

Improving E-bike mid-drive motor durability through internal humidity management.



Master thesis

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Abstract

This study investigates the premature failure of mid-drive e-bike motors and develops a solution to make them more durable. The research direction was motivated by surveys conducted by van Dam (2025) and Wertgarantie (2024), which highlighted that 24.2% of e-bike technical failures involve the motor. When an out-of-warranty e-bike motor fails, the whole bike often gets discarded because the high replacement cost of the motor (over €1,000) makes consumers purchase a new e-bike.

To understand the causes of these failures and address the hypothesis that environmental and thermodynamic factors play a role, a mixed-methods approach was utilized. Qualitative data was gathered through 11 interviews with local repair mechanics and 4 interviews with specialized remanufacturers. Additionally, physical product teardowns were conducted on 9 different mid-drive e-bike motors to analyze their internal architectures and component failure points.

The findings showed that the thermodynamic "breathing cycle" is a cause of e-bike motor durability. As the motor cools, pressure differentials draw ambient humidity past the seals, causing internal condensation that leads to the failure of bearings and electronic components. Recognizing that standard hermetic seals cannot stop this cycle, the design vision shifted from passive water sealing to active internal humidity management. As a result, a modular Desiccant Cartridge filled with indicating silica gel has been developed to absorb internal moisture and prevent condensation on components. The cartridge is filled with 10 grams of silica gel and has to be replaced every 2 years with heavy use.

We conclude that the Desiccant Cartridge concept works theoretically to avoid condensation, but it has not yet been physically tested in practice. Important limitations of this study include the lack of detailed OEM data regarding component failure rates, which necessitated a reliance on qualitative field reports and third-party surveys. A suggestion for further research is to conduct user experience testing to investigate the willingness and confidence of e-bike owners to perform DIY repair and maintenance using these cartridges.

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1 Introduction

1.1 Context

The global transition towards more sustainable transportation is critical in the effort to mitigate climate change and get a reduction in carbon emissions. This shift involves moving away from internal combustion engine vehicles towards more sustainable alternatives such as public transport and (personal) electric vehicles. Within this context, the e-bike has been an enabler of urban mobility in Europe. Germany and the Netherlands report that over half of all bicycle sales are electric at this moment (VSF [German Service & Bicycle Association] & ZIV [German Bicycle Industry Association], 2025). Research supports this trend, Dutch commuters are willing to substitute their cars with e-bikes for journeys up to 20 kilometers (De Kruijf et al., 2018). Consequently, the annual travel distance for a commuter could be approximately 5,000 to 10,000 kilometers. This trend is supported by survey data: 21.8% of respondents cycle over 4,000 km/year, with 2.4% exceeding 10,000 km/year (Wertgarantie, 2024). However, the long-term viability of the e-bike is being undermined by the limited durability of its core electronic components. According to a 2024 survey by Wertgarantie in Germany, 40.9% of e-bike technical failures involve the battery, 28.6% the display, and 24.2% the motor. While battery degradation is a known issue, estimated at 800-1000 charge cycles (Contò & Bianchi, 2022), subject to external factors like temperature. E-bike motor failure rates are less researched but common failures are caused by wear, water ingress, and electronic errors (van Dam, 2025). Current data and anecdotal evidence from repair shops suggest that e-bike motors fail prematurely.

As shown in Figure 1.1, around 60% of failed survey units failed under 15,000 kilometers, while only around 15% exceeded 30,000 kilometers in total. This means that the average commuter may require motor replacement every 1.5 to 4 years, a short lifespan for a component that is perceived as durable.

Premature e-bike motor failures create significant economic and environmental waste. Replacement motors cost over €1,000 (van Dam, 2025) and repair options are not broadly available, consumers often discard entire out-of-warranty bicycles. For example, a Maassluis commuter's motor failed after just 790 kilometers. Because the manufacturer, Stella, went bankrupt, the warranty was voided. Unable to repair the motor, the consumer was forced to scrap the otherwise intact e-bike and purchase a new one.

Discarding entire e-bikes due to motor failure generates excessive (e-)waste and loss of critical raw materials of the electronics. This "throwaway" cycle contradicts circular economy principles of repair and reuse, undermining both the consumer's investment and the environmental promise of e-mobility.

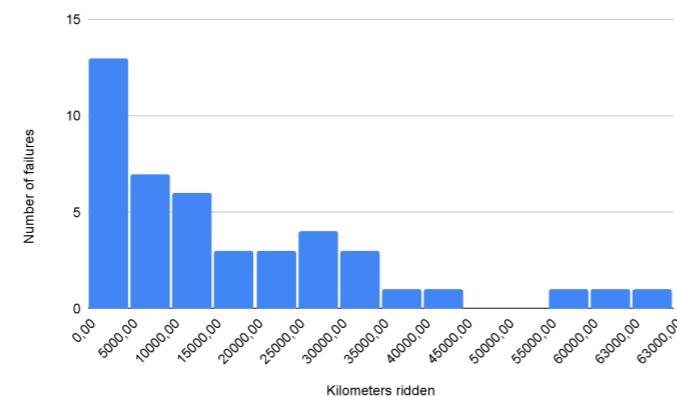


Figure 1.1. Histogram on kilometers ridden and number of failures.

1.2 Assignment and Research Questions

The context shows a misalignment in the sustainable promise of e-bikes and the limited durability of the core components and its costs to repair or remanufacture. The thesis will investigate how we can improve the durability of e-bike motors. The goal is to design an e-bike motor that is more durable, requires less frequent repair, and achieves a place in the circular economy through longevity and proactive failure prevention. Extending the motor's lifespan to 100,000 km would increase its life expectancy from the current 1.5 - 4 years to at least 4 years.

The context of these problems leads to the following design assignment:

“Design a durable e-bike motor concept to extend the lifetime expectancy to 100.000km, while being maintenance free for its users.”

To successfully proceed with this design assignment, we require additional information that will be gathered by addressing the following three research questions.

Why do current e-bike motors fail prematurely and do not achieve a service life of 100.000km?

What supply chain and regulatory barriers prevent the repair and life-extension of e-bike motors?

What are measures that are being taken at the moment to increase the service life of an e-bike motor?

1.3 Approach

This research follows the Double Diamond (Figure 1.2) design framework to systematically explore the problem space and converge on a validated solution.

The “Discover” and “Define” phases combine quantitative technical analysis with qualitative field data. To understand internal architectures, sealing quality, and physical failure points, a Disassembly Map method is applied to systematically tear down nine different e-bike motors. This technical assessment is then contextualized through interviews with 11 local bicycle mechanics and four specialized remanufacturing companies, providing field-level data on common failure modes and supply chain barriers.

Based on the identified root causes, the “Develop” and “Deliver” phases focus on functional requirements, exploring thermodynamic design strategies, and developing a functional prototype to actively extend motor longevity.

Chapter 1 introduces the context of premature e-bike motor failures, defines the design assignment and research questions, and outlines the Double Diamond methodology used for the project.

Chapter 2 establishes background knowledge regarding mid-drive motor components, market trends, and relevant regulatory frameworks like the “Right to Repair” directive.

Chapter 3 discusses the method used during the “Discover” phase, combining physical teardowns of nine motors with qualitative interviews of bicycle mechanics and remanufacturing experts.

Chapter 4 analyzes the technical data to identify the root causes of motor failure, emphasizing how the thermodynamic “breathing cycle” drives internal moisture ingress and component degradation.

Chapter 5 investigates the broader supply chain, regulatory, and economic obstacles that prevent the repair and life-extension of e-bike motors.

Chapter 6 evaluates existing industry developments, including third-party repair protocols and the introduction of new oil-filled motors.

Chapter 7 translates the research findings into a new design vision and sets the functional requirements for the solution.

Chapter 8 evaluates potential design strategies (Prevention, Absorption, Regulation), selects the Absorption method, and details the thermodynamic sizing, prototyping, and manufacturability of a silica gel-based solution.

Chapter 9 presents the developed “Desiccant Cartridge,” detailing the user interaction for maintenance, technical integration, and alignment with regulatory standards.

Chapter 10 reflects on the physical and systemic implications of the research, evaluates the proposed solution against the initial goals, and acknowledges the study’s limitations.

Chapter 11 summarizes the findings, and discusses recommendations for future testing and industry reform, and concludes with a personal reflection on the project.

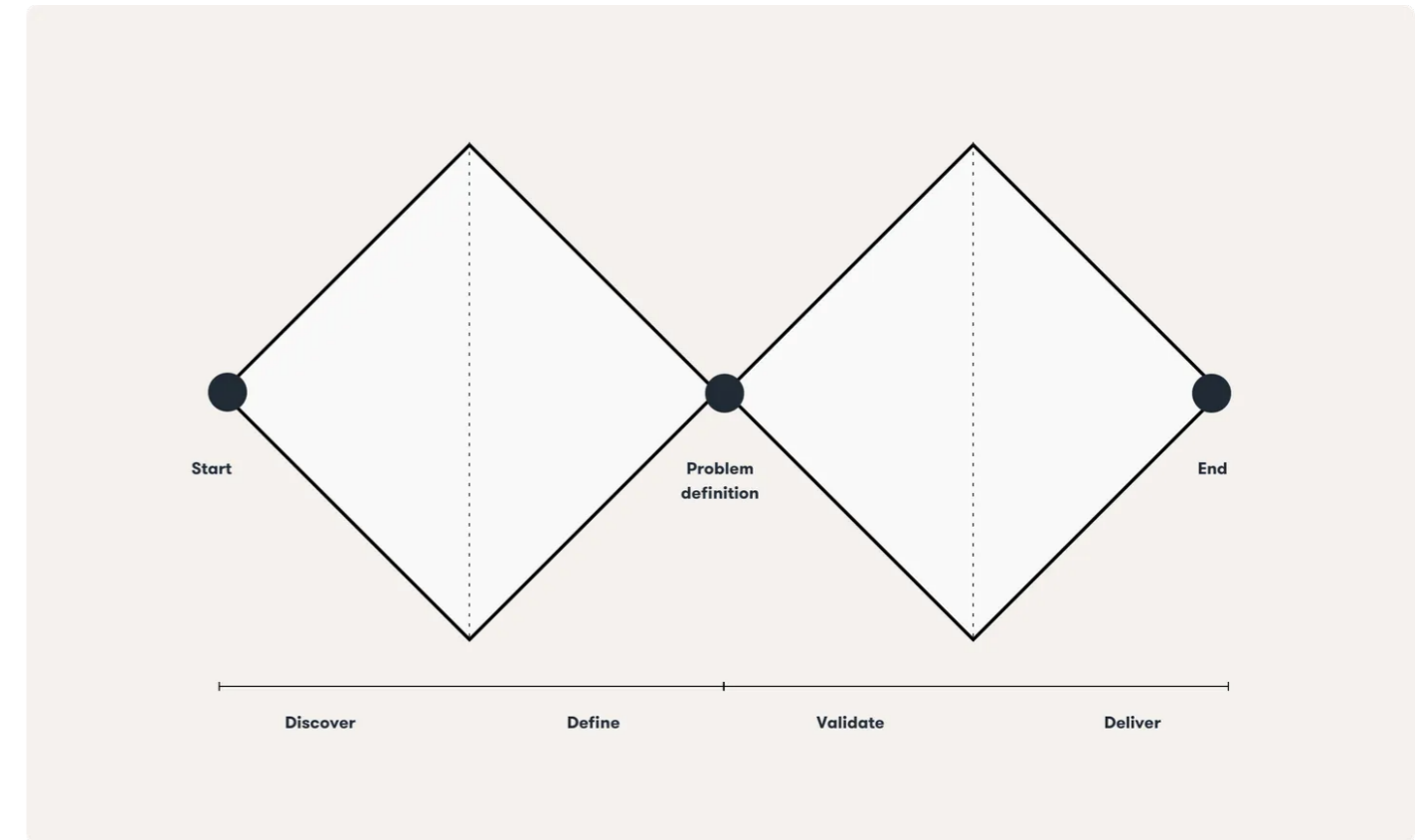


Figure 1.2. The Double Diamond design framework.

2. Background

This chapter explains fundamental components and functionality of mid-drive motors and

explores market trends, brand dominance, and the regulatory “Right to Repair” directive.

2.1 Basics of an E-bike motor

2.1.1 System Components

Unlike hub motors, which are located in the front or rear wheel, the mid-drive motor is positioned at the bicycle’s bottom bracket. The crankset of the bike is directly integrated in the motor (Contò & Bianchi, 2023). This central and low placement provides a significant advantage in weight balance, handling, and hill-climbing performance. The motor applies torque directly to the bicycle’s chain ring, leveraging the bike’s existing gear system for optimal efficiency across different speeds and terrains.

The mid-drive motor is one part of a larger, integrated electrical and mechanical system. A typical e-bike drive system consists of five primary blocks (Contò & Bianchi, 2023):

Battery: The energy source, typically a 36V or 48V Lithium-ion battery pack. These sit inside of the frame or on top of the bike rack.

Power Converter: An electronic device that connects the battery to the motor, regulating the current and voltage supplied, and is integrated inside of the PCB of the motor.

Controller/ECU (Electric Control Unit):

The “brain” of the system. It receives inputs from the rider (via sensors) and the battery, and it controls the power converter to deliver the appropriate amount of motor assistance. The ECU is integrated on the PCB of the motor and is located in the heart of the casing.

Electric Motor: The unit that converts electrical energy into mechanical torque, it sits inside of the e-bike body.

Sensors: In a pedal-assist system, sensors (such as pedaling speed/cadence sensors or force/torque sensors) detect the rider’s effort and send this information to the controller, these sensors are integrated inside of the body of the motor (Contò & Bianchi, 2023).

2.1.2 E-bike Motor Functionality

The functionality of the mid-drive e-bike motor is an integrated system that assists the rider’s effort in providing force to the wheels. The operation of the system is defined by the input and the output: pedal-assist and parallel configuration.

Pedal-Assist (Input): The motor only activates when the rider is actively pedaling, when the rider is not pedalling, there is no assistance. The opposite would be a motor with a throttle that would not require pedalling at all. The controller determines the level of assistance based on parameters, such as rider torque, cadence, and speed. The motor’s power output is proportional to the rider’s power until the maximum legal speed is achieved, after which the assistance gradually decreases to comply with the speed limit (Hsu et al., 2012).

Parallel Configuration (Output): Human torque (from the rider) and the motor torque are “combined in the mechanical domain via gears” (Corno et al., 2017). Both power sources apply force to the same drivetrain (the chain and rear gears), allowing the motor to benefit from the mechanical advantages of the bicycle’s gearing.

2.2 E-bike Motor Brands & Market Trends

2.2.1 E-Bike Motor Brands and Market Share

The European e-bike motor market has an estimated market size of USD 17.5 billion in 2024 (GMI Insights, 2025). Motor design in Europe is primarily dictated by regulatory compliance of the EU (25 km/h, 250 W continuous power) and the consumer’s expectations for product quality and refined ride dynamics (Mordor Intelligence, 2025a).

The market share by brand is characterized by different strategies (Ernst Brust, 2024):

Bosch (Market leader, 50%): Their strategy relies on its “Smart System” portfolio. This system integrates the motor, battery, display, and firmware as a single, connected package for bike manufacturers. This strengthens “ecosystem lock-in” for Original Equipment Manufacturers (OEMs) (Ernst Brust, 2024).

Shimano (20%): More prominent in the sporty and performance-oriented segments.

Bafang (15%): Leading in hub motors which are used in more affordable and entry-level e-bikes.

Brose/Yamaha (12%): Represents the market’s ongoing consolidation, a shift highlighted by Yamaha’s recent acquisition of Brose’s e-bike motor division.

Others: Account for the remaining 3% of the market.

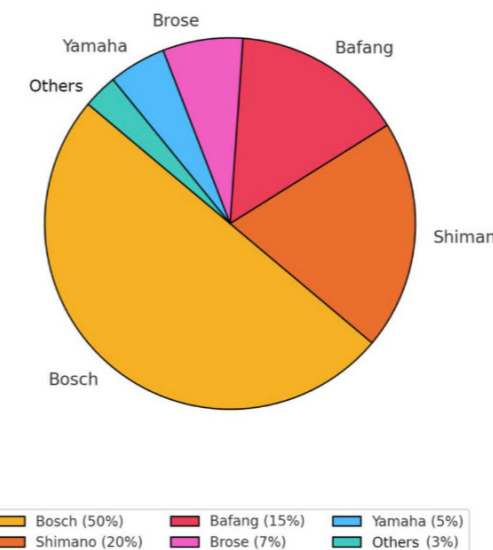


Figure 2.1. European market shares of motor companies (Ernst Brust, 2024)

2.2.2 Mid-drive vs Hub Motor

Historically, the market started with hub motors. Some early iterations were simple retrofit kits, but systems like the Sparta ION demonstrated that hub motors could be part of a high-quality integrated system. The ION (Figure 2.2) was launched in 2003 as the first e-bike, which appealed to the wider Dutch public and set the trend for adaptation of the e-bike. However, the introduction (around 2010) of the mid-drive system shifted the market standard from hub motors to mid-drive motors. The mid-drive motor offers improved torque on hills, weight distribution and ride dynamics. At the moment the mid-drive system dominates the hub system in Europe, with 63,45% market share (Mordor Intelligence, 2025b).



Figure 2.2. The Sparta ION.

2.2.3 Market Trends

Innovation and market competition will lead to lighter systems and integration of smart systems and functionalities (the ecosystem around the motor). Systems can for example hold GPS or an application where the user can adjust the driveability, torque output, and the gear length of the motor. (Mordor Intelligence, 2025a)

The market is shifting to B2B (business to business). Tax-advantaged leasing in several countries cuts costs by 30–50%, making premium bikes accessible to employees. Logistics companies DHL, Amazon and UPS are adopting e-cargo

bikes to cut last-mile costs by 25% and switch to zero-emission deliveries. Subsidies (up to €4,000 in France) and infrastructure projects (Paris and Spain) are accelerating e-bike adoption. Cities with protected lanes see 40% higher adoption rates. (Mordor Intelligence, 2025b)

The future of the market holds growth due to urban-commuter uptake, more focus on health and fitness trends, people that want a more sustainable commute and the influence of the improvement of bike infrastructure across EU countries. (GMI Insights, 2025)

2.3 Right to Repair

In 2024, the European Union introduced a new “Right to Repair” directive, a policy that is designed to promote product sustainability, durability, and overall life expectancy (Directive (EU) 2024/1799, 2024). The directive legally enables consumers and professionals to repair products. To achieve this, manufacturers are obliged to:

1. Ensure the availability of spare parts.

2. Utilize an architecture and connections designed for repair.
3. Provide support for a specified number of years after a product is discontinued.

