous downtube.



The triangular structure and the downtube are the same for every E-bike allows for limiting complete frame customization options for fleet-owners to a single aesthetically desirable E-bike base frame, which is either limited in terms of customizability by fleet-owners or employs an alternative form of frame customization. An alternative form of customizability could be the addition of aesthetical modules to differentiate the single component base frame, e.g., the addition of a separable top tube.

Influence of the aesthetics on the modular design solution

The rear triangle of the bike being similar in form and structure for all E-bikes reduces the need to implement a fully customizable fleet-owner rear frame in the E-bike concept. This allows for an alternative design approach than foreseen: The redundancy of rear frame customization allows integration of the drivetrain (as envisioned by the company in The conceptual E-bike as a platform) and rear frame into a single part instead of designing a separated drivetrain and frame that needs to be connected both mechanically/electrically.

This same principle applies to a slightly lesser extent to the front frame: all E-bikes incorporate similar downtube geometries. If the battery is located within the downtube, which is desirable in terms of aesthetics and bike handling, the front frame, rear frame, and drivetrain can be integrated into a single frame. A single frame solution reduces the frame complexity through the removal of the mechanical and electrical connection that is required to join the envisioned split frame halves and their incorporated electronics in an (easy) separable manner. This direction makes the alteration of the E-bike function (e.g., into the cargo bike) potentially more complicated or impossible.

Integration of the drivetrain, rear frame, and possibly the front frame allows for a broader range of product architecture opportunities. For example, modules can be located throughout the whole frame and within the volume of the tubing, similar to the integration of the battery in the downtube.

The full circle.

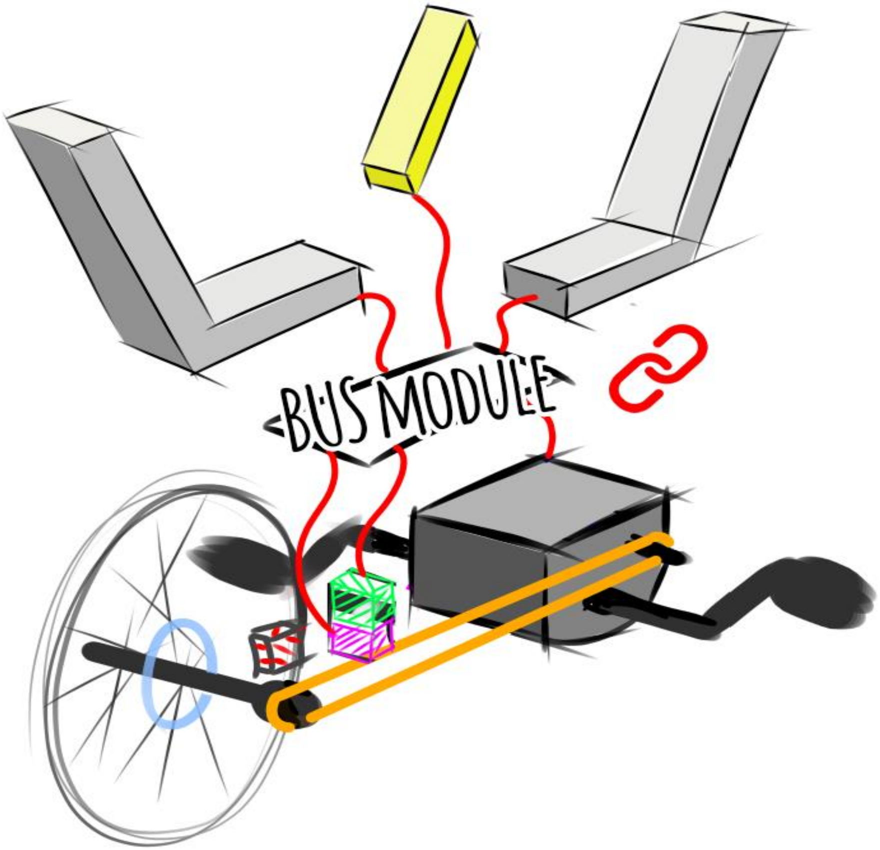
The envisioned solution of a full-frame structure leads to the logical thought of the E-bike design, making a full circle back to the traditional integral E-bike design.
The proposed architecture option, however, is still modular in terms of its allowance to separate and exchange the integrated modules in a manner that is required to tackle the fleet-owners' cost of ownership and sustainability problems. Optimal problem solving for the fleet-owner in the most desirable manner could go at the cost of the extended functionality possibilities: a single frame architecture dismisses the front frame alteration possibility. Ultimately, it is the problem-solving ability of the E-bike concept that creates the potential interest of fleet-owners in the E-bike concept, losing the additional E-bike functionality feature could be perceived as an acceptable loss if it does not directly solve the problems- or serves a significant need of potential E-bike fleet-owner.