Despite these benefits, e-bike motors are not included in this directive. While the official reason for this exclusion is not verified, it appears linked to the lack of an underlying eco-design directive (Regulation (EU) 2024/1781, 2024), for example, excludes motors over 50 V).

3. Methods

To investigate the misalignment between the sustainable promise of e-bikes and the premature failure of their motors, a mixed-methods approach was utilized.

This chapter outlines how physical product analysis was combined with qualitative field data to answer the primary research questions.

3.1 Disassembly Map

The disassembly method employed in this research utilizes a Disassembly Map approach (De Fazio et al., 2021) to systematically analyze and compare various motors. This method is used to systematically deconstruct products, in this case e-bike motors. With the goal of understanding each motor's architecture, components, build quality, internal connections, waterproofness, repairability, and durability. Furthermore, this process provides an opportunity to develop a tactile and spatial understanding of how the

motor's components interface and function as an integrated system. The teardowns were done in collaboration with Dion Vijverberg.

The process requires a controlled setup to make sure that the outcome can have repeatable and documentable results. This involves securing the motor and surrounding workspace, using a tripod-mounted camera to film the entire process, and having a comprehensive tool kit readily available (e.g., the iFixit toolkit). The setup of the method is shown in Figure 3.1.

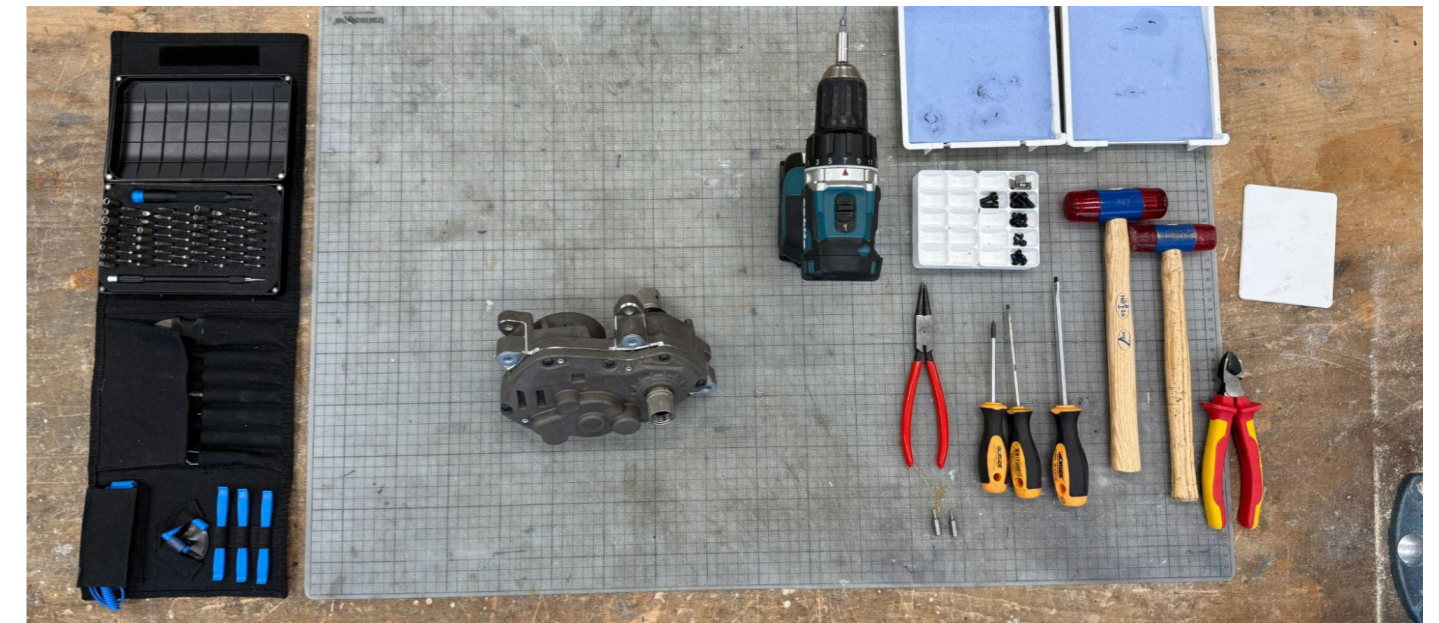


Figure 3.1. Setup of product teardown.

The physical disassembly is documented in three areas:

1. The specific tools required for each connection.
2. The sequence of steps to access internal components.
3. Any notable features (e.g., seals, specialized connections).

The collected data is then used to construct a disassembly map, a visual and sequential flowchart that illustrates the path, type of connections and tools necessary to reach any given component of the motor. For a more detailed step-by-step

explanation I refer to the methodology developed by Francesco de Fazio (De Fazio et al., 2021). Figure 3.2 shows the legend that is used to make a disassembly map (Arriola et al., 2025).

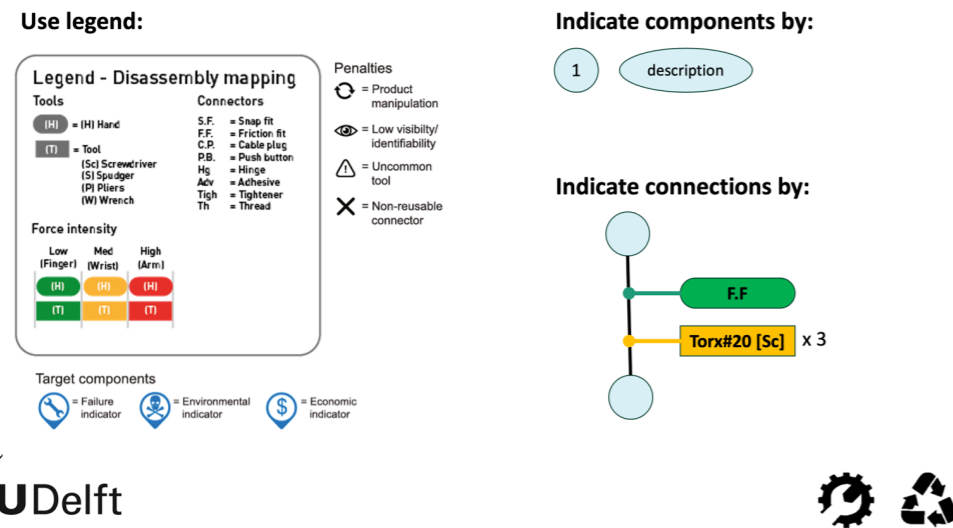


Figure 3.2 Legend of disassembly mapping.

9 e-bike motor teardowns were performed for this method, Table 3.1 gives an overview of the motors and brands used.

The disassembly maps of the motors can be found in Appendix C.

Table 3.1. Motors for product teardown.

	Brand	Motor Type
1	Shimano	DU-E5000
2	Shimano	DU-EP600
3	Shimano	DU-E6110
4	Bosch	BDU 250 (Gen 2)
5	Bosch	BDU 350 (Gen 3)
6	Bafang	M210
7	Ananda	M81
8	Brose	Drive S
9	Gobao	P101

3.2 Interview Bike Mechanics

Qualitative interviews with bike mechanics uncovered challenges related to motor failures, supply chain dynamics, manufacturer support, and the full product lifecycle as experienced by

professional repairers and their clients, e-bike owners. The interviews were conducted in collaboration with Dion Vijverberg.

3.2.1 Type of Interview

The data collection followed an unstructured to semi-structured interview format, prioritizing an open conversation with a few standard questions, followed by natural follow-up questions. The goal of this qualitative method is to explore the broader context of the problems surrounding the e-bike motor. This included understanding the motor's ecosystem: contact with manufacturers, issues within the supply chain, and the problems faced by mechanics and their clients. The unstructured approach of the interview is deliberately chosen to reduce research bias. By allowing mechanics to speak freely about the issues they deemed most concerning, to avoid biasing the discussion towards problems preconceived.

A summary of the type of questions asked during the interview (Appendix D)

Context: Introduction and questions into the percentage of e-bikes repaired and the specific brands of motors and bicycles in the shop's portfolio.

Motor failures: Questions regarding the typical lifespan of motors, top three common defects, and root causes such as moisture or software errors.

Repairability: An investigation into the 'repair vs. replace' decision-making process, spare parts availability, and permissions regarding opening motor housings.

Manufacturer relations: An evaluation of the support provided by brands concerning warranty claims, technical documentation, and parts delivery.

3.2.2 Sampling Strategy

Interviews were conducted by one or two interviewers. The conversation started with an introduction of the thesis research and the goal of finding failures in the e-bike motor context to inform a redesign for a longer service life. A natural conversation and discussion then ensued, with a duration of approximately 5 to 10 minutes depending on the flow and availability of the bike shop.

The target population of the interviews consisted of bicycle mechanics specializing in the service and repair of e-bikes, as their daily experiences provided insight into failure modes and logistical challenges.

The participants of the study were sourced with convenience sampling to make a selection of local shops in Delft and Leiden. These potential participants were filtered by bike shops that, in addition to repairing normal bicycles, also sell and repair E-bikes. This was necessary because not every bicycle shop does service, repair or sell e-bikes. Most of them do regular repairs, fixing a flat tire and replacing a brake cable, but do not work on the electrical side of the bike. A total of 11 interviews were conducted across three locations: 5 shops were interviewed in Leiden, 2 shops in De Lier and 4 shops were interviewed in Delft (Table 3.2).

Table 3.2. Companies interviewed.

Type of Company	Job Title	Duration (min)	Location
1 Repair and sales	Mechanic	5	Delft
2 Repair and sales	Owner	10	Delft
3 Repair and sales	Mechanic	7	Delft
4 Repair and sales	Mechanic	8	Delft
5 Repair and sales	Mechanic	5	Leiden
6 Repair and sales	Owner	10	Leiden
7 Repair and sales	Mechanic	10	Leiden
8 Repair and sales	Mechanic	8	Leiden
9 Repair and sales	Mechanic	9	Leiden
10 Repair and sales	Owner	10	De Lier
11 Repair and sales	Mechanic	7	De Lier

3.2.3 Data

All participants were first informed of the research topics and the overall goal of the thesis before the interviews were conducted.

Data capture was written down in notes, which were compiled and transcribed by the interviewers after each conversation concluded. These notes exist of statements and quotes relevant to the research.

The interviews were conducted anonymously. For this reason, all notes and reported findings are anonymized, preventing specific statements traceable to any individual participant or repair shop and can be found in Appendix E.

3.3 Interview Remanufacturers

Technical insight into component durability and failure mechanisms on product level were acquired through qualitative interviews with

remanufacturers. The interviews were conducted in collaboration with Dion Vijverberg.

3.3.1 Type of Interview

In contrast to the unstructured conversations with bike mechanics, these interviews followed a semi-structured format. This approach was chosen to ensure consistent data collection on specific technical topics, such as component failure rates and wear patterns, while retaining the flexibility to explore the business models and strategic challenges of the remanufacturing sector.

The semi-structured interviews helped to focus the conversation on specific topics and themes related to technical longevity and material failure. Following the structured questions, an open discussion was facilitated to broaden the conversation beyond technical problems to include business models and strategic challenges in the remanufacturing industry.

All sessions were conducted by two interviewers

to facilitate a dynamic conversation and make sure notetaking could be done at same time. The questions can be seen in Appendix D.

A summary of the questions:

Motor failures: Technical questions regarding failure rates, common causes (wear vs. misuse), and diagnostic tools.

Repairability: An investigation into standard repair procedures and the availability of spare parts for motors.

Reconditioning: Detailed inquiries into the overhaul process, including time/cost estimates and the specific parts that require replacement.

Manufacturers & general: A critique of manufacturer support and an open discussion on broader trends and problems in the e-bike industry.”

3.3.2 Sampling Strategy

A targeted sampling strategy was used to select companies that are specialized, have the knowledge and expertise regarding repair and remanufacturing of e-bike motors. There are not a lot of companies that do these activities. These interviews included 5 unique companies from the remanufacturing sector (Table 3.3).

1. The first company (UK-based) that established the e-bike motor remanufacturing process.
2. Two partner (Netherlands based) companies of the UK-based remanufacturer, that are in the process of expanding their e-bike remanufacturing processes and volume.
3. One company (Netherlands based) that is developing a commercial remanufacturing line for a major e-bike lease provider, offering insights in scaling solutions and logistics.
4. One company (German based) that is manufacturing and remanufacturing e-bike motors.

Table 3.3. Companies interviewed.

Type of Company	Duration (min)
1 Uk company	30
2 Dutch company	60
3 Dutch company	60
4 Dutch company	60
5 German company	60

3.3.3 Data

Three interviews were conducted in online meetings, with a duration ranging between 30 to 60 minutes. The other two interviews were conducted during physical company visits, which provided context and visual information of the remanufacturing processes.

Data capture was done by mixture of voice-recording the online sessions and notetaking. The data of the on site interviews were done via note-taking by the second interviewer. These field notes served as the source for thematic analysis.

All data collected was anonymized during reporting to ensure confidentiality and protect the proprietary information shared by these companies and can be found in Appendix E.

4. Analysis of Failure Mechanisms

Premature motor failure is driven primarily by the interaction between environmental factors and internal thermodynamics, specifically the “breathing cycle.” While mechanical wear plays a role, analysis shows that thermal fluctuations create pressure differentials that draw humidity

past external seals. This moisture ingress leads to internal condensation, causing corrosion in bearings and short-circuits in electronics, effectively preventing current motors from achieving the 100,000km target.

4.1 Causes of Failure

The everyday use of an e-bike outside, is a bike that has to go through a variety of contexts: cycling mechanics, parking & storage, transport and maintenance.

The natural elements and contaminants that interact directly with the motor casing and seals lead to component failure.

4.1.1 Water Ingress

Water ingress is the most significant external failure factor. According to remanufacturers (1, 2, 3 and 4), this includes water from rain, road spray, riding through puddles (Figure 4.1) and the breathing cycle. If water gets inside of the motor, it can cause failures to bearings, electronics and sensors.



Figure 4.1. E-bike motor through water.

The breathing cycle can be explained in 5 steps (Lucas et al., 2022):

1. When a motor operates, it generates heat, causing the internal air to expand. As the internal pressure rises, this expanded air "bleeds out" of the motor through any gaps, seals, bearings, or vents.
2. When the motor is turned off or placed in storage, it cools down. As the internal temperature drops, the remaining air inside the casing contracts.
3. This contraction creates a lower pressure effect that pulls external air into the motor to equalize the pressure. This intake air brings environmental moisture and humidity with it inside of the motor.
4. While air moves in and out, moisture often becomes trapped. The text notes that moisture drawn into a machine does not come out naturally unless specific drainage provisions (like seepage holes) are present. Even "fully enclosed" motors are prone to this because seals are rarely gas-tight.
5. Once the moist air is inside, the lag in temperature equalization (thermal inertia) can cause the internal surfaces to drop below the dew point. This causes the moisture in the air to condense into liquid water on colder internal components and surfaces.

4.1.2 Cycling Mechanics

Rider behaviour impacts the mechanical and thermal load on the motor, which has an effect on the durability, according to remanufacturer 2 and 3:

High-torque, low-cadence: Riding in a high gear at low pedaling speeds forces the motor to operate inefficiently, generating higher temperatures and high strain on the system. This mechanical and thermal stress has a negative impact on the durability of the motor.

This is governed by the Ideal Gas Law:

$$PV = nRT$$

Where P is pressure, V is volume, n is the amount of substance, R is the ideal gas constant, and T is temperature. Since the volume (V) of the motor housing is fixed, changes in Temperature (T) directly result in changes in Pressure (P).

The working range of an e-bike motor is between 50 °C and 80 °C. If the ambient temperature is 20 °C, it will give a temperature difference of 30 °C to 60 °C. This temperature difference gives a pressure difference of 100 to 200 mbar.

A temperature drop of just 15–30°C creates enough negative internal pressure (50–100 mbar) to pull the seal open and suck in ambient air to equalize the pressure (Stiemcke et al., 2024).

Mechanical load: Riding with heavy loads, such as cargo or trailers, places mechanical stress on the motor's internal components. This stress forces the crankshaft to flex slightly while rotating. This deformation prevents the seals from hermetically sealing and leaves the motor vulnerable to moisture ingress.

Vibration and impact: Riding on rough surfaces like cobblestones or hitting potholes transmits vibrations and sharp impacts to the motor, risking internal damage to gears and bearings.

4.1.3 Abrasive Contamination

Fine particles of sand and road grit act as a mechanical abrasive. This grit becomes embedded in the outer seals and, with every rotation of the crankshaft, grinds away at both the seal and the shaft (Figure 4.2). This process accelerates the failure of the seal, creating gaps for water to follow. This problem is more prominent with e-mountainbikes, which are riding in more tough conditions than city bikes and endure more harsh riding styles.



Figure 4.2. Dust and grit around the crank.

4.1.4 Maintenance

According to mechanics, the lack of maintenance directly increases motor workload and stress:

Maintenance: Users should perform regular maintenance on their e-bikes by mechanics or themselves. Causes of early failure consist of a worn chain, soft tires and not doing regular software updates. Regular maintenance can improve the durability according to the interview with remanufacturer 3.

Cleaning: Following survey results (van Dam, 2025) 9% of e-bike owners use a pressure washer to clean their bike (Figure 4.3). A high-pressure washer generates a force that not all e-bike motor seals are designed to withstand. The focused pressure could force water past the crankshaft seals and even the housing gaskets, which lead to water contamination of the bearings, mechanical components and internal electronics. Cleaning properly and timely can increase the service life and durability.



Figure 4.3. Washing an e-bike motor with a pressure washer.

4.1.5 Parking & Transport

Storing the bike outside in a damp environment constantly exposes the motor to humidity, even when not in use (Figure 4.4). In the Netherlands, 20% of e-bikes are stored outside at home, this figure rises when owners go out and park their e-bike outside (Jerom Götz & Dennis van Soest, 2025).

Bikes that fall over when parked receive an impact on the crank, potentially causing internal damage to gears and bearings, according to remanufacturer 1, 2 and 3.



Figure 4.4. E-bike storage outside.

Transporting an e-bike on the back of a car or caravan (Figure 4.5), creates a low-pressure zone behind the vehicle that, combined with road spray, draws moisture inside the motor through the seals, which has a negative effect on durability. Confirmed by remanufacturer 1.



Figure 4.5. E-bike transport on the back of a car.

4.2 Component Failures

Component analysis reveals that failure is rarely isolated, it is systemic. While bearings and PCBs are the failure points, their degradation is a symptom

of inadequate protection against moisture and thermal stress, rather than component weakness.

4.2.1 Ball Bearings

Inconsistent bearing sealing quality across brands creates weak points. The quality of ball bearings and the integrated water seal vary across brands, ranging from unknown Chinese manufacturers to

established manufacturers (SKS & NSK). The ball bearings are sealed on both sides with rubber (sealed RS-type) or metal (shielded ZZ-type) (Figure 4.6).



Figure 4.6. Ball bearing with metal sides ZZ (left), rubber sides RS (right).

The RS contact seals provide high protection effectiveness against external contaminants. In this type of seal, the sealing lips are in contact with the inner ring, which may lead to increased frictional moment. Due to the higher friction, bearings with contact seals operate at lower rotational speeds.

Bearings with non-contact seals typically use

metal sealing plates (ZZ-type bearings), which do not make contact with the inner ring. Compared to bearings with contact seals, they exhibit lower frictional moment and can operate at higher rotational speeds. However, their sealing performance is lower, so they should be used in less dusty and less aggressive environments. (Zmarzły et al., 2025)

The ball bearings are pressed into the cartridge body of the motor and/or onto the crankshaft

(Figure 4.7) and can be extracted with a bearing pulley or put on with a bearing press (Figure 4.8).

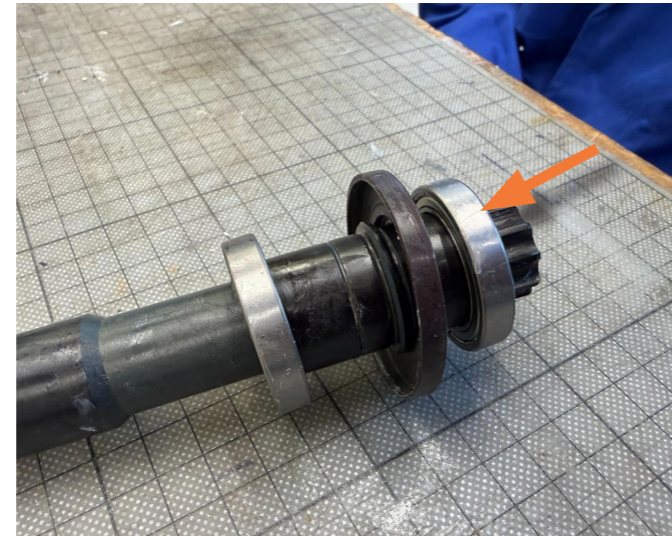
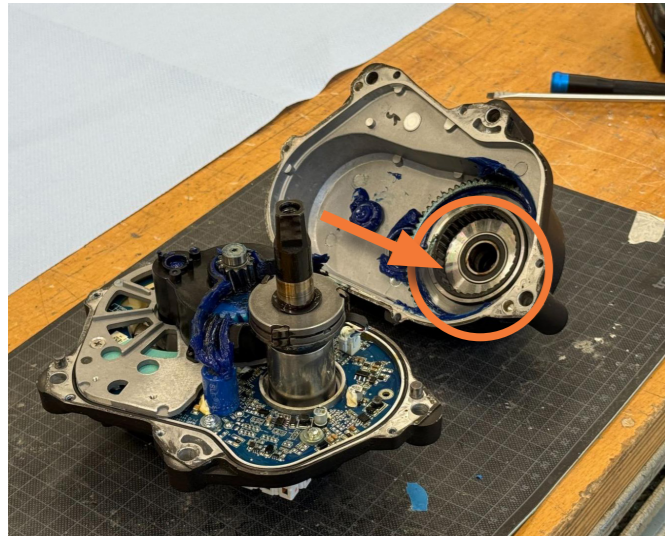


Figure 4.7. Ananda cartridge (left) and Brose crankshaft (right).

Not every OEM uses the same specification of ball bearings: only ZZ-type, only RS-type or mixed (Table 4.1).

Table 4.1. Type of bearings used per brand.

Bearings Choices	Brand
Ball bearings ZZ-type (metal)	Shimano DU-E5000 Shimano DU-EP600 Shimano DU-E6110
Ball bearings RS-type (rubber)	Bosch DBU 250 Ananda M81
Mixed use ZZ-type (metal) and RS-type (rubber)	Brose 3.1 Specialized Gobao P101 Bosch BDU 350

Brands use different methods of holding the ball bearings in place. Shimano and Brose hold the ball bearings in place by press fitting them in the body

and onto the crankshaft. On the contrary Bafang, Bosch, Ananda and Gobao use circlips in addition to the press fit to keep them in place (Figure 4.9).



Figure 4.8. Extracting ball bearing with a bearing pulley (left) and fitting with a bearing press (right).

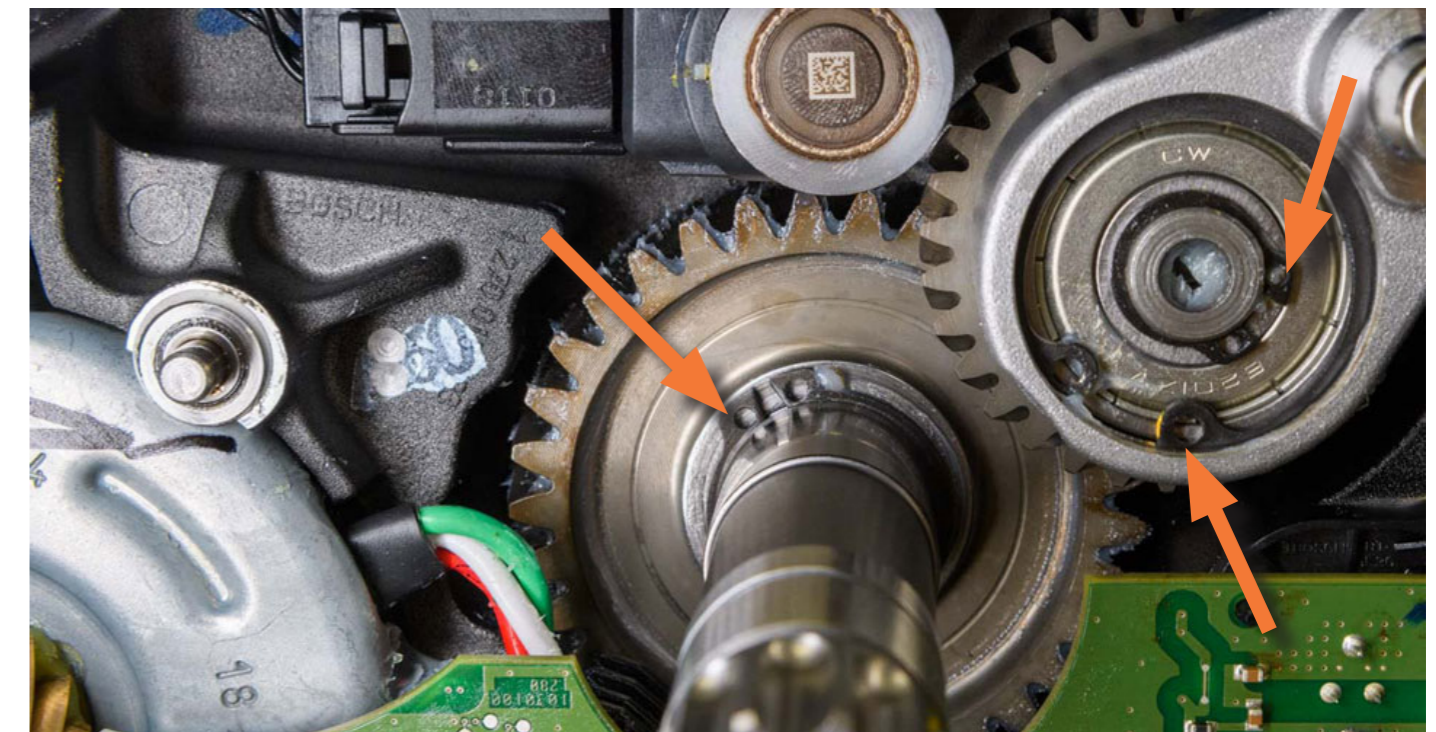


Figure 4.9. Circlip that holds ball bearing.

The type of fitting and type of bearings for every individual brand shown in Table 4.2. A circlip can guarantee the location of the bearing and hold it securely in place, in case of an impact of great force

or an accident. It takes more time to take out and needs a special circlip tool. With the teardowns it is not possible to assess which of the two ways is better for durability.

Table 4.2. Number of circlips in different motors.

	Brand	Motor Type	Type of Fitting	Number of Bearings
1	Shimano	DU-E5000	Press-fit	3
2	Shimano	DU-EP600	Press-fit	4
3	Shimano	DU-E6110	Press-fit	4
4	Bosch	BDU 250 (Gen 2)	Circlip-fit	8
5	Bosch	BDU 350 (Gen 3)	Circlip-fit	3
6	Bafang	M210	Circlip-fit	3
7	Ananda	M81	Press-fit	4
8	Brose	Drive S	Press-fit	3
9	Gobao	P101	Circlip-fit	5

According to the interviews with remanufacturers moisture ingress, the breathing cycle and corrosion is the cause of ball bearing failure and a problem for durability of the e-bike motor. The failures are also influenced by the riding style and maintenance of the user.

The SKF Group (2025) has written a report on bearing failure which explains moisture corrosion of bearings and failure. At standstill, free water in the lubricant will accumulate at the bottom of the bearing (Figure 4.10), which can lead to corrosion, and leads to structural failure:

Oxidation: When the motor is at a standstill, "free water" (undissolved moisture) separates from the lubricant due to its higher density. It settles into the contact zones between the rolling elements and raceways. This promotes localized electrochemical oxidation, resulting in greyish-black etched patches at rolling element intervals.

Abrasive wear: These etched patches create pits and flaking. During subsequent motor operation, these corrosion products act as abrasive particles, further degrading the raceway surface and increasing internal friction.

Structural failure: The localized corrosion significantly reduces the effective load-bearing area. Under the cyclic loading typical of e-bike propulsion, these weakened zones experience stress concentrations that lead to subsurface fatigue (Figure 4.11).

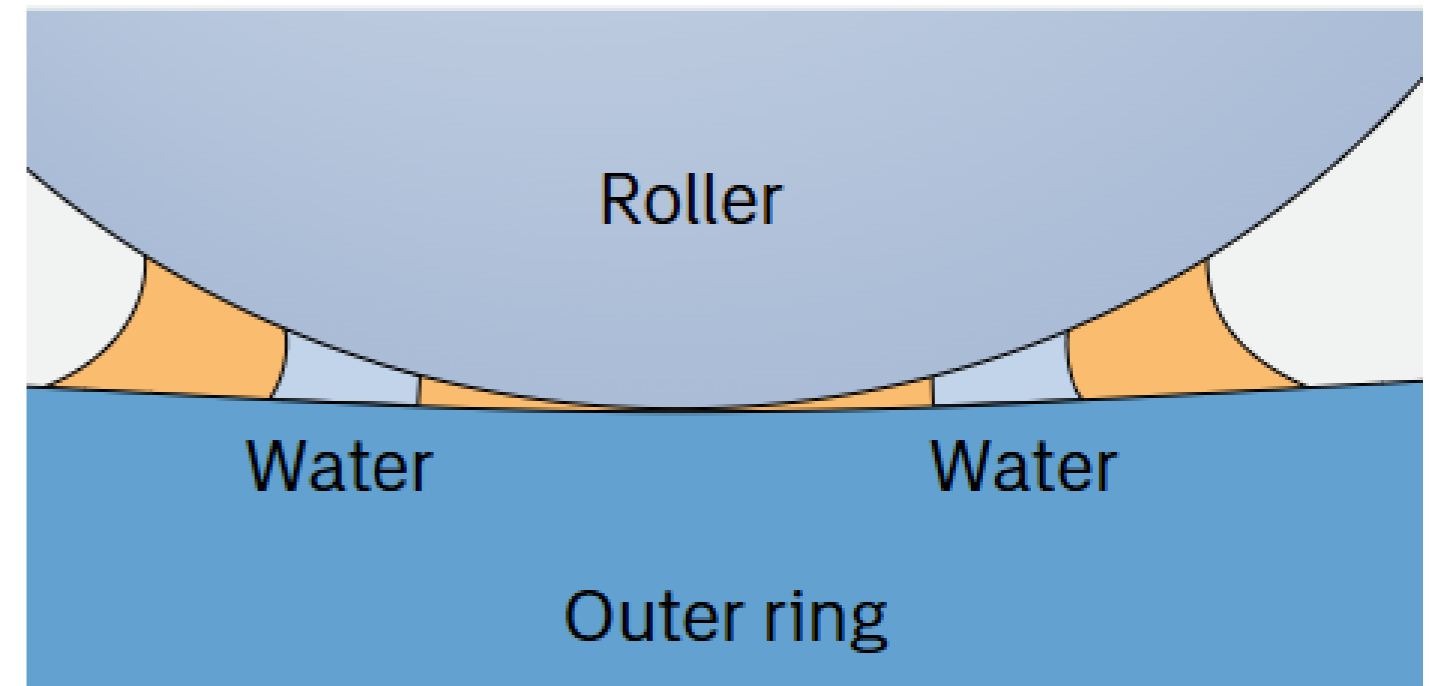


Figure 4.10. Free water in the lubricant accumulates at the bottom of the bearing (SKF Group, 2025).

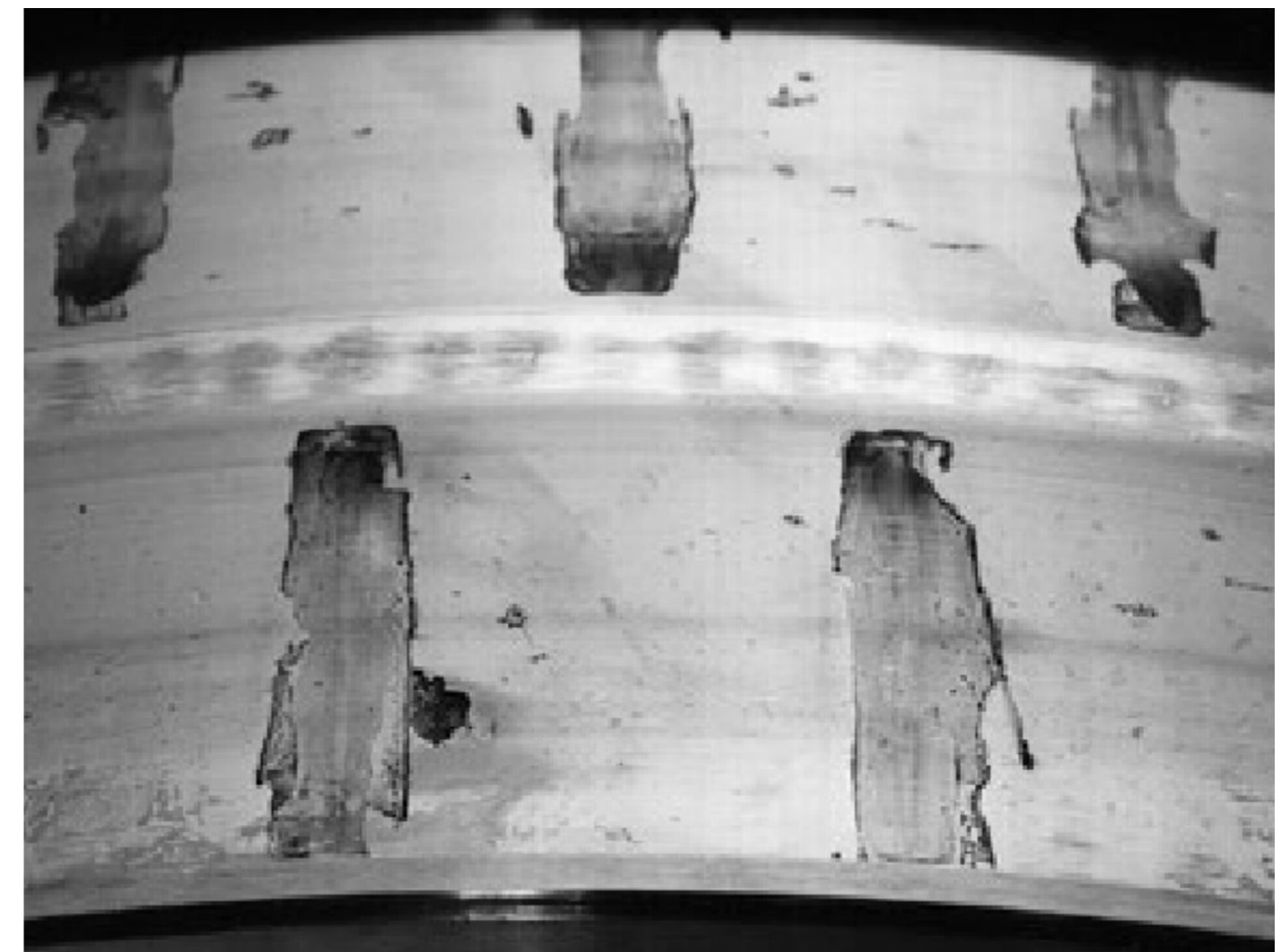


Figure 4.11. Initial patches of etching on raceway due to subsurface fatigue (SKF Group, 2025).

4.2.2 Needle bearing

Needle bearings are installed on the crankshaft to enable the motor's freewheel effect (Figure X). By connecting the crankshaft to the transmission, these bearings allow the components to spin freely of one another during operation.

According to remanufacturer 1, failure on the needle bearing is caused by build-up of dust and grit or moisture ingress that leads to corrosion and rust of the rollers (Figure 4.12).



Figure 4.12. New (right) and failed (left) needle roller bearing.

4.2.3 Shaft Seals

The sealing of the crankshaft is done by rubber seals that surround the crankshaft and sit tightly in the cartridge (Figure 4.13). The bearing behind this sealing has a metal or rubber sealing. Moisture ingress happens during the breathing cycle, which the seals can not prevent. They are unable to hermetically seal the unit between the crankshaft and cartridge.

Humidity can leak through them, reach the bearing, condense and oxidize bearings. In addition, if the user does not regularly clean around the seals, abrasive contamination degrades the seals over time, which can lead to more water ingress.



Figure 4.13. Water seal around crankshaft.