6.6 Product architecture design (extended)

Bus-modular product architecture

Modularity has been researched in Analysis 2: Modularity to solve the fleet-owners' problems. The bus-module has been identified as a potential feasible modular product architecture to minimize module connections within the E-bike, resulting in a minimal complex product. The minimized complexity enhances the diagnosing, isolation, and there with the E-bike maintenance and the repair of faulty components. The final modular system design will revolve around the implementation of a bus-module. This bus module has to accommodate a variety of specific functioning modules in the right locations through slot-modular-interfacing (Modularity research.) and interface standardization of similar functioning modules.

Based on the aesthetical analysis E-bike structure. The bus-modular product can decide on the final product architecture of the company E-bike platform in a variety of manners. These either keep the main platform-components separated as initially envisioned by the company, partially integrates the platform-components through the drivetrain and rear frame integration, or fully integrate the platform-components into a full-frame solution. All architectures have their perks and implications on the final circular E-bike design.

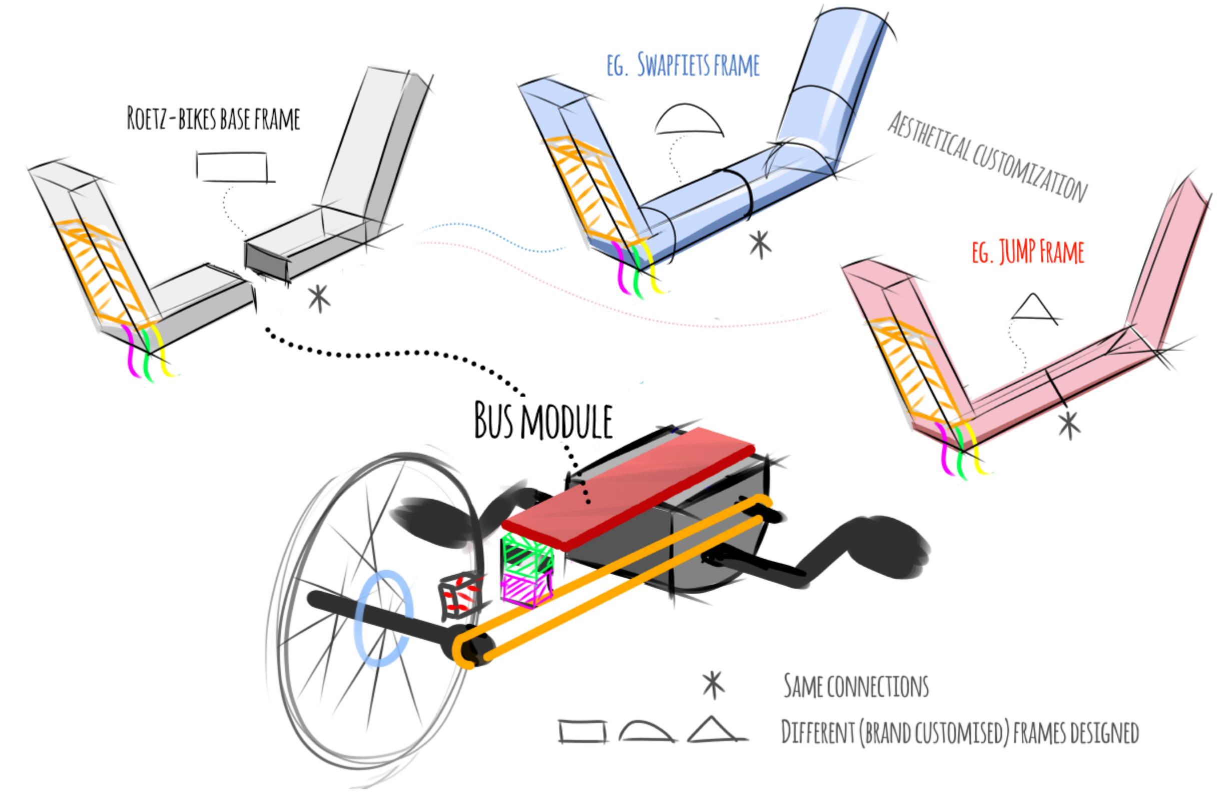


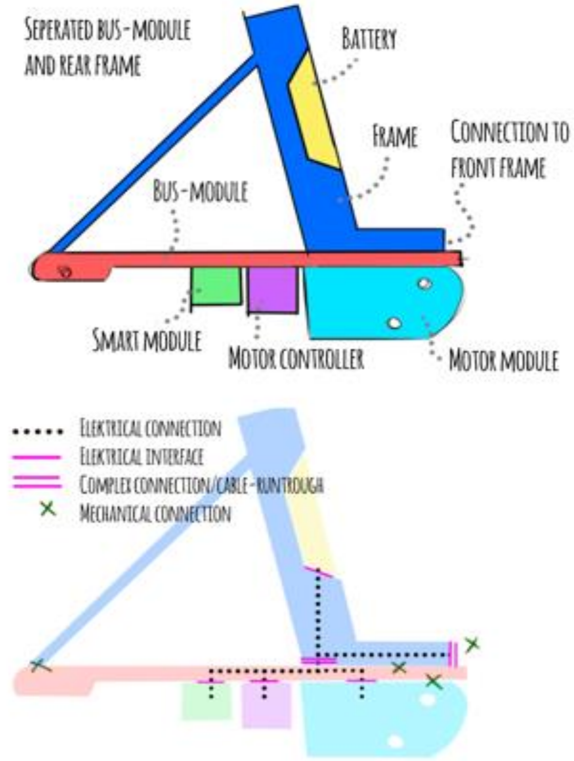
Separated Bus-modular architecture.

The bus-module can form the specific drivetrain architecture that holds and interconnect the drivetrain incorporated modules that connect the drivetrain and the frame (halves). This architecture keeps the company platform fully intact. The front frame allows for functional differentiation while the rear frame is likely to remain unaltered (E-bike structure.). In addition to that, the battery is likely to sustain its envisioned location within the rear frame. Either with and without a modular bus structure, the drivetrain needs to be mechanically and electronically connected to the frame and battery. The same recounts for connecting the front and the rear frame. The needed connections add relative complexity to the E-bike design and are likely to add costs to the final design and upkeep of the final design in relation to the alternative bus-modular architectures.

+ Frame customization options in terms of function and aesthetics.
+ Re-use of modular drivetrain with alternative frames.

- Added complexity in terms of connections
- Limited possibilities of display and controller module location within drivetrain.
- Lots of wiring: drivetrain to battery and drivetrain to handlebar interface.
- Fleet-owner customized front frames have no end of life value other than recycling value.
- Battery located in the rear frame limits aesthetics of base frame and frame comfort.
- Frame split makes the frame more complex, potentially less stiff, less robust, and more costly relative to single frame solution.