4.2.4 Cartridge Seals

The two halves of the cartridges are sealed in different ways by brands: a gasket in between the cartridges that needs to be replaced when reassembled (Brose and Bafang), a silicone seal line (Bosch and Ananda) and some type of waterproof glue (Shimano and Gobao). The gasket has a tight fit between the two cartridge halves, and is easy to replace when broken. The silicone seal line, when properly applied, like Bosch works, but when disassembled is easy to damage with a tool or screwdriver.

The Shimano seal has cracked parts and separations around its perimeter of the seal before opening the casing (Figure 4.14), which leads to water ingress and negative effect on durability. The cause of this could be bad design or manufacturing failure. If we look at the combination of durability and reparability the gasket has the upper hand. The cartridge seals only break with repair or refurbishment and does not get damaged by causes discussed in chapter 4.1.

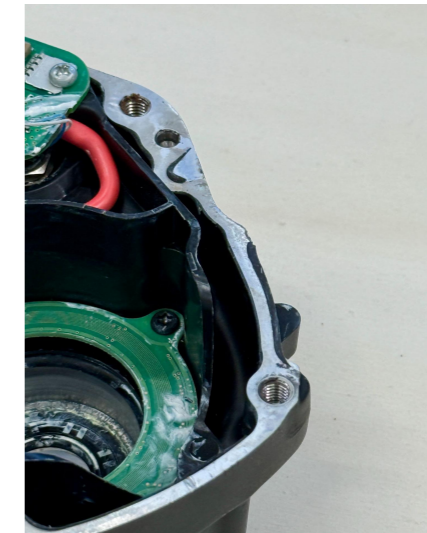
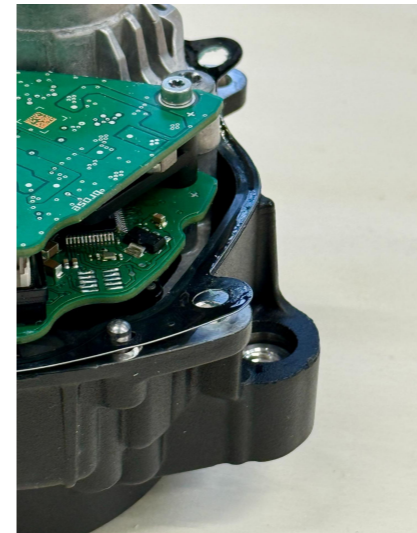


Figure 4.14. Gasket seal (left), Shimano seal (middle) and Bosch seal (right).

4.2.5 PCB

Brands have a different philosophy on the placement of the PCB. Different architectures show a top, down or side placement (Figure 4.15). Due to gravity, water droplets (liquid) will most likely accumulate at the lowest point of the motor according to remanufacturer 4. Condensation can form on all internal surfaces. The upper placement prevents the PCB from sitting in the

water, in a scenario where the motor would be flooded with water, unlike the lower placement. The side placement is also favoured over the low placement. Following the interviews from remanufacturers, the lower placement has a negative effect on durability due to vulnerability of ingressed water accumulating at the bottom of the motor.

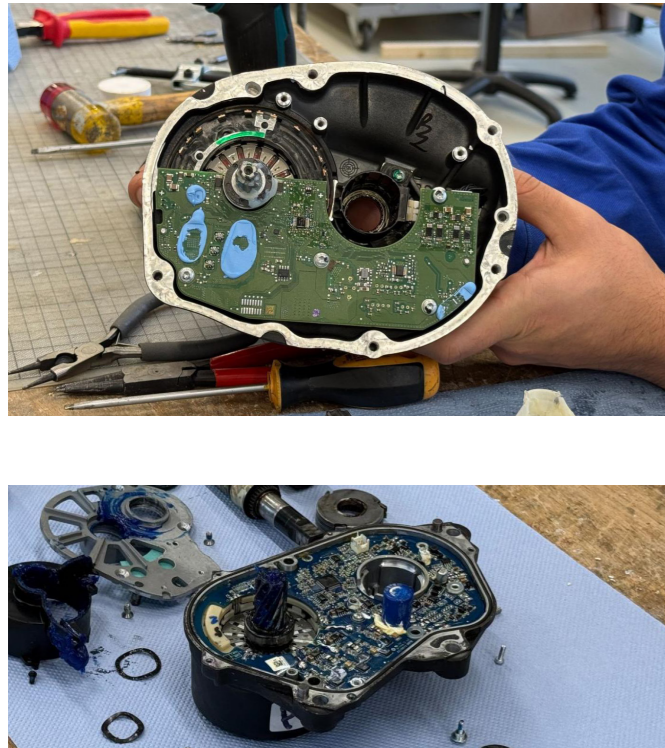


Figure 4.15. Different types of PCB placing.

In addition some of the PCBs are sprayed with a form of protective lacquer, conformal coating, to create a layer against humidity, condensation and water that directly comes onto the PCB. These coatings are from a range of different materials: Acrylic (AR), Silicone (SR), Polyurethane (UR), Epoxy (ER), and Parylene (XY) (Kumar et al., 2020).

This is a simple but efficient measure to reduce the risk of water ingress negatively affecting the electronics and increase the durability. On the other hand it makes it harder to perform PCB repairs which negatively influences repairability and remanufacturing.

4.2.6 PCB Connections

The majority of connections are done with a variety of screws: to close the cartridge, to fix the PCB to the body and other components. The fit is tight, the connections are robust and it enables it for repairability and remanufacture.

It is important to look at the electronic connections between the PCB, electric motor and the sensors, these are different with each brand.

Shimano soldered the PCB to the electric motor and made it hard to replace and disassemble. Brose and Bosch have invented a new connection

where it is possible to interchange the PCB units without soldering and risking the destruction. Figure 4.16 shows the difference between these brands.

The solution of Brose and Bosch enables repair, remanufacturing and replacement, but it is unknown whether the connections have the robustness and durability of soldering.

The solder connections could fail due to excessive vibrations and hard impacts that can follow from riding style and input.

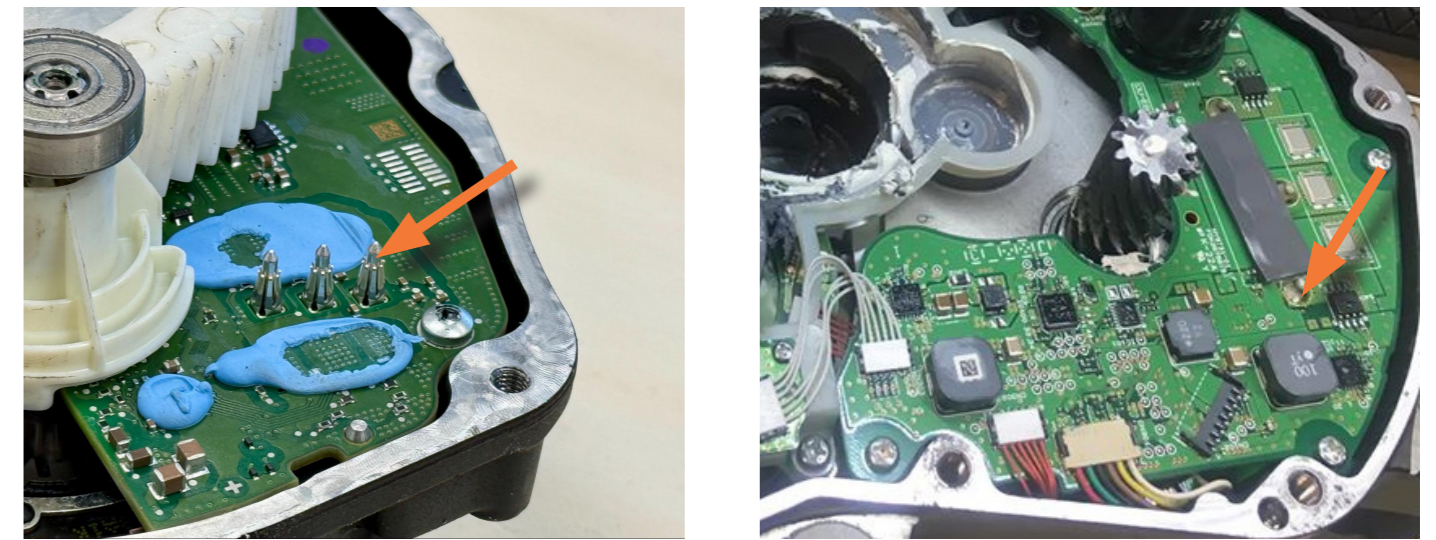
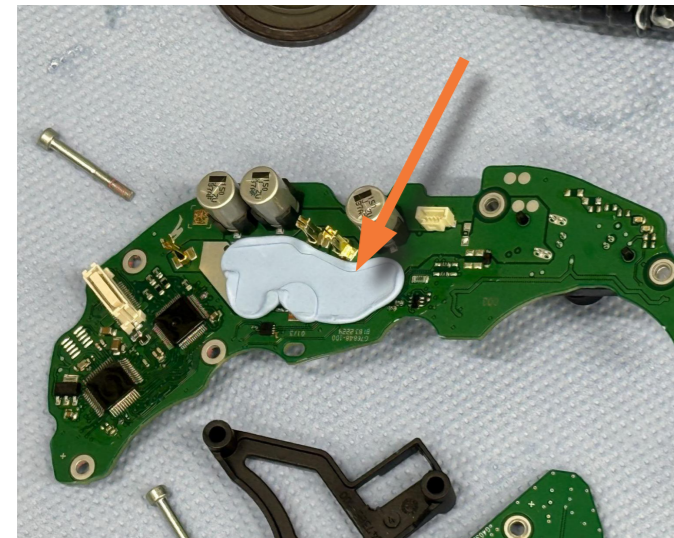


Figure 4.16. Difference between PCB connection Bosch (left) and Shimano soldering (right).

4.2.7 PCB Heat Management

The PCB heat management is done by using thermal paste, which reduces internal temperatures of the electronics by dissipating heat.

Thermal management is compromised during reassembly due to the instability of the thermal paste interface. According to remanufacturer 5, one of the problems is the thermal paste, that does not retain sufficient contact with the housing when the motor is reassembled (Figure 4.17).



This causes problems with the heat management of the PCB and has an impact on the wear which causes a negative effect on durability. To maintain the same level of performance it is required to add more thermal paste when reassembling the motor. The thermal paste only fails with repair or refurbishment and does not get damaged by causes discussed in chapter 4.1.

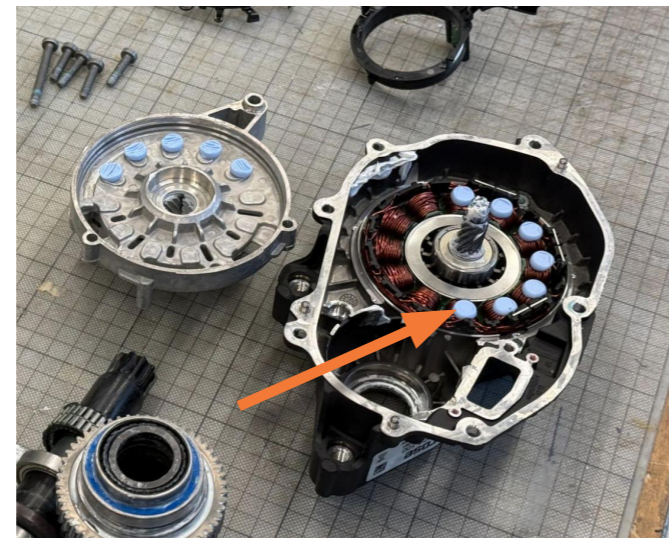


Figure 4.17. Cooling paste of the Brose motor on the PCB (left) and coils (right).

4.2.8 Hall Sensor

The e-bike motor has a variety of sensors, two of them are in the crankshaft: the hall sensor, which detects the rotor position and motor speed (Dora & Gouse Basha, 2023), and the torque sensor, which measures the torque input of the cyclist. The one that breaks most often according to remanufacturer 4 is the Hall sensor.

According to remanufacturers, these sensors are prone to breaking by water and by great force or vibrations. User input could reduce the risk of failure with maintenance and non-aggressive riding style. This is harder to achieve on an e-mountain bike than a city e-bike.

Figure 4.18 shows different crankshafts from multiple brands.

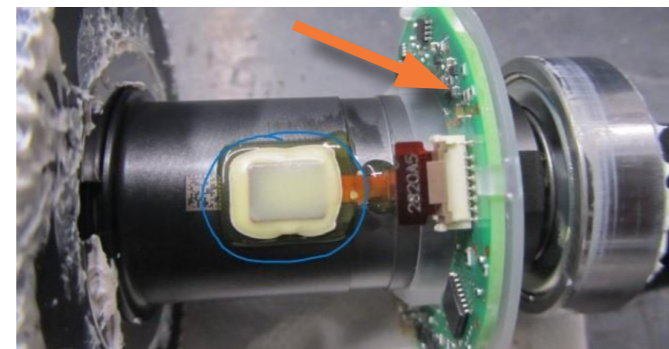


Figure 4.18. Shimano hall sensor (above) & Ananda hall sensor (under).

4.3 Conclusion

The primary barrier to achieving a 100,000km service life is not mechanical fatigue, but moisture ingress driven by the thermodynamic "breathing cycle".

Standard sealing solutions prove insufficient because they address the wrong problem: they attempt to block water physically, but fail to counteract the pressure differentials (up to 200 mbar) caused by thermal expansion and contraction. As the motor cools, negative pressure draws ambient humidity past the seals into the housing. Once inside, temperature fluctuations cause this humidity to condense, leading to bearing oxidation and electronic short-circuits. Abrasive contaminants like dust and grit grind away crankshaft seals, creating more pathways for water to enter via the breathing cycle. Rider behavior, specifically high-torque, low-cadence riding and improper cleaning with high-pressure washers, accelerates mechanical and sealing degradation.

Therefore, extending motor durability requires a fundamental shift in design philosophy: from passive moisture blockage (attempting to create an impossible hermetic seal) to active internal climate management.

Main Takeaways

From Sealing to Management

Since hermetic sealing is not achievable in dynamic conditions, the design must actively regulate internal relative humidity to prevent condensation.

Systemic Protection

Critical components (PCBs and bearings) require intrinsic protection (placement, coating) rather than relying solely on the integrity of the external housing.

Brand and motor type difference

Brands vary in their defense against water, some use gasket seals and conformal coating on PCBs, while others rely on silicone seals and vulnerable component placement. Every motor has their own positives and shortcomings, but not one is clearly better than the other.

5. Systemic Barriers to Durability

While Chapter 4 established the thermodynamic root causes of motor failure, this chapter explains why component failures result in the premature disposal of the entire motor unit.

Analysis of the e-bike value chain reveals that a closed supply chain, a regulatory void, and unfavorable repair economics create a systemic barrier to product life-extension.

5.1 Supply Chain

The primary barrier to motor repairability is the closed product ecosystem maintained by Original Equipment Manufacturers (OEMs). To understand this ecosystem, it is essential to analyze the structural disconnects within the e-bike motor value chain.

The value chain illustrated in Figure 5.1 is the result of the interviews with mechanics and remanufacturers. It maps the ecosystem of the e-bike motor, categorizing the interactions between stakeholders into four flows: Financial, Information, Goods/Service, and Political. Analysis of these flows reveals specific structural disconnects that hinder durability.

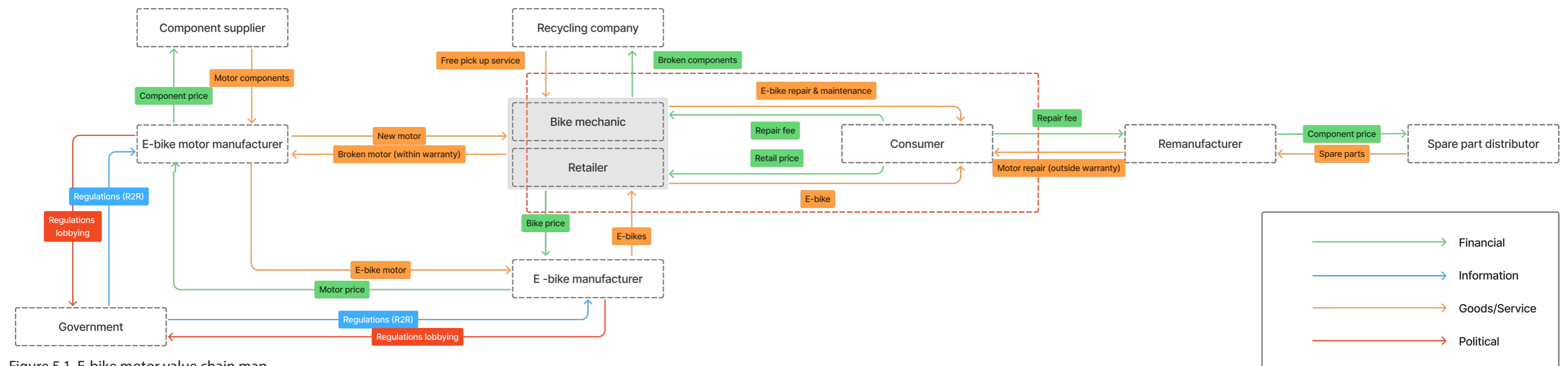


Figure 5.1. E-bike motor value chain map.

Goods & Service flow: In a circular model, spare parts flow from the OEM to bike mechanics and remanufacturers. However, the current chain restricts the flow exclusively to authorized dealers or retains them within the OEM's production cycle. Independent mechanics and remanufacturers are physically cut off from this supply.

Information flow: OEMs provide integration manuals to bicycle manufacturers, but detailed repair schematics and diagnostic firmware are withheld from the independent aftermarket. This creates a dependency where diagnostics can only be performed by mechanics with authorized digital keys, effectively barring independent intervention.

Financial flow: The primary revenue stream flows from the consumer to the bike manufacturer, and then to the e-bike motor OEM, in exchange for goods (complete e-bikes and motor aggregates). In the aftermarket, financial flows for services remain within the independent repair sector. However, the financial flow for spare parts does not exist. The OEM generates revenue almost exclusively from the production of new units, with no direct financial mechanism to capture value from maintenance or life-extension of existing motors.

Political flow: The regulatory feedback loop is currently inactive for this product category. Unlike consumer electronics, e-bike motors are excluded from the "Right to Repair" directive. Consequently, there is no legislative pressure forcing OEMs to open the goods or information flows, leaving the system closed.

Beyond the supply chain, practical barriers limit repair and remanufacturing efforts by repair shops. The components that make up the motor are quite technical, but replaceable. The high threshold to repair has several reasons. Parts are connected in a way that could break upon disconnection, for example with soldering and snapfits. Specialized OEM tools and jigs are required to open, service, and re-seal the motor housing to ensure it remains waterproof. According to remanufacturer 1, a procedure that is difficult to execute correctly without OEM equipment and/or parts, which OEMs do not supply.

5.2 Regulatory

The “Right to Repair” directive from the EU enables professionals and consumers to repair a broken product. Manufacturers have to provide spare parts, repair manuals, and software tools to enable and lower the threshold for repair. Unfortunately e-bike motors are not included under "Right to Repair" regulations. This means that at this moment Original Equipment Manufacturers (OEMs) are under no legal obligation to provide spare parts, repair manuals, diagnostic tools, or firmware to independent repair professionals or consumers making it more difficult to achieve a durable motor.

Including it in the regulations stimulates improvement of the motor service life. Professionals and remanufacturers who wish to repair or service an e-bike motor face three barriers:

Lack of repair manuals: Some manufacturers, like Shimano, provide documentation for system integration onto bike frames, but repair manuals for internal motor failures are rarely available. This forces repair professionals to rely on community-generated guides for bearing or gear replacements.

5.3 Economic

From an economic perspective, the business case for independent bike shops is difficult. Most shops are already occupied with routine maintenance and repairs of (e-)bikes. Interviews with local bike shops revealed that the process of diagnosing and

Specialized tools: Physical tools and digital tools to disassemble and/or fix error codes are only accessible by specialized authorized dealers, which are picked by the OEMs. These are not available to every bike mechanic shop.

Limited access to spare parts: Supply chains favor a 'Unit Replacement' model over component-level repair. OEMs rarely supply internal sub-assemblies (such as nylon gears, control boards, or torque sensors), forcing consumers to replace the entire motor unit for minor failures after warranty. Availability of these internal components are limited to certain OEMs (for example Bafang) or third-party reproductions

Including the e-bike motor in the Eco-Design and the Right to Repair directive improves the durability. It would force manufacturers to make spare parts available and enable remanufacturers to remanufacture e-bike motors (Erdmann et al., 2023).

repairing or remanufacturing a single failed motor is too time-consuming and costly, making it more expensive for the consumer than standardized, high-volume repairs and remanufacture processes.

5.4 Conclusion

The motor's lifespan is currently limited by its weakest component, once a seal or bearing fails, the lack of systemic support forces the disposal of the entire unit.

The findings of this chapter can be summarized through three primary systemic challenges:

Supply Chain: Original Equipment Manufacturers (OEMs) have a closed system withholding essential spare parts, detailed repair manuals, and diagnostic digital keys from independent professionals. Third-party remanufacturers cannot easily source the parts needed for life-extension.

Regulatory: Despite the 2024 EU "Right to Repair" directive's aim to promote sustainability, e-bike motors are currently excluded from these protections. This allows manufacturers to withhold the spare parts and manuals necessary for maintenance.

Economic: For local bike shops, the high time-cost of diagnosing and performing internal repairs makes the service economically unfeasible.

Because the current market ecosystem fundamentally prevents reactive repair, extending the e-bike motor lifespan to 100,000 km cannot rely on improved aftermarket serviceability. To bypass these systemic barriers, the design solution must be proactive rather than reactive. The motor must be engineered to manage internal humidity and prevent failure before it occurs, reinforcing the necessity for the active climate management strategy established in Chapter 4.

6. Current Measures

Current industry responses are from 3rd party companies that have developed repair protocols, they are unfortunately hindered by software locks and the inconsistency of scavenged spare parts.

OEMs are making incremental improvement to mid-drive motors and introducing a new generation of oil-filled motors to solve water ingress issues.

6.1 Repairability and Remanufacturing

E-bike motors are not free of failures. However, OEMs, refurbishment by 3rd party companies

and bike mechanics have taken measures for improving the service life of motors.

6.1.1 Routine Maintenance by Bike Mechanics & Consumers

According to interviews with bike mechanics, the first line of defense is routine bike maintenance. This includes cleaning the bike, maintaining the drivetrain, checking for external wear, to prevent the motor from having to deliver additional power to overcome increased friction. These measurements can be taken by mechanics and consumers.

Mechanics can address symptoms like creaking and failed external bearings but can not address the cause (for example, the internal condensation that destroyed the bearing), as this requires opening the sealed motor and expiring the warranty.

6.1.2 Parts and Information by Manufacturers

OEMs are slowly releasing more information on mid-drive motors, but brands use different strategies:

- Manufacturer Bafang has made replacement parts more accessible to the market.
- Brose has released public exploded-view guides for professionals.
- Bosch offers a service kit (Figure 6.1) for their second generation motor to repair, upgrade, and regrease the inside. The downside of the Bosch kit is that it can only be used after warranty expires and not for regular maintenance.

- Shimano does not yet offer any support on their products for consumers and/or professionals.



Figure 6.1. Bosch service kit for second generation.

6.1.3 Refurbishment by 3rd Party Companies

Third-party remanufacturers offer the service of remanufacturing e-bike motors. According to interviews, repairs are difficult due to OEMs not wanting to provide spare parts, manuals, or technical support to these companies. Third party remanufacturers need to scavenge spare parts and build their own stock from old and broken motor.

They invest in developing new components to upgrade the motors, by using higher quality bearings and improving waterproofing by adding extra layers of protection. Remanufacturer 2, from the interviews, aims for motors that are serviced to have an increased running time of a factor 2 with these upgrades. Refurbish company 1 has two examples on how they improve the service life of a Bosch generation 4 (Figure 6.2) motor and Brose motors with the remanufacturing process and are described in detail in Appendix F.

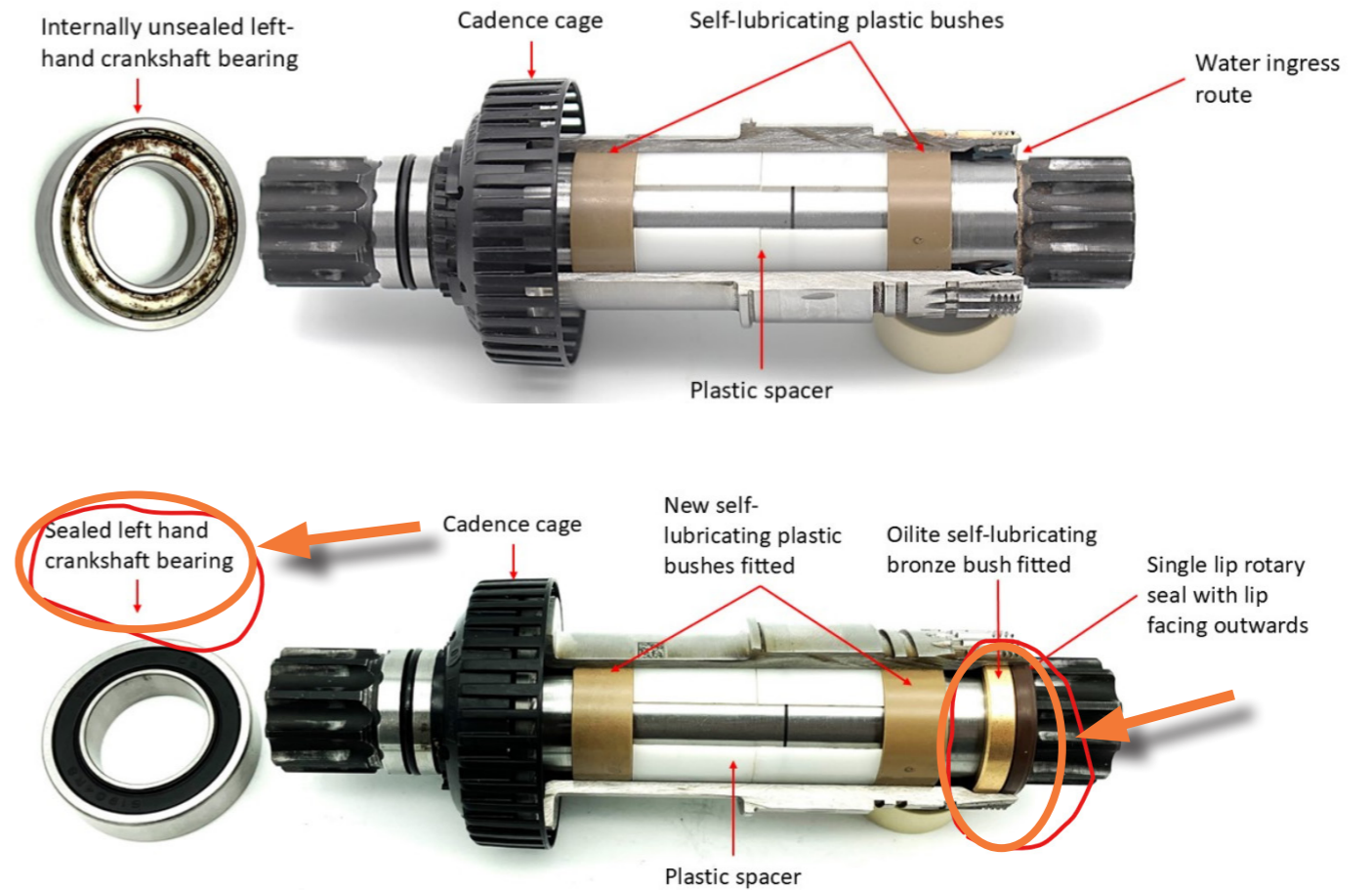


Figure 6.2. Bosch adjustments by eBike Motor Centre (2025).

The Brose motor is refurbished and upgraded in the following order (eBike Motor Centre, 2025): The refurbishment for the Brose prioritizes reinforcing the drivetrain transmission and creating a multi-stage water barrier. The process upgrades the

internal mechanics with a thicker carbon fibre belt and heavy-duty sprag clutches to handle torque loads, while sealing the crankshaft and bearings with X-rings, rotary seals, and waterproof grease to prevent ingress (Figure 6.3).

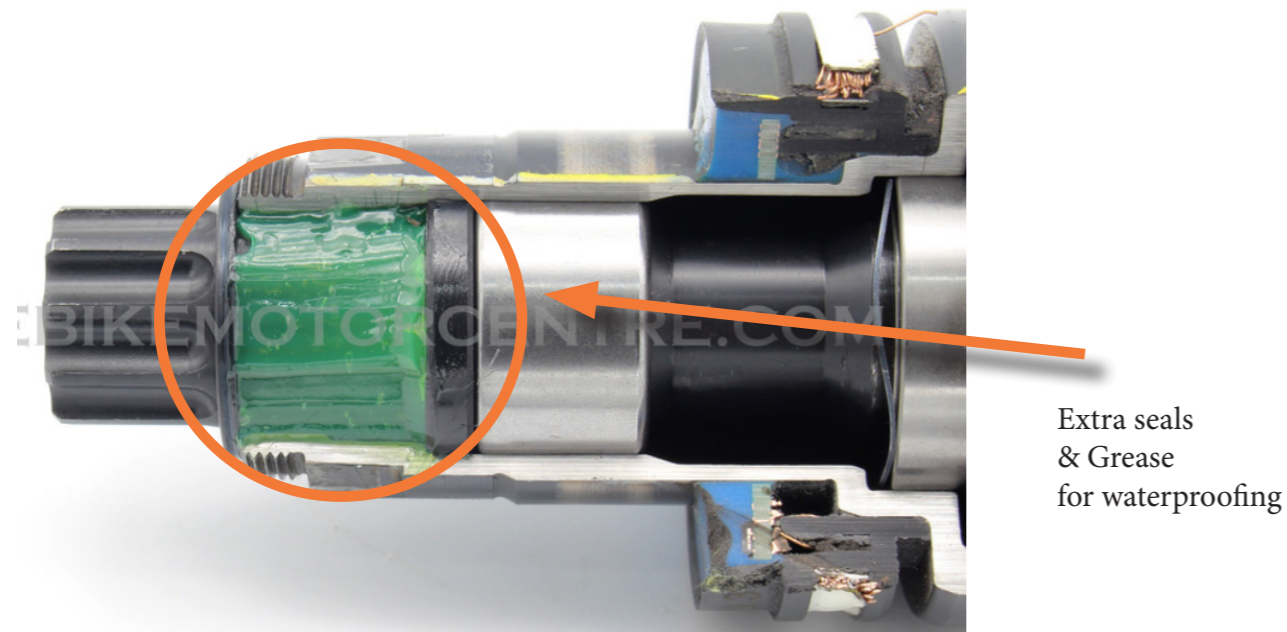


Figure 6.3. Brose adjustments by eBike Motor Centre (2025).

While these third-party upgrades are more effective at blocking liquid water and debris, they are thermodynamically incapable of stopping the 'breathing cycle.' Because these measures do

not account for the pressure differentials created during thermal cooling, moisture will still enter the motor as vapor, leading to the same internal condensation and bearing failure over time.

6.2 New Generation Mid-drive Motors

Newer motor generations (e.g., Bosch Gen 4, Shimano EP8) show improvements in sealing, but fail to address the thermodynamic pressure

differentials defined in Chapter 4. A new generation of oil-filled motors is introduced, that aims to solve water ingress and lubrication issues.

6.2.1 Design for Disassembly

Manufacturers Bosch and Brose have moved towards designs with fewer parts and simpler assemblies with their newer generation of e-bike motors. This approach, observed in the results from the disassembly method (Chapter 3.1), reduces the number of potential failure points and enables the motor to have a higher chance

of reparability, and one of the critical parts, the PCB, is enabled to be replaced. In addition, remanufacturer companies would need less time to service a motor. While this increases serviceability, it does not solve the root causes of water ingress.

6.2.2 New Generation of E-bike Motors

New motor designs that are fundamentally different from the current mid-drive motors are the Pinion E1.12 (Figure 6.4), the ZF CentriX (Figure 6.5) and the Intradrive GD8 (Figure 6.6). The Pinion and ZF motors are filled with oil, which has the benefit of keeping water ingress in the system to a minimum. The Intradrive has been designed with a circular vision for reparability and reuse.

1. Pinion developed a mid-drive motor with an integrated 12 speed transmission which functions similar to an automotive transmission (Pinion, 2025). The E1.12 is almost maintenance free and only requires an oil change every 10.000km. The oil change can be done by the consumer or a mechanic within 10 minutes. They claim that the waterproofness has improved over other brands, but this has to be evaluated over time.



Figure 6.4. Pinion E1.12.

2. ZF developed the CentriX (Figure 6.5) mid-drive e-bike motor (ZF E-Bike Systems, 2025). It is a small compact motor that is filled with oil which lets the motor run smoothly. ZF claims that the motor is “maintenance free” for the consumer, but the motor has not been on the market for enough time to claim this with certainty.

At the moment they do not have any remanufacturing capabilities, but they make spare parts available. The CentriX is designed for a minimal service effort by only attaching it to a bike frame by four bolts and a clamp. Allowing a certified dealer to remove and replace the motor in a short time period.



Figure 6.5. ZF CentriX.

3. Intradrive (Figure 6.6) developed a premium mid-drive motor with an integrated 8-speed transmission, which functions electronically similar to the Pinion motor (Intradrive, 2025). Its unique selling point is a foundation built on the circular economy: it is explicitly designed for repairability and reuse by guaranteeing long-term spare parts availability to extend service life after a failure. The fitting is the same as the Shimano EP8 and can therefore be exchanged on the same frame. Intradrive focuses on the production process being powered entirely by renewable energy.



Figure 6.6. Intradrive GD8.

6.3 Conclusion

In conclusion, the analysis of current market measures answers the third research question by revealing that the industry is currently divided between two conflicting approaches: improving repairability or durability. While OEMs are actively developing solutions to extend the lifespan of e-bike motors, no single strategy currently provides a validated solution to achieve the 100,000km goal.

Independent mechanics and remanufacturers are attempting to extend service life through maintenance and upgrades, such as better seals and bearings. However, this approach is limited by a lack of OEM support: without access to official spare parts or manuals, remanufacturers are forced to use parts of broken motors or engineer their own components. Furthermore, these physical upgrades still fail to address the underlying thermodynamic 'breathing cycle,' leaving the motor vulnerable to internal condensation.

From a durability perspective, the new generation of motors from Pinion and ZF represents a shift toward sealed, oil-filled motors. These designs aim to solve the water ingress and lubrication issues and make it possible to service these motors, for consumers and mechanics, by changing the oil. However, if something fails internally it is still difficult to repair due to the motor being sealed. It remains to be seen how these motors perform in practice, which may take several years.

Main Takeaways

Remanufacturing is hindered by closed supply chains

While remanufacturers can technically extend the life of motors by upgrading bearings and seals, they are systemically blocked by the refusal of most OEMs to supply necessary spare parts and service manuals. Some OEMs are trying to release more and more information.

Incremental changes do not fix root causes

Updates to current generations, such as simplified assemblies for easier disassembly (Bosch/Brose), improve the repair process but do not fundamentally solve the "breathing cycle" or water ingress issues that cause failures.

New generations of oil-filled motor could be the future

New innovations like the Pinion and ZF oil-filled motors address the root cause of water ingress and wear. They could be the future of the e-bike motor sector, but there is not enough research done yet on how they perform after multiple years of service

7 Design Direction

The analysis changes the design direction. To achieve the 100,000km target, the solution must

actively manage internal humidity rather than only attempting to block moisture out.

7.1 Main Findings

The initial assignment set out to "design a durable e-bike motor concept to extend the lifetime expectancy to 100,000 km, while being maintenance-free for its users". Through the disassembly of nine motors and interviews with repair professionals, the research has identified specific barriers preventing this goal. The findings answer the research questions regarding why motors fail and what measures are currently insufficient.

cycle. As the motor heats and cools, pressure differentials (up to 100–200 mbar) create a negative pressure. This "breathing cycle" sucks ambient humidity past the seals, which condenses on internal surfaces when the temperature drops below the dew point.

Once condensation forms, it leads to the oxidation of bearings (specifically the separation of water in lubricant) and short-circuits in the PCB or sensors. The motor's life is currently limited by its components that are sensitive to moisture.

The barrier to durability is not mechanical fatigue, but moisture ingress driven by the breathing

7.2 Design Vision

The research findings make a shift in design vision to achieve a durable motor. Current OEMs rely on attempting to create a hermetic seal with standard sealing technology, which is insufficient to counteract the pressure differentials (up to 200 mbar) generated by the motor's thermal cycles (breathing cycle).