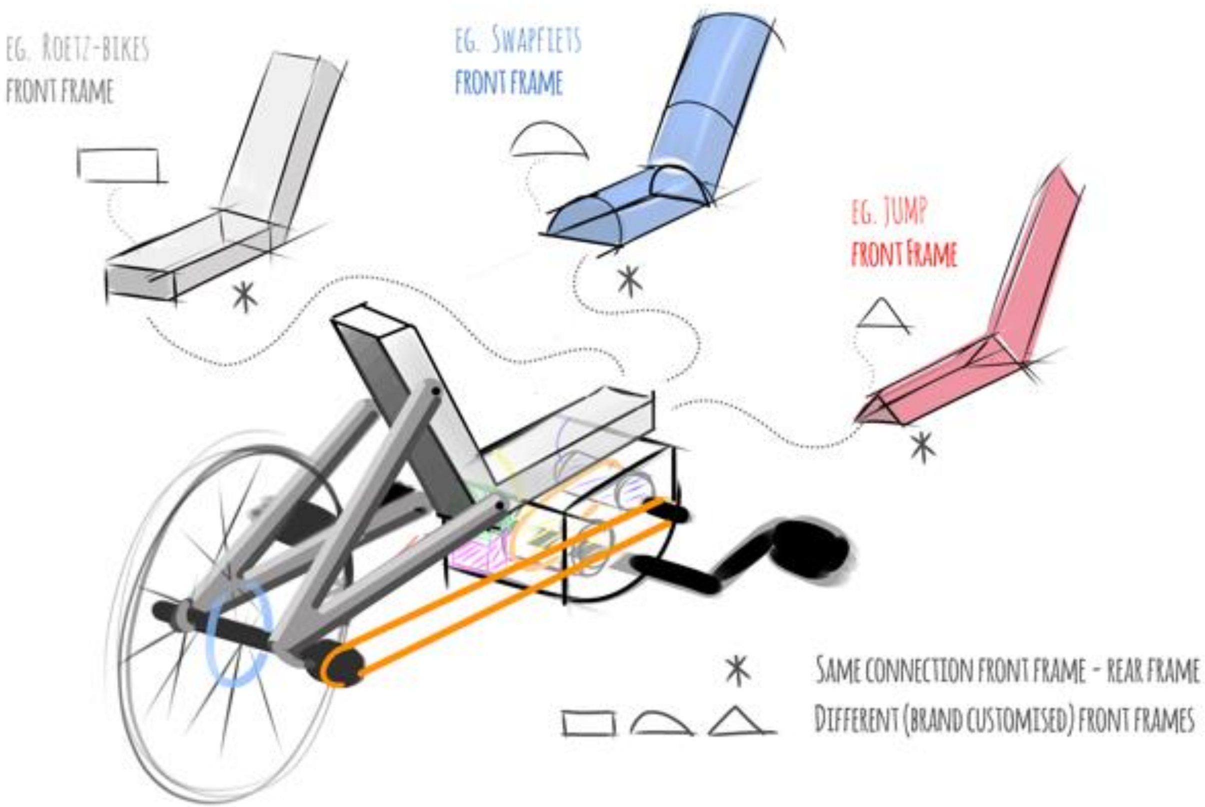
Partially integrated Bus-modular architecture.

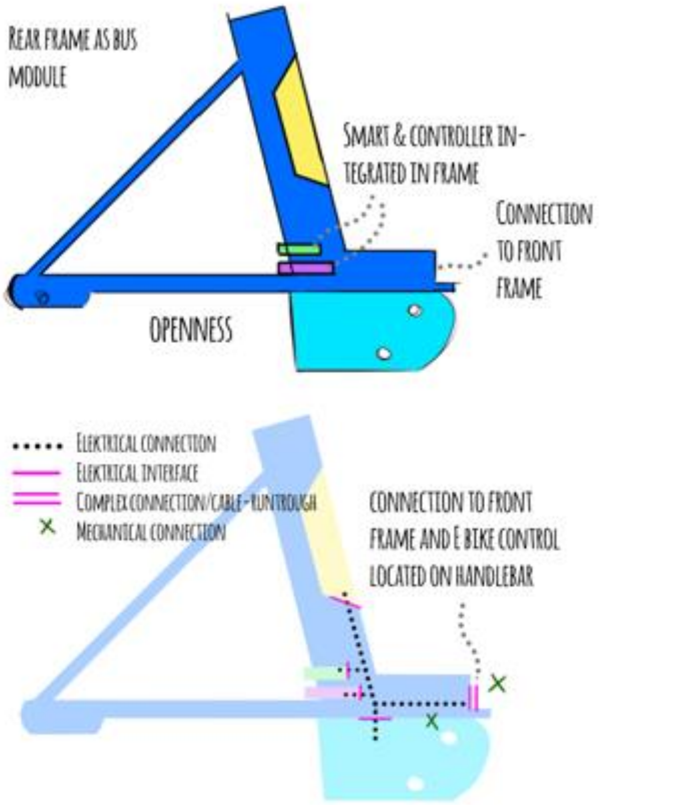
The chapter on E-bike aesthetics showed the similarities in rear frames among different E-bikes, which makes the need for rear frame customization potentially redundant. The redundancy of rear frame customization allows for the integration of the drivetrain and the rear frame. The combination becomes the envisioned bus-module.

Integration of the rear frame and drivetrain significantly reduces the complexity of the E-bike through taking out of the complex connection(s) between the frame and the drivetrain. In this split frame, the battery will again remain, within the rear frame due to the front frame customization ability allowed by this architecture. Although the standardized rear frame can be re-used, e.g., when a fleet-owner goes bankrupt, a customized front frame does not allow for re-use and will likely be recycled. The effort and costs involved with adding new front frames to the existing rear frames could potentially obstruct re-usability.

+ Frame customization options in terms of function and aesthetics sustained
+ Less complex than separated architecture in terms of connections between rear frame and drivetrain. Relative compact electronic scheme with less connections.
+ Desired openness of drivetrain by the possibility to locate modules within the rear frame. Openness of the E-bikes' drivetrain
+ Usage of existing rear-frame volume to locate the modules
+ Welding instead of mechanical fastening.
+ Less parts, less complexity, less costs relative to separate architecture.

- Rear frame less customizable than separated architecture.
- Added volume to frame through module integration could result in bulky frame look.
- Fleet-owner customized front frames have no end of life value other than recycling value.
- Battery located in the rear frame limits aesthetics of base frame and potential frame comfort.
- Frame split makes the frame more complex, potentially less stiff, less robust, and more costly relative to a single frame solution.





Fully integrated Bus-modular architecture

In addition to the existing rear frame similarities, the chapter E-bike structure. showed similarities in the existing E-bikes' downtube as well. The similarities of the front frames of existing E-bikes identify the possible integration of the downtube with the described partially integrated architecture in the last section.

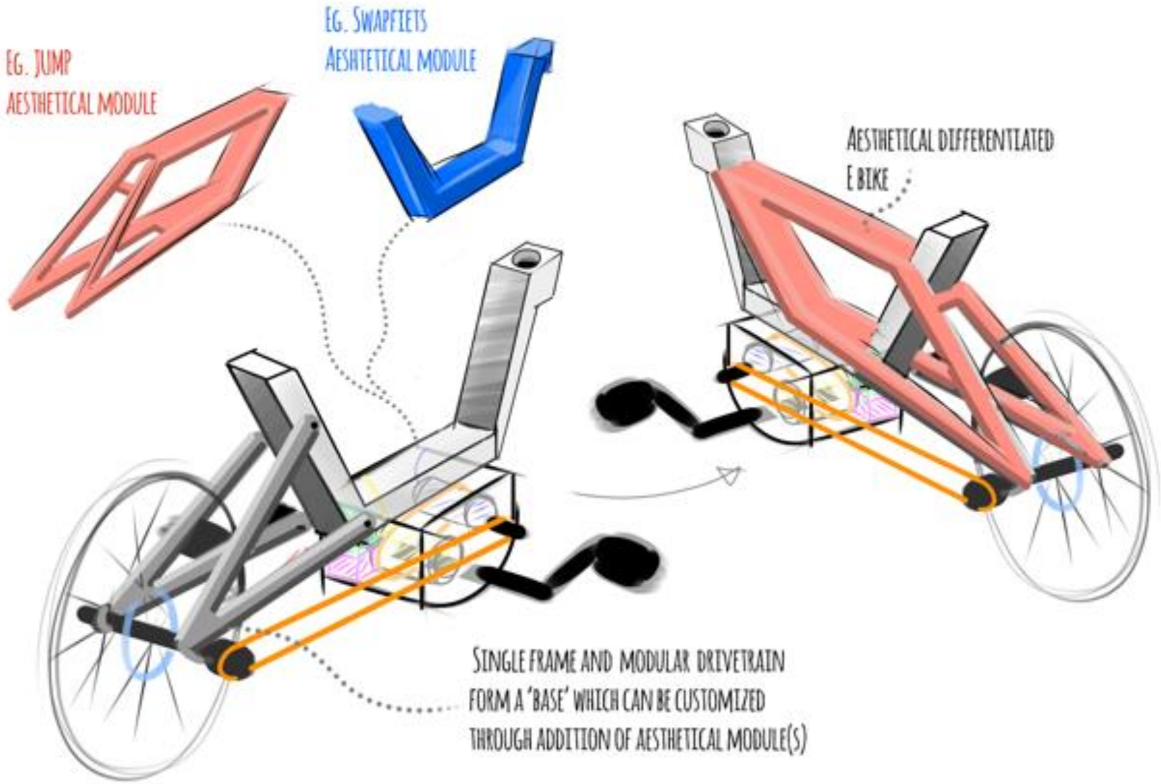
As described in the Influence of the aesthetics on the modular design solution, section: a minimalist E-bike, it is desirable to locate the battery within the downtube in terms of creating a future robust E-bike.