Acceptance of ingress: Recognizing that standard seals cannot remain gas-tight under dynamic negative pressure.

Prevention of condensation: Maintaining the internal environment above the dew point through active humidity regulation.

The new design vision is based on managing the internal climate of the motor. This approach acknowledges that moisture ingress is a byproduct of the "breathing cycle" and shifts the objective from blocking air exchange to regulating internal Relative Humidity (RH).

7.3 Function Requirements

The requirements drafted from the research can be seen in Table 7.1.

Table 7.1. Table of function requirements.

	Function Requirements	Reference
1	The concept must be able to be integrated into existing motor architectures.	Chapter. 4
2	The concept must facilitate serviceability and maintenance for mechanics and non-expert users.	Chapter. 4
3	The concept must regulate the humidity level within the motor housing to prevent condensation.	Chapter. 4
4	The concept must be durable.	Chapter. 5

8. Ideation & Prototyping

To eliminate condensation as the primary root cause of motor failure, the design strategy must shift from passive moisture blockage to active management of internal humidity through absorption. Based on the thermodynamic analysis of the breathing cycle (Chapter 4), three strategies were evaluated: Prevention, Absorption, and Regulation.

Following this evaluation, the chapter outlines an iterative design process used to develop the chosen absorption strategy. It describes the various prototyping cycles and design decisions that had to be made to develop the concept into a viable physical solution

8.1 Selected Strategy

To manage moisture ingress driven by the breathing cycle, three fundamental strategies exist: Prevention, Absorption, and Regulation.

Unlike Prevention, which fights the pressure differential, and Regulation, which adds complexity, Absorption aligns with the requirement for a passive, maintenance-friendly solution to prevent condensation

An evaluation against the functional requirements (Chapter 7.3) identifies Absorption as the best strategy.

8.2 Strategies

8.2.1 Prevention

This design direction focuses on prevention of water ingress by defending with improved water sealing and protection methods (Figure 8.1).

This concept focuses on the "First Line of Defense." This design aims to improve the existing sealing of the motor against water ingress while neutralizing the internal pressure difference with the external pressure. With the goal to prevent the motor from sucking in humid air due to its lower pressure after working mode. This approach could mean one or a combination of the following measures:

Improved sealing: Use newer off-the-shelf shaft seals, for example labyrinth seals that make water ingress more difficult to occur.

Crankshaft stabilization: Stabilize the crank with extra shaft rings to prevent deflections which degrade the seals at a faster rate.

Potting electronics: Encasing the electronics in a solid compound. This measure is seen in some motors to prevent failure from water, but it has a negative impact on reparability or recycling and does not help to protect the bearings.

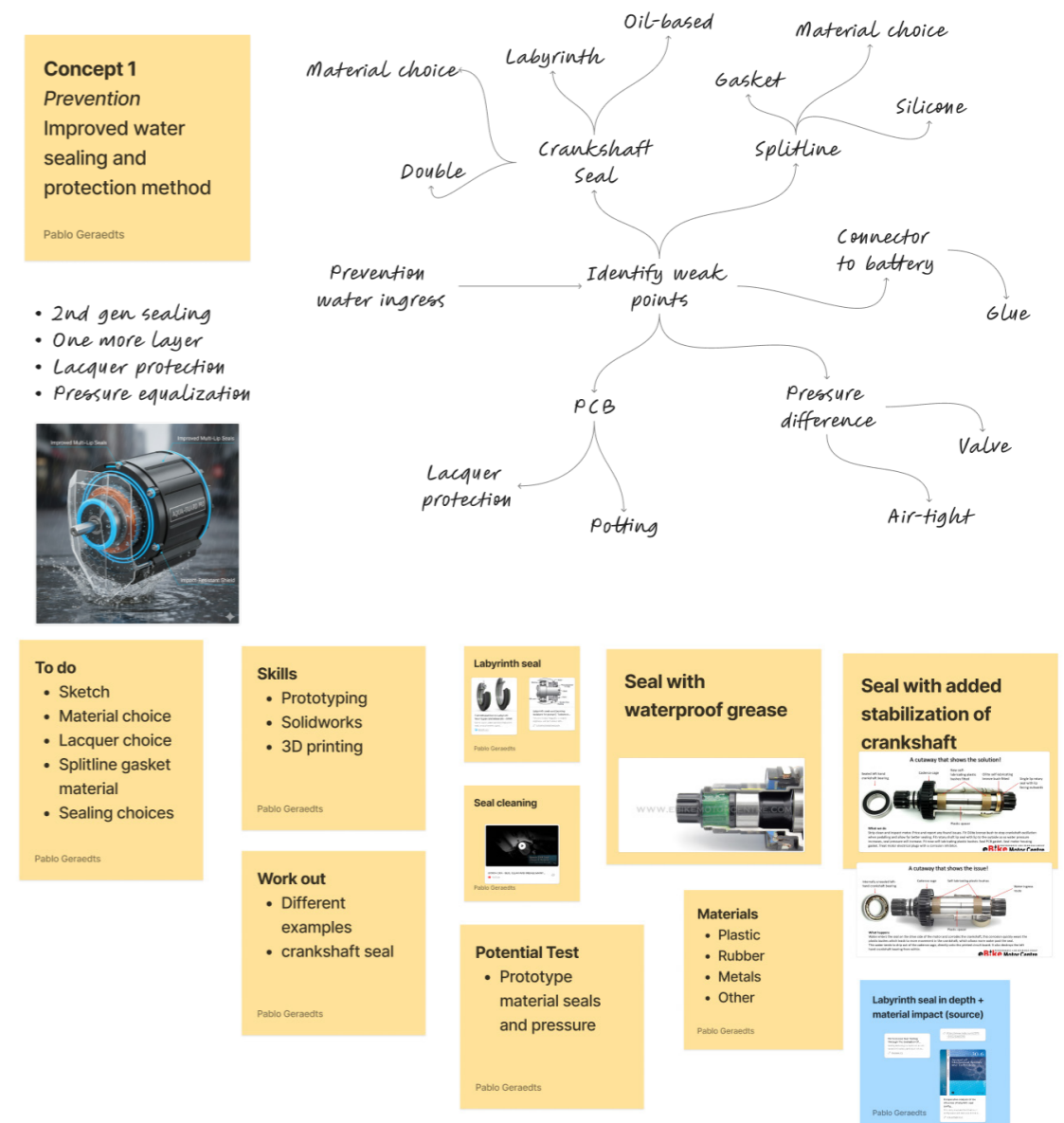


Figure 8.1. Brainstorm on prevention.

8.2.2 Absorption

This design direction focuses on the absorption of ingressed moisture inside of the motor and increasing durability by lowering the humidity to prevent condensation (Figure 8.2).

This concept shifts the strategy from "perfect sealing" to "absorbing moisture ingress." It addresses failure mode of the breathing cycle, where cooling air contracts and pulls in humid air. The system prevents the condensation by introducing a moisture absorbent material, which works as a sponge, in the motor.

This keeps the internal relative humidity below the dew point, preventing the condensation that corrodes bearings and short-circuits PCBs. This approach could include:

Passive desiccant: The passive use of a water-absorbent material.

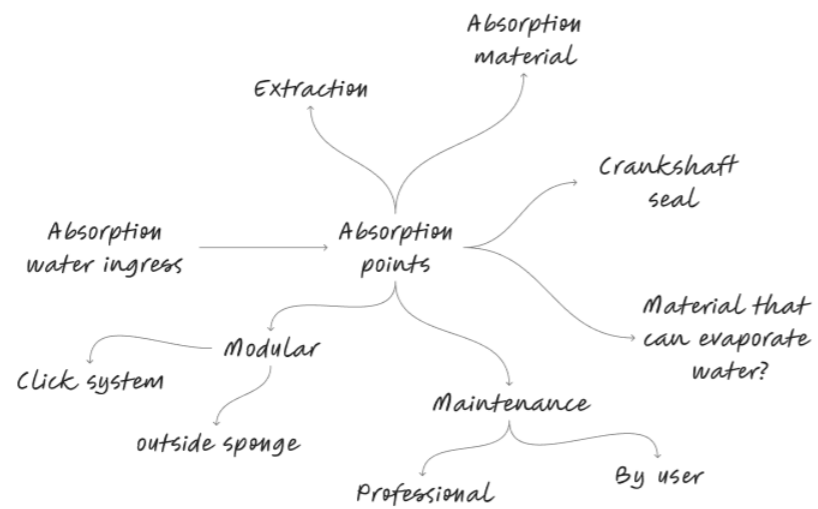
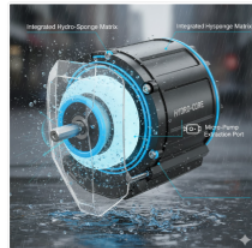
Saturation indicator: An indicator as a visual cue to indicate when the material is full.

Modular slider: A mechanism that enables the option to replace the absorbent material when saturated.

Concept 2 Absorption Water absorption inside the motor & How to extract

Pablo Geraedts

- Sponge
- Modular slot



8.2.3 Regulation

This design direction focuses on regulation of water by evaporation of water with a "heating cycle" inside of the motor with the use of heating elements (Figure 8.3).

This direction actively manages the internal environment rather than passively blocking or absorbing moisture. It would use the motor's power source to actively dry the inside of the motor with a "heating cycle".

Instead of allowing the motor to cool after a ride, this system heats up the motor to a temperature of 70-80 °C for X amount of time to evaporate moisture that got in during the ride or does a cycle once per week when the battery is charging. The goal is to reset the internal humidity inside of the motor every week through active heating and consists of:

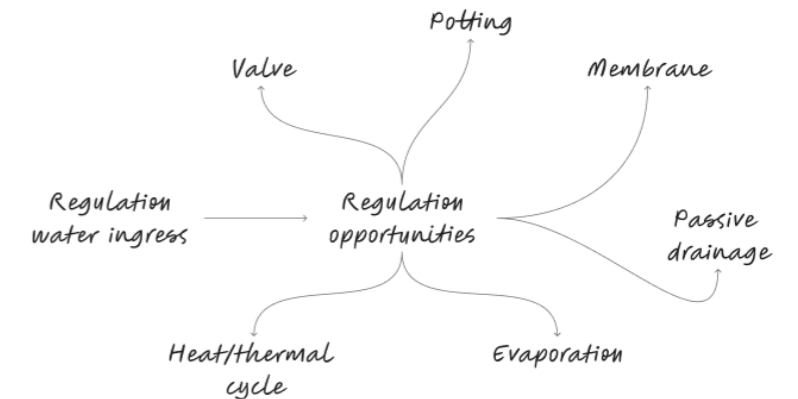
Thermal regulation: Active heating and pressure maintenance.

One way purge valve: Allow evaporated moisture to escape.

Concept 3 Regulation Water regulation/ evaporation with motor electronics

Pablo Geraedts

- Passive drainage
- Heat evaporation
- One-way valve



To do <ul style="list-style-type: none"> • Sketch • Brainstorm modular slot • Sponge choice • Placement 	Skills <ul style="list-style-type: none"> • Prototyping • Arduino • Solidworks • 3D printing 	Mechanism <ul style="list-style-type: none"> • Standard slide • Screw motion • Leave in • Placement? 	Requirements <ul style="list-style-type: none"> • X amount of water • Maintenance x time
Potential Test <ul style="list-style-type: none"> • Setup with different materials • Measure water absorption levels • Prototype slider 	Work out <ul style="list-style-type: none"> • First mechanism • Materials • Ability to attract water • Other sector examples 	Materials <ul style="list-style-type: none"> • Silica • Polymer • Sponge-like • Gel • Calcium 	Other sectors <ul style="list-style-type: none"> • Industrial

The Component: Molecular Sieve (Type 4A or 13X) Packet.
 • Scientific Backing: Unlike silica gel, Zeolites (molecular sieves) retain trapped water even at 100°C and work efficiently at very low humidity levels (<20% RH). They will not "release" moisture back into the motor during a hot ride.

• Molecular Sieve
 • Gore automotive venting

The Component: Adhesive ePTFE Vent (e.g., Gore-Tex patch).
 • Scientific Backing: Research confirms ePTFE allows water vapor (0.0004 microns) to escape while blocking liquid water (2+ microns) and contaminants. It equalizes internal pressure (ΔP = 0), preventing the "vacuum effect" that sucks water past seals.

To do <ul style="list-style-type: none"> • Sketch • Brainstorm evaporation 	Skills <ul style="list-style-type: none"> • Prototyping • Arduino • Thermodynamics 	Heat with <ul style="list-style-type: none"> • Current parts • Extra heating element • External • X degrees for x time 	Trigger <ul style="list-style-type: none"> • Time • Moisture levels • Temperature 	Pressure relieve <ul style="list-style-type: none"> • Valve • Membrane • Active opening 	Stator heating DC
Potential Test <ul style="list-style-type: none"> • Setup with heating element • Measure evaporation & moisture levels • Heatcycle prototype 	To Do <ul style="list-style-type: none"> • touchpanel machine • Other sector examples • Heatcycle example 	Cycle <ul style="list-style-type: none"> • High level of moisture • Heat up for x amount of time • Open valve • Cool down • Be fully dry 	Other sectors <ul style="list-style-type: none"> • Automotive • Industrial • EV motors 	Gas Purging system	Scientific Backing: Industrial standards (IEEE 1415) for protecting large electric drives recommend maintaining windings at 5-10°C above ambient to prevent condensation. For drying, a controlled current heats the copper coils from the inside out.
			Gore Tex venting membranes in car headlights	Condensation	

Figure 8.2. Brainstorm on absorption.

Figure 8.3. Brainstorm on regulation.

8.2.4 Strategy Selection

The three strategies were evaluated through the function requirements of Chapter 6.3 (Table 8.1) and the absorption strategy fits the requirements.

Table 8.1. Strategy Decision Matrix.

RQ	Prevention			Absorption			Regulation		
RQ1 Integration			■			■			■
RQ2 Maintenance		■						■	
RQ3 Regulate Humidity						■			■
RQ4 Durability		■				■			■

Together with a remanufacturer and an OEM, the strategies were evaluated against the requirements, to conclude that the absorption direction would have the most potential and is the most interesting to work out:

Prevention: This direction was rejected because it resembles an "off-the-shelf" improvement of sealing. It functions as a "put together improvement" rather than a novel solution to the breathing cycle.

Absorption: This direction was selected. It represents a novel approach in the e-bike motor sector, drawing inspiration from desiccant use in industrial applications. It proactively manages the internal climate to prevent condensation before it forms.

Regulation: This direction was rejected because it does not address the breathing cycle itself. It is a reactive measure that actively dries an environment where condensation may have already occurred.

Based on the selection process, the absorption direction has been chosen for further development. It aligns with the design vision of managing internal humidity to prevent condensation and improve the durability of critical components.

8.3 Fundamentals

The selected design direction, Concept 2: Absorption, shifts from the current strategy, attempting to create a hermetic seal to managing the internal climate of the motor. To successfully implement a moisture-absorbing solution that

extends the motor's lifespan, the design must be based on thermodynamic principles to prevent condensation. This section outlines the physical fundamentals of pressure, water vapor, humidity and dew point.

8.3.1 Pressure Difference

Moisture ingress in e-bike motors occurs with a pressure differential between the internal and the external environment. This phenomenon is governed by the Ideal Gas Law:

$$PV = nRT$$

Where P is pressure, V is volume, n is the amount of substance, R is the ideal gas constant, and T is temperature. Since the volume (V) of the motor housing is fixed, changes in Temperature (T) directly result in changes in Pressure (P)

The motor generates heat, causing the internal air to expand and creating positive pressure that pushes air out through the seals. Vice versa, when the motor is stopped and cools down, the internal air contracts. This decrease in temperature creates a negative pressure inside the housing.

The working range of an e-bike motor is between 50 and 80 °C. If the ambient temperature is 20 °C, it will give a temperature difference of 30 °C to 60 °C. This temperature difference gives a pressure difference of 100 to 200 mbar.

While axial lip seals are effective at retaining grease under positive pressure, they are often designed to be compliant and can allow air to bypass them under negative pressure. This effect sucks moist ambient air past the seals and into the motor, filling the internal air volume with humidity.

8.3.2 Water Vapor Pressure & Relative Humidity

To prevent condensation, it is necessary to understand the behavior of the moisture once it has entered the motor. Relative Humidity (RH) is defined as the ratio of the partial pressure of water vapor ($P_v(T)$) to the saturation pressure of water vapor ($P_{sat}(T)$) at a given temperature:

$$RH = \frac{P_v(T)}{P_{sat}(T)} 100$$

The amount of water vapor (P_v) inside the motor remains constant, but the pressure also changes depending on the temperature. The saturation pressure fluctuates (less than P_{sat}) depending on the temperature.

Although only a portion of the internal air volume (~25%) is exchanged during a single thermal cycle, the psychrometric analysis (Figure 8.1) must account for cumulative moisture ingress. Initial cycles have a lower humidity with a lower dew point. However, without a mechanism to actively dehydrate the motor internally, the RH inside will rise and the chance of condensation becomes higher as the saturation temperature rises.