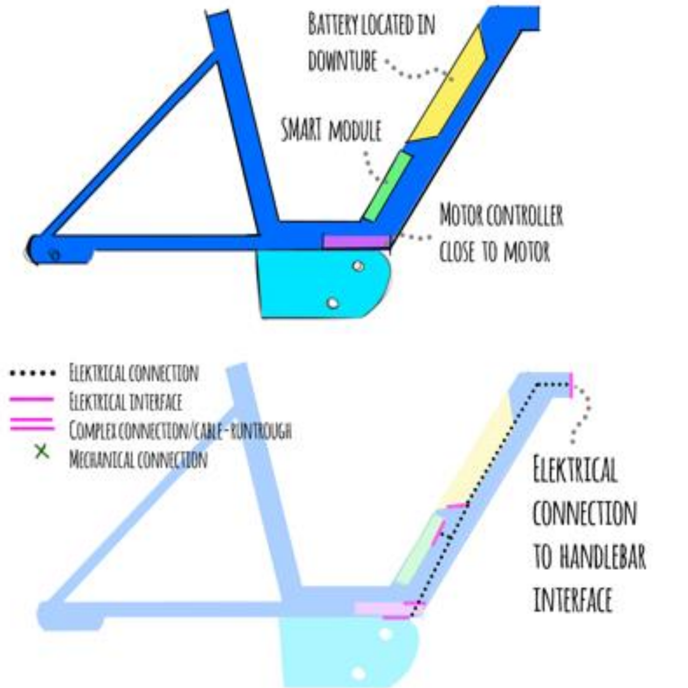
With the downtube forming most of the front frame, integration of the downtube limits the envisioned front frame customizability of the original E-bike platform. In contrast, the integration of the battery in a customized front frame makes the original split fully redundant. (Impact of battery location on E-bike aesthetics.).

The described integration of platform-components results in a single frame, that is considered to be the bus-module, which removes the need for the original frame/drivetrain connections and in addition to that allows for a cost-effective and robust single frame. The E-bike customizability is reduced since the fleet-owner's choice is limited to the base frame and the usage of the aesthetical module. Removal of the aesthetical modules allows for accessible re-use of the full-frame at the end of its life. The full-frame has the best reusability and end-of-life value.

- \+ Optimal end of life re-use value of full-frame due to accessibility of its re-use.
- \+ Allows for future robust E-bike aesthetics due to the battery location within the downtube.
- \+ Optimal E-bike weight distribution and resulting in handling with battery in the downtube.
- \+ Least complex electrical scheme
- \+ Clean integration of modules in existing frame volume which allows for the open drivetrain.
- \+ No complex platform-component connections, cost-effective, robust single frame solution.

- \- Original front frame customization options significantly limited.
- \- Aesthetical differentiation requires the addition of potentially non-re-usable components.



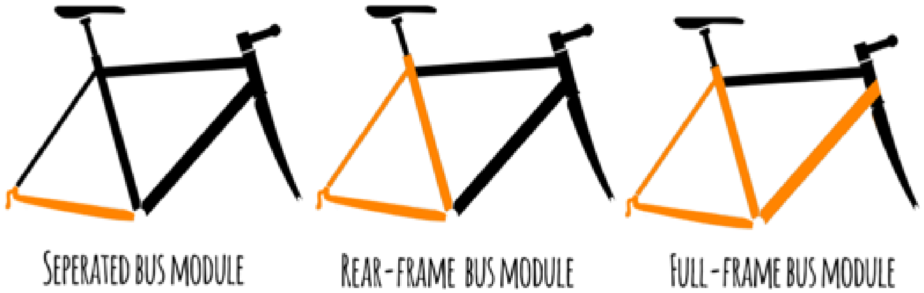


The most feasible bus-modular architecture

The proposed bus-modular structures allow for different integration possibilities as well as the interface possibilities of the modules within the E-bike. Within the focus of this project on tackling fleet-owners' problems through the circular E-bike design, the fully integrated bus-modular architecture is identified as the least complex architecture that is most promising in reducing the total cost of E-bike ownership and enhancing end-of-life usage.

The single-frame solution allows for downtube battery integration, which is most feasible in terms of timeless E-bike aesthetics and handling comfort of the E-bike. The lack of frame splits, adding complexity through the requirement of both mechanical and electronically connectivity, allows for a robust and low-cost single frame that enhances the frame longevity and allows for accessible frame re-use by (future) fleet-owners. The full-frame allows for a relatively concentrated and straightforward electrical scheme, further reducing the E-bikes complexity and enhancing its repairability.

Within the envisioned architecture, the full-frame is the bus-module. The bus-module frame therewith forms bearing structure of the E-bike as well. The essential characteristic of the bus-module is not changed: the bus-modular frame allows the separate implementation of the modules with minimal interdependencies between the modules.



6.7 Battery and module removal

The E-bike modules can be located within the E-bike frame and can be accessed through the large battery slot and can be protected through the battery cover. This module location makes use of the large and already required frame opening required for battery removal without compromising the frame integrity any further.

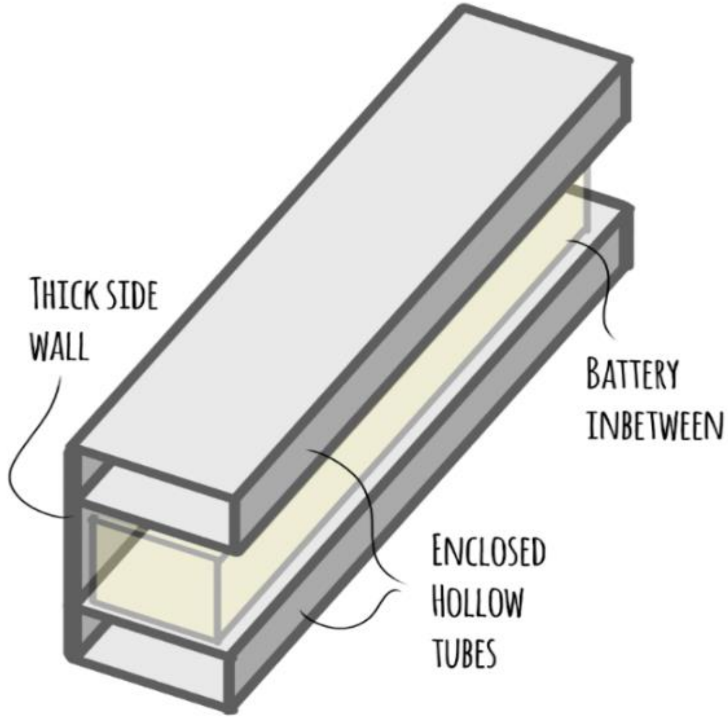
Sleek integration of the E-bike battery within the downtube of the frame requires a voluminous downtube as well as a ‘cut’ in the downtube through which the battery can be removed. The battery is to be easily accessible due to the constant need to replace depleted batteries by charged batteries. The battery also needs to be well protected against both theft and the weather; thus, it will be protected by a well locked and sealed cover.

Locating the other modules underneath/behind the battery and taking them out through the same hole (after battery removal) eliminates the need to add more slots in the hole and thus keeps the frame simple and stiff. In this system, the secure battery covers’ protection characteristics can be optimally utilized.

The existing manners in which the battery is located and removed from the frame are numerous. The different battery locations allow for a variety of module locations and manner of module removal, which impact both the ease of module removal and the frame as well as the maximum battery size.
Some of the possibilities are visualized.

6.8 Frame integrity

Two hollow rectangular tubes that run across the downtube are to enclose the rectangular battery to compensate for the reduced frame stiffness resulting from the cut-out for the battery in the downtube.
Integrating the E-bike battery in the downtube in a removable manner is common practice in both regular E-bikes, E-mountain bikes, and shared E-bikes. The internal battery location in the downtube requires a cut out in the downtube in order to remove the battery. This cut out compromises the frame stiffness. The compromised frame stiffness resulting from the cut-out is overcome by the integration of enclosed tubes within the downtube structure and/or increasing the thickness of the downtube. This is done by JUMP: JUMP uses two enclosed 20mm rectangular tubes that run along the downtube both above and beneath the battery for frame stiffness in combination with up to 6 mm thick walls. This principle simulates the usage of an additional tube above the downtube as visualized on the consumer E-bike.