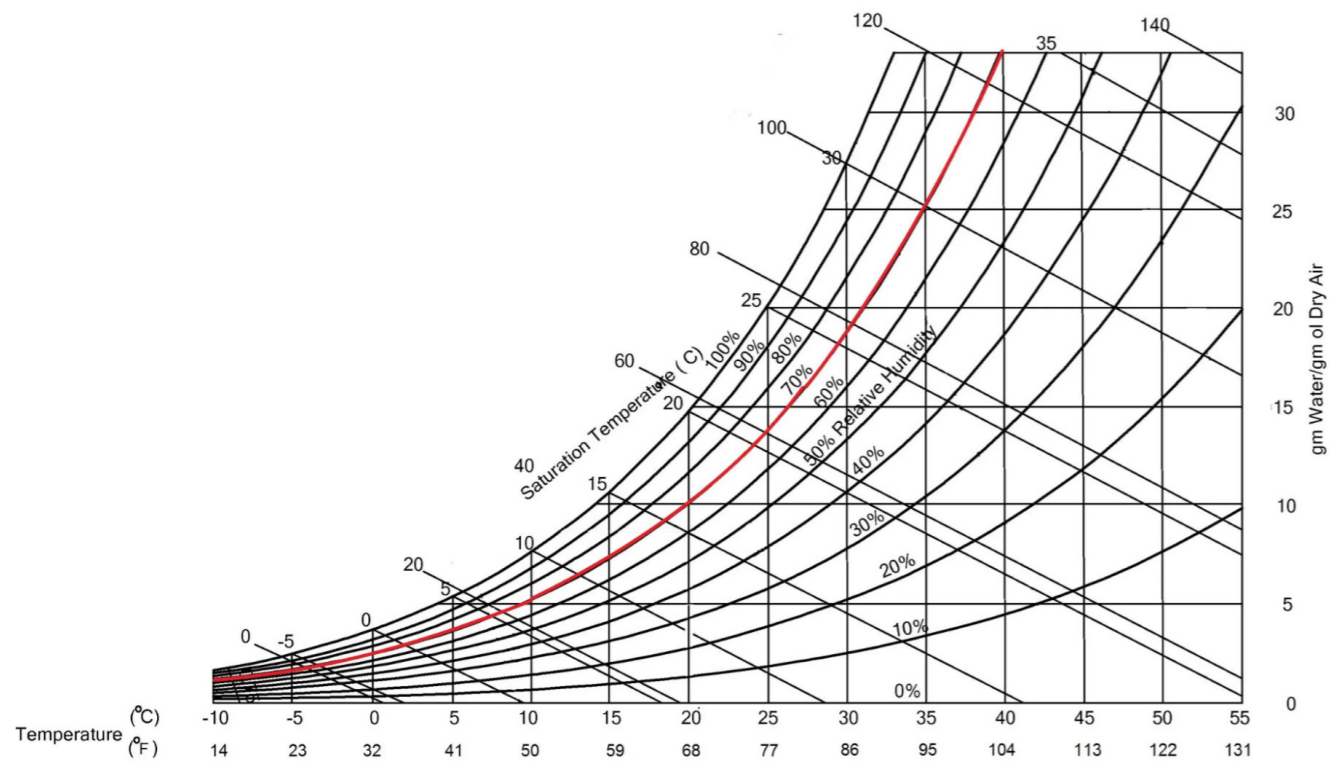


Figure 8.1. Psychrometric chart relation between air temperature and moisture.

The water vapor pressure is the measurement of the absolute amount of water held by the air. As the e-bike motor cools down after a ride, the capacity of the internal air to hold water decreases. If the absolute amount of water vapor remains constant, the Relative Humidity rises as

the temperature drops. If the RH reaches above 100%, the air becomes supersaturated (dew point), and the water vapor will condensate into liquid water on the internal surfaces of the motor that cools down the fastest.

8.3.3 Dew Point

The dew point is the temperature to which air must be cooled, at constant pressure and water vapor content, for it to become saturated with humidity (100% RH). When the temperature of the internal components (such as the metal motor housing or bearings) drops below the dew point, the air can no longer hold its water vapor. The excess moisture condensates onto those cooler surfaces.

In the context of an e-bike motor, the dew point is dynamic. If the "breathing cycle" draws in moist ambient air during the cooling phase, the absolute amount of water vapor inside the motor increases. When the temperature of the internal

air lowers, so does the dew point.

The goal of the Absorption concept is to use silica gel to keep the actual water vapor pressure (P_v) low enough that the dew point always remains below the ambient temperature.

By maintaining this buffer, the system ensures that even during rapid cooling, the internal component surfaces do not fall below the dew point, thereby preventing condensation.

8.4 Embodiment/Prototyping

8.4.1 Desiccant Material

Silica Gel is selected (Table 8.2) with the requirements. to control the water vapor pressure (P_v) and with that affect the Dew Point. The desiccant has a linear absorption rate, high absorption to weight ratio of 35%, regeneration temperature of 120 °C (above the working temperature of e-bike motors), it does not expand

with absorption and it changes color (orange to green) when saturated.

This provides a clear visual cue to the user or mechanic that the cartridge requires replacement.

The materials that were taken into consideration: Silica Gel, Calcium Chloride, Bentonite and Zeolites (molecular sieve).

Table 8.2. Matrix on choosing material with requirements.

RQ / Wish	Silica Gel	Calcium Chloride	Bentonite	Zeolites
RQ 2.4	Available	Limited availability	None	None
RQ 3.1	Linear	Exponential (better at high RH)	Good at low RH	Best < 20% RH
RQ 3.2	105 - 120 °C	Not possible	120 °C	350 °C
Wish 3.2.1	Yes	No	Possible (capacity degrades)	Yes
RQ 3.3	Stable	High Risk	Stable	Extremely stable
Wish 3.3.1	None	Expands in Volume	Minimal change of Volume	None
Wish 3.3.2	30 - 40%	300% +	25%	20 - 25%
Wish 3.3.3	Moderate	Excellent	High	Moderate

	Requirements
RQ 2.4	The saturation level of the desiccant must be visible without removing the motor cover.
RQ 3.1	The desiccant must be able to reduce relative humidity inside the casing from [X]% to [Y]% within [Z] minutes (response time).
RQ 3.2	The desiccant must be able to be used multiple times.
Wish 3.2.1	The desiccant should be able to be regenerated for a minimum of 5 times.
RQ 3.3	The moisture must not be able to evaporate out of the desiccant under a minimal temperature of 90 °C.
Wish 3.3.1	The desiccant material expansion should be as minimal as possible.
Wish 3.3.2	The absorption to weight ratio should be as high as possible.
Wish 3.3.3	The volume needed for the desiccant should be as minimal as possible.

8.4.2 Desiccant Sizing

Calculations (Appendix G) determine a yearly moisture ingress of 0.567g, totaling 1.134g over the target two-year period. By applying a Safety Factor of 3 to account for usage variability, and considering the specific absorption capacity of silica gel, a total mass of 10 grams is required.

To ensure a maintenance-free interval of two years (RQ 2.1 Table 2.1), the desiccant volume was calculated based on regional humidity data (KNMI, 2021). This model accounts for fluctuating Absolute Humidity in the Netherlands and assumes a high-usage scenario of 3 bike trips per day (1,000 rides per year).

Table 8.3. Desiccant requirements.

	Requirements
RQ 2.1	The motor must be maintenance free for a minimum of 2 years.

8.4.3 Cartridge Geometry

The Brose motor is used as a reference model to demonstrate the fit and physical interaction of the desiccant cartridge. The medium/medium geometry (Figure 8.4) minimizes interference with internal gears and requires minimal machining of the magnesium housing, making it a feasible design to integrate into the Brose motor and meet requirements (Table 8.4).

Defining the geometry of the cartridge requires balancing the perimeter of the bolt. A larger perimeter provides the advantage of requiring less magnesium in the motor casing. However, the disadvantage is that a larger perimeter creates a bigger sealing area, which increases the potential risk of water ingress.

Figure 8.4 demonstrates different aspect ratios with the same volume sizes.

- Deep/narrow
- Medium/medium
- Shallow/wide

The positioning of the silica gel within the motor is flexible: as long as the material remains in direct contact with the internal air, it will extract humidity regardless of its exact placement. Because of this flexibility, the measurements of the cartridge bolt can be adapted to suit the specific architectures of different motor manufacturers.

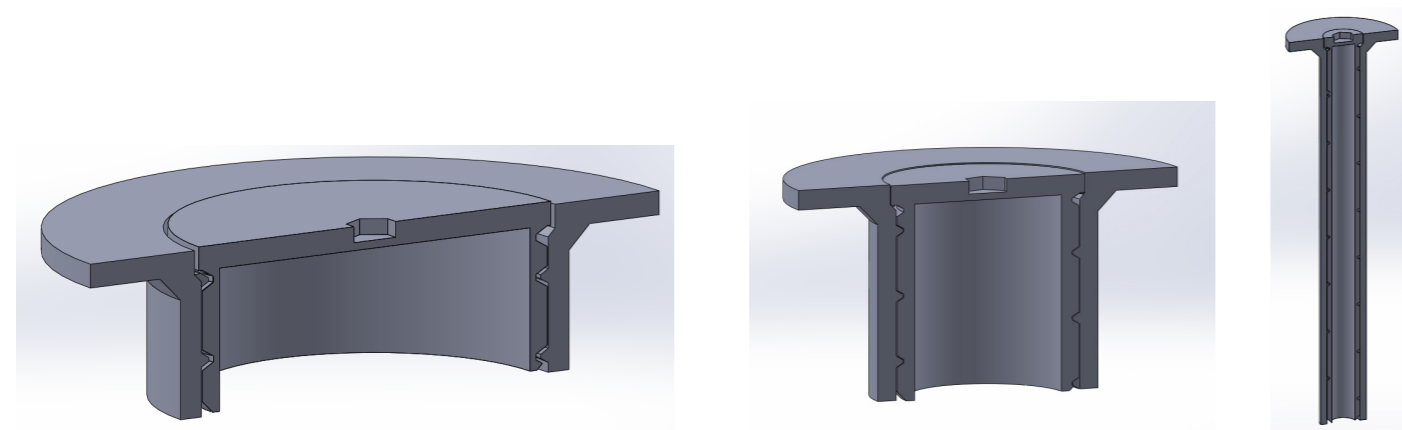


Figure 8.4. Three SolidWorks models with different aspect ratios and the same volume.

Table 8.4. Requirements cartridge geometry.

	Requirements
RQ 1.1	The body design change must be able to be made with existing manufacturing methods.
Wish 1.1.1	The cartridge should be able to be integrated without major redesigns of the casing.
RQ 1.2	The desiccant must comply with standards and regulations that the motor meets.
RQ 1.4	Desiccant must be in contact with the internal air.

8.4.4 Sealing Cartridge Mechanism

The requirements (Table 8.5) for the sealing mechanism were verifiable waterproofness, manufacturability, and the ability to withstand operational shocks without failing. During the ideation phase, multiple locking mechanisms were evaluated, including magnets, sliders, snap-fits, and threaded connections.

water bottles, this mechanism allows the user to apply a specific torque. This torque ensures that an O-ring is sufficiently compressed to guarantee a robust seal against moisture ingress. To comply with ISO 4210 standards for e-bike vibrations, the threaded design provides continuous friction. If minor loosening occurs over time due to vibrations, the threaded cap can be easily retightened by the user, ensuring the waterproof seal is maintained.

A threaded connection was selected as the most viable solution. Drawing on proven waterproofing applications such as automotive fuel caps and

Table 8.5. Sealing cartridge requirements.

	Requirements
RQ 1.3	The cartridge and its locking mechanism must withstand vibrations and shocks of e-bike usage (ISO 4210 standards (ISO, 2023)) without rattling, loosening, or causing the desiccant beads to damage internal components.
RQ 2.2	The maintenance must be able to be done by mechanics and e-bike owners.
RQ 2.5	The waterproofness of the product must be maintained when swapping the saturated desiccant.
RQ 2.8	The cartridge locking mechanism must be able to be used multiple times.
Wish 2.8.1	The locking mechanism of the cartridge should not lose its waterproof quality when opened and closed multiple times.

8.4.5 O-Ring Specification

Nitrile (Shore 70 hardness) is selected as the optimal material for the O-ring with axial compression (Figure 8.5). Axial instead of face compression is chosen to achieve the squeeze necessary to become waterproof.

It withstands the thermal operating range and provides resistance to maintenance chemicals and the required silicone assembly grease.

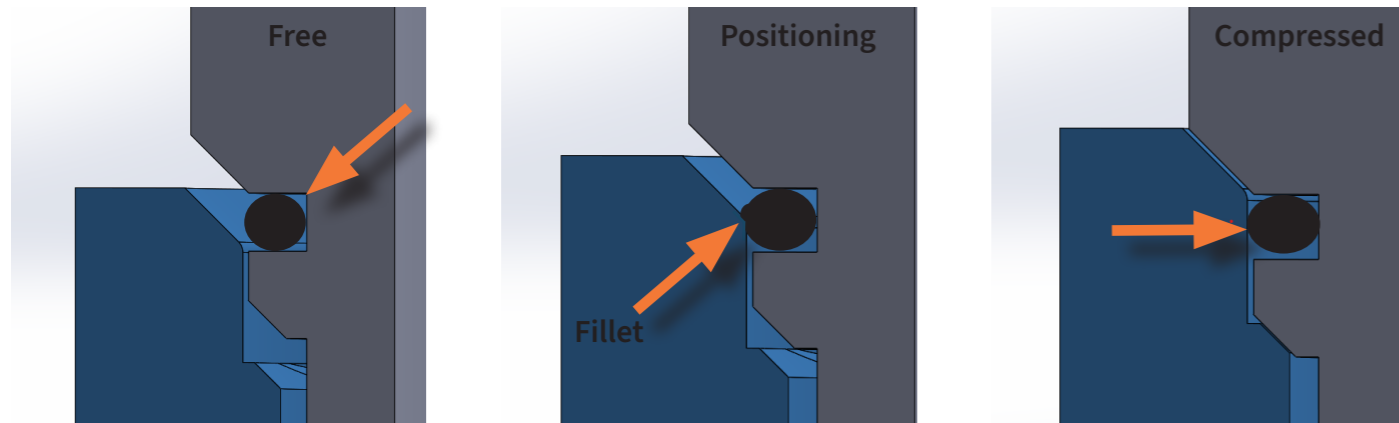


Figure 8.5. Axial O-ring compression design.

To guarantee a static seal within the male gland, four materials were evaluated: Nitrile, Viton, Silicone, and EPDM.

Evaluation: The motor operates in temperatures from 20 °C to 80 °C and the external face is exposed to petroleum-based bike greases and chain lubes.

- EPDM fails in oil resistance.
- Silicone lacks durability and tear strength.
- Viton offers excellent chemical resistance but is unnecessarily expensive for this temperature range.

The groove and O-ring dimensions are engineered using industry standards and requirements (Table 8.6), Parker O-Ring Handbook (Parker Hannifin Corporation, 2021) and Figure 8.6, to prevent failure:

Dimensions: A 33x1.1 mm O-ring provides sufficient thickness to exceed the groove depth, ensuring proper clamping compression.

Tolerances: The design restricts O-ring stretch to a maximum of 5% and compression to 3% to prevent material fatigue over the two-year maintenance cycle.

Torque: O-rings do not require high bolting forces (torque) to seal perfectly, closing it by hand should be enough for waterproofing (Parker Hannifin Corporation, 2021).

Thermal Expansion: The cross-sectional (CS) area of the groove is designed to be at least 15% larger than the CS area of the O-ring. This critical void allows the Nitrile to swell slightly when exposed to greases or thermal expansion without extruding from the joint.

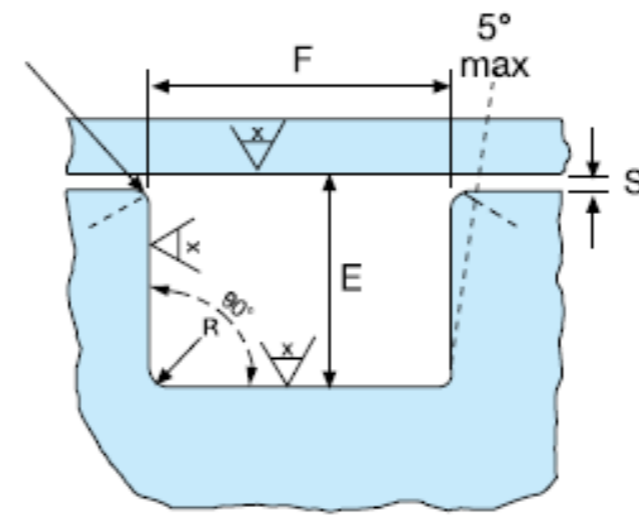


Figure 8.6. O-ring dimensions (Stijn de Cnop, 2025).

Table 8.6. Requirements O-ring specifications.

	Requirements
RQ 5.1	The design restricts O-ring stretch to a maximum of 5% and compression to 3% to prevent material fatigue over the two-year maintenance cycle.
RQ 5.2	The cross-sectional (CS) area of the groove needs to be at least 15% larger than the CS area of the O-ring.
RQ 5.3	The material must withstand motor operates in temperatures from 20 °C to 80 °C and exposure to petroleum-based bike greases and chain lubes.
RQ 5.4	Corners must be chamfered during seal installation to limit damage and reduce wear and tear, stress, and maintenance issues.
RQ 5.5	The O-ring must have a squeeze of at least 0.1 mm to ensure its waterproofing.

8.4.6 Serviceability

Serviceability is achieved through an All-in-One Cartridge strategy. While regenerative options were explored, the disposable unit is the only method that guarantees waterproof seal integrity and desiccant performance upon replacement.

All-in-One Replacement

The user removes the entire saturated cartridge (bolt, desiccant, and seal) and discards it. It is replaced by a new OEM-certified unit containing fresh desiccant and O-ring. This is illustrated in Figure 8.7, The cartridge is transparent and the motor body is black.

DIY Regeneration

The user extracts the saturated silica beads, regenerates them in an oven, and refills and reseals the original cartridge. (Figure 8.8).

Modular Puck

The desiccant is housed in a separate, pre-sealed “puck” or tablet that is swapped out from inside the reusable bolt (Figure 8.9).

Silicone Only

The entire bolt is manufactured from high-temperature silicone with integrated O-rings of the same material. The user removes the whole unit, regenerates the entire bolt in an oven, and re-installs it (Figure 8.10).