6.9 The belt

the company wants to make use of a belt in the system and envisions the belt as a separate module like a cassette tape. The belt is pre-tensioned over two central cassette gears in a stiff module housing. When the belt is placed into the system, the open gears fit onto the bottom bracket axle of the motor module and the rear axle after which the belt can translate the energy of the driving axle tot the rear wheel. This system allows the fleet-owner to easily replace the belt when it needs replacement and minimizes the effort and time to do so.

Question is whether this modular solution is feasible. Ease of maintenance is a plus of the modular solution however the solution in this manner might be too complex and/or undesired.

- The belt does not need maintenance and does not wear quick. It does not need frequent replacement and/or does not add significantly to cost of ownership of the E-bike. Therewith, modularity of this component becomes redundant. (Cyclingabout, 2019)
- The position of the cassette gears in the belt housing has to move with the axles which either requires a new belt drive or the belt drive to be adaptable to the moving axle. This again adds complexity to the housing or result in obsolescence of the initial housing when being replaced. Placing the belt directly over the axles with an alternative manner to tension the belts could potentially be a less complex and less costly solution which could still allow easy replacement of the belt when required.
- Minimizing interdependencies between modules is desired. The structure of the belt drive as envisioned by the company is highly dependent on position of the driving axis position of the motor module. Dependency could be reduced by making the belt dependent on its connection to the driving axle and taking away the dependence on its specific position.
  At the same time, alteration of the motor module is made more accessible with the belt drive not being dependent on an exact position of the motor driving axle.
- The belt housing has potential implications for the aesthetics: it reduces the 'open character' of the system and goes against E-bike design trends. A minimal drivetrain is most feasible. Safety however should be kept in mind thus a minimal cover of the belt might be required to be implemented.

Perks of chain guard removal

The (fully enclosed) chain guard is considered aesthetically unpleasant. (Chapter 9. Aesthetics) The naked chain/belt gives the E -bike a more minimalist and sportier look. At the same time, chains got more durable and urban roads are cleaner than ever which significantly reduces wear and the need for maintenance. In fact, a carbon belt does require very little service or no servicing at all even without a chain guard. Removal of the chainguard is traced back to current belt driven E-bikes. Adding a chain cover adds to cost, weight complexity and additional breakdown risk of the E-bike whilst the addition might be infeasible or even unnecessary. A minimal chain guard over could be implemented to cover to take away the risk of the user's pants getting stuck in between front gear and belt.

Perks of the pre-tensioned belt

The rear wheel needs to be maintenance or replaced relatively often. A potential need for (de)-tensioning the chain during this process adds time and costs for the fleet-owner. A pre-tensioned belt reduces would these costs. The belt drive however is not the only manner to keep the belt under tension. The stiff bus-module or an easy-release cable tensioner could as well be feasible solutions to minimize required time for maintenance processes.

Belt tensioner as an alternative to pre-tensioned belt.

A belt tensioner can be installed to either the front or the rear (or somewhere in the middle). Moving the tensioner up or down (depending on example) applies or removes the tension in the belt/chain as desired. Rotating the pedal till it's positioned horizontally to the rear allows easy placement or removal of the belt/chain. The belt tensioner will be replacing the other belt in the final design.

6.10 Influences of the original idea on the final embodied concept

One of the original ideas was to implement all wiring and module connections to a module holder that incorporates the electrical connectors. The modules would only need to be slid into the module holder to be connected to the full electrical system as visualized.
The module holder would become the most complex electrical part, and space needed to be reserved in the back of the frame to locate the cables and their connectors. Separating and re-mounting of modules would be optimal due to the redundancy of required contact with both the connectors and the cables. The exchange of modules is optimal in terms of minimum performance needed to separate and re-mount the modules.

The main problem identified with the envisioned system is the repairability of the module holder: Whenever a fault occurs within the wiring or the connectors, one has to take out the complete module-inlay (which can thus considered to be a module as well) in order to repair the system which is an undesirable characteristic in terms of optimal ease of repair. Also, the motor module has to be located vertically to the bottom of the frame in order to connect it to the module holder located within the back of the frame. The module connector is sticking out from the motor module un-ables sliding of the motor module underneath the frame, which is, again, undesired in terms of ease of motor module exchange.

To allow for better cable and connector management and to allow the sliding of the motor module underneath the frame, whilst locking/connecting it from inside of the frame, the module-inlay has been designated to only hold the modules whilst the cabling and the connectors have been moved into the free space in the front of the frame underneath the battery.