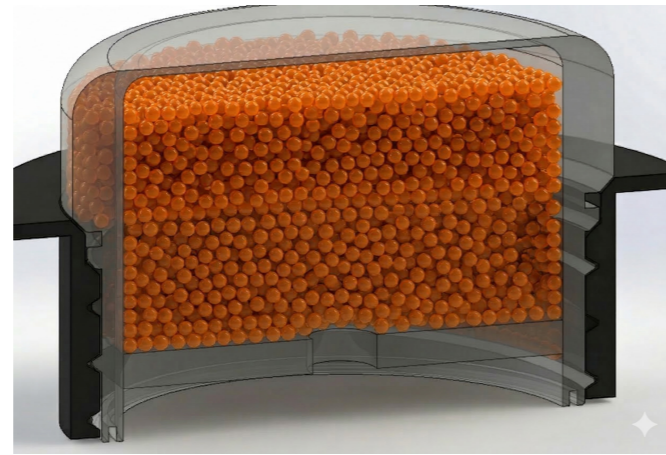


Figure 8.7. SolidWorks model of All-in-One replacement. (With help of AI to illustrate)

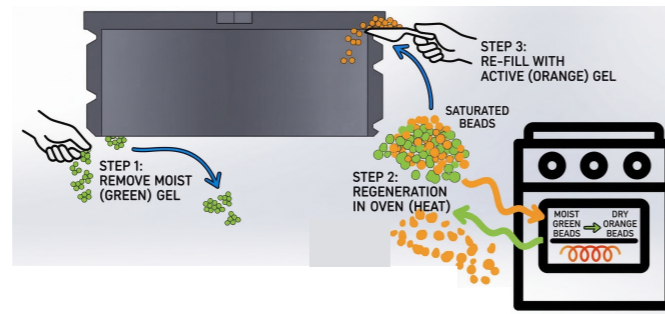


Figure 8.8. Sketch of DIY regeneration. (With help of AI to illustrate)

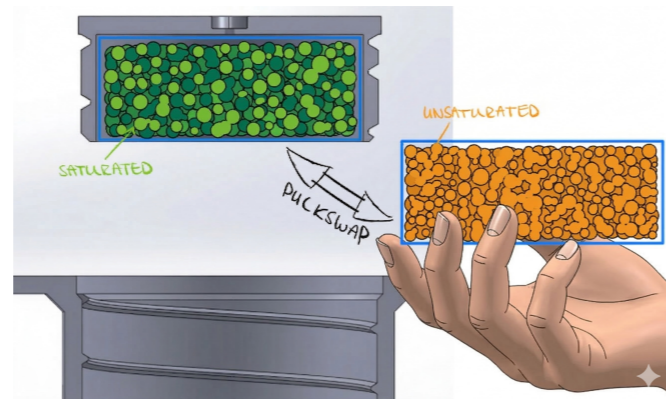


Figure 8.9. Sketch of modular puck. (With help of AI to illustrate)

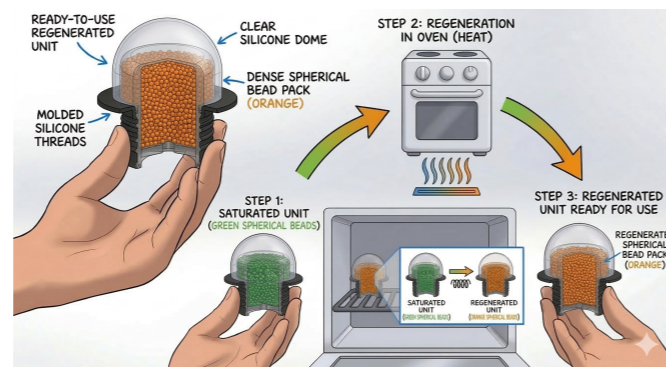


Figure 8.10. SolidWorks Silicone only model. (With help of AI to illustrate)

To determine the most viable path forward, these concepts were evaluated against design requirements (Table 8.8), as outlined in Table 8.7.

Table 8.7. Decision matrix on concept.

RQ	All-in-One	DIY	Modular Puck	Silicone Only
RQ 4.2				
RQ 2.2				
Wish 2.2.1				
RQ 2.3				
RQ 2.6				
RQ 4.1				
RQ 1.1				
Wish 4.4.1				

Table 8.8. Requirements for serviceability.

	Requirements
RQ 4.2	The external face in the insert must be resistant to common bicycle maintenance chemicals (degreasers, chain lube, soap) and road grit.
RQ 2.2	The maintenance must be able to be done by mechanics and e-bike owners
Wish 2.2.1	The service time should be as short as possible.
RQ 2.3	The cartridge must be able to be removed with a standard bike maintenance tool.
RQ 2.6	The cartridge must not be able to be installed incorrectly.
RQ 4.1	The cartridge housing material must withstand the operating temperature range of the motor (often -20°C to +80°C).
RQ 1.1	The body design change must be able to be made with existing manufacturing methods.
Wish 4.4.1	The cartridge should lead to the least waste possible.

The All-in-One concept was selected because it is the only design that scores positively in both manufacturability and absolute watertightness, the primary functional requirements of the product. By supplying a complete, factory-sealed unit, the OEM guarantees the integrity of the water seal with a new O-ring and membrane, eliminating the risk of user error during maintenance.

As detailed in the matrix, while the Refill and Silicone concepts score highly in Sustainability and Price, they fail in Watertightness and Durability. Consultation with experts confirmed that silicone threads lack the mechanical stiffness

8.4.7 Permeable membrane

To complete the cartridge assembly, a permeable membrane must be placed on top of the bolt to allow for moisture transmission while keeping the silica beads secure and protecting them from internal motor greases. Three configurations were

Table 8.9. Decision matrix permeable membrane.

RQ	Combo 1			Combo 2			Combo 3		
RQ 1.4									
RQ 1.1									
RQ 4.2									
RQ 2.1									
Wish 2.9.1									

required to hold an IP68 seal under vibrational stress. The Refill concept has a risk of user error, a mistake during a DIY refill would result in moisture ingress, leading to motor failure. The Puck-Insert concept was rejected due to its complexity in manufacturability.

A disposable cartridge creates more plastic waste than a reusable one. According to remanufacturer 5, from a Life Cycle Assessment (LCA) perspective, discarding a small plastic cartridge every two years is a justifiable trade-off even with an increased service life of a few days.

evaluated (Table 8.9) with requirements from Table 8.10: a membrane with a plastic insert (combo 1), a sintered disc fixed via ultrasonic welding (combo 2), and a simple mesh with a snap-fit mechanism (combo 3).

Combo 2 is selected, a sintered disc (Figure 10A) secured by ultrasonic welding. The combination offers good vapor transmission and clog resistance at a moderate manufacturing complexity and medium price. Combo 3 performs poorly in potential clogging from the internal motor environment and combo 1 has more manufacturing setup difficulties.

The specifications for the sintered polycarbonate disc made for the requirements:

Thickness: Set between 1.5 mm and 2.0 mm. A thinner disc risks failure under vibrations and a thicker disc affects water vapor transmission.

Pore Size: Specified at 50 to 100 microns. Pores smaller than 50 microns restrict airflow, while pores larger than 100 microns risk material degradation of silica beads against the disc.

Surface Treatment: An oleophobic coating is added to the disc to reduce oil and grease adhesion from the motor's internal environment, preventing clogging.

Table 8.10. Requirements sintered disc.

	Requirements
RQ 1.4	Desiccant must be in contact with the internal air.
Wish 1.1.2	The cartridge should be able to be manufactured with accessible manufacturing methods.
RQ 4.2	The external face in the insert must be resistant to common bicycle maintenance chemicals (degreasers, chain lube, soap) the internal motor environment and road grit.
RQ 2.1	The motor must be maintenance free for a minimum of 2 years.
Wish 2.9.1	The cartridge should be as cheap as possible.



Figure 8.10A. Permeable sintered disc.

8.5 Manufacturability

To ensure the "All-in-One Cartridge" can be produced at scale while maintaining the strict tolerances required for an IP68 waterproof seal,

8.5.1 Materials

Polycarbonate (PC) was chosen as the material for the cartridge body. A comparative analysis evaluated (Table 8.11) PMMA, HDPE, PC, PEI, and PP against the requirements of Table 8.12. PC provides a combination of properties: it offers 89% transparency (allowing users to easily view the

the design was optimized for three specific manufacturing processes: Injection Moulding, Thixomoulding, and Ultrasonic Welding.

saturation indicator), sufficient impact strength to resist abrasives, and a thermal resistance up to 120°C, which easily handles the motor's typical operating range of -20°C to +80°C. PEI offers higher durability with a premium cost, which makes it unsuitable for a disposable maintenance part.

Table 8.11. Decision matrix injection moulding material.

	PMMA	HDPE	PC	PEI	PP
RQ 2.4 (Transparent)	92%	80%	89%	82%	Hazy
RQ 4.2 (Impact)	High impact brittleness	Sufficient	Sufficient	Sufficient	Sufficient
RQ 4.1 (Temperature)	70 - 85	80	120	170	100
Wish 2.9.1 (Price)	\$\$	\$	\$\$\$	\$\$\$\$	\$
Wish 4.4.2 (Sustainability)	Moderate	Excellent	Moderate	High durability	Good

Table 8.12. Requirements injection moulding material.

	Requirements
RQ 2.4	The saturation level of the desiccant must be visible without removing the motor cover.
RQ 4.2	The external face in the insert must be resistant to common bicycle maintenance chemicals (degreasers, chain lube, soap) the internal motor environment and road grit.
RQ 4.1	The cartridge housing material must withstand the operating temperature range of the motor (often -20°C to +80°C).
Wish 2.9.1	The cartridge should be as cheap as possible.
Wish 4.4.2	The cartridge should be made from sustainable materials as much as possible.

8.5.2 Cartridge Body: Injection Moulding

The main body of the disposable cartridge is manufactured using injection moulding.

The Process (Figure 8.11): Granulated plastic pellets (such as Polycarbonate) are fed into a

heated barrel, melted, and forced under high pressure into a machined metal mold cavity. Once the plastic cools and solidifies, the mold opens to eject the finished part.

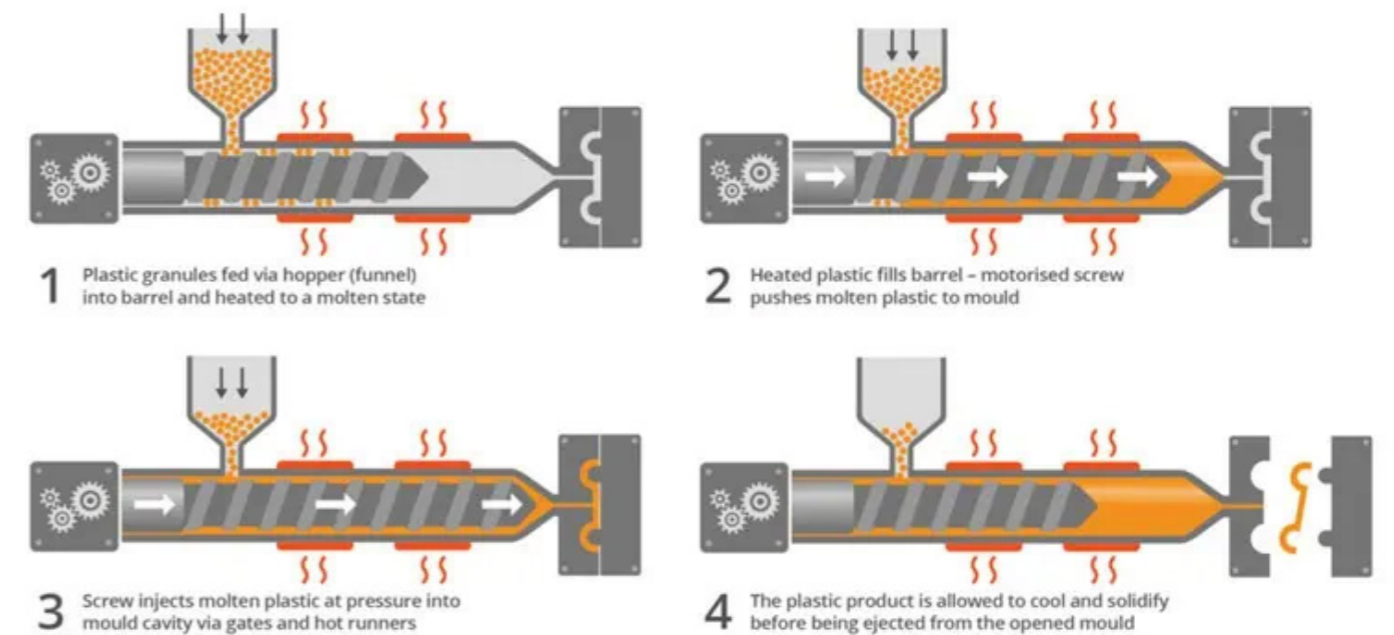


Figure 8.11. Schematic of the injection moulding process.

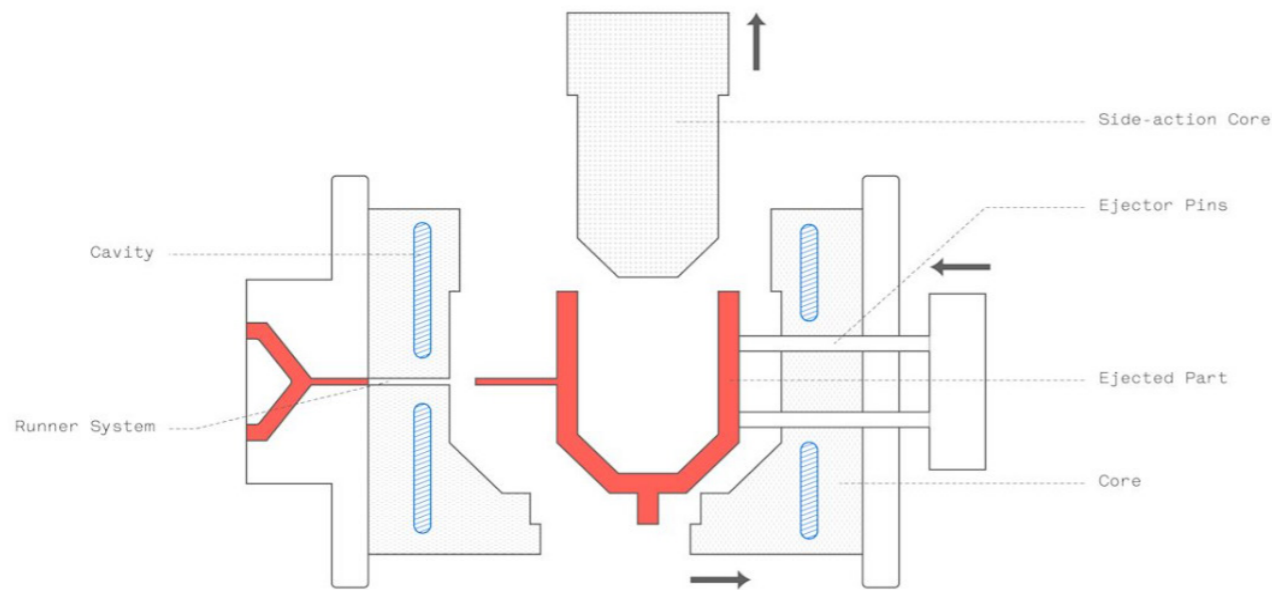


Figure 8.12. Side-action core setup.

DFM-RQ 1 (Side-Action Core): The injection mold must incorporate a side-action core (Figure 8.12), due to the external threads and the O-ring groove that function as undercuts (sliders). This tooling feature allows the mold to pull away horizontally, releasing the geometry.

8.5.3 Assembly: Ultrasonic Welding

To enclose the desiccant while allowing the motor to "breathe," the semi-permeable sintered disc must be attached to the top of the cartridge housing. Ultrasonic welding is a well-known and reliable post-processing method for injection-molded products to seamlessly join two plastic components (Plus Welding, 2025).

DFM-RQ 2 (Mold Ejection): To ensure the cartridge can be easily removed from the mold without friction or warping, the part design must account for additional requirements, such as incorporating sufficient draft angles on all vertical walls, fillets in the corners and maintaining a uniform wall thickness.

The Process (Figure 8.13): Ultrasonic welding uses high-frequency acoustic vibrations (20 kHz to 40 kHz) applied to workpieces held together under pressure. The localized friction generates rapid heat that melts the plastic surfaces together, creating a weld.

Ultrasonic Plastic Welding Process Diagram

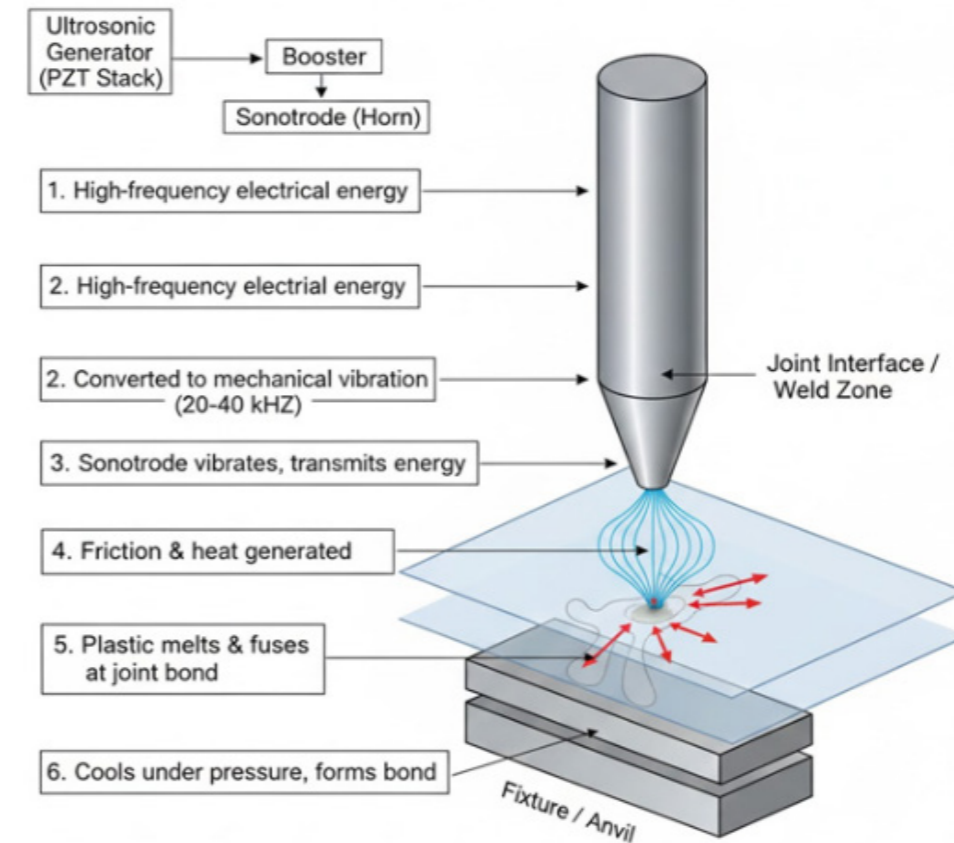


Figure 8.13. Schematic of the ultrasonic welding process (Plus Welding, 2025).

To ensure this process is successful and scalable, the design must adhere to the following DFM requirements:

DFM-RQ 3 (Material Compatibility): The sintered disc will be the same material as the injection-molded cartridge body, Polycarbonate (PC), to ensure the two components fuse together. To disc needs a solid PC border for adhesion.

DFM-RQ 4 (Energy Director): The top rim of the polycarbonate cartridge body must be designed with an integrated "energy director" (a specific, triangular sacrificial ridge). This ridge concentrates the high-frequency vibrations, causing the plastic to melt and fuse the parts (Figure 8.14).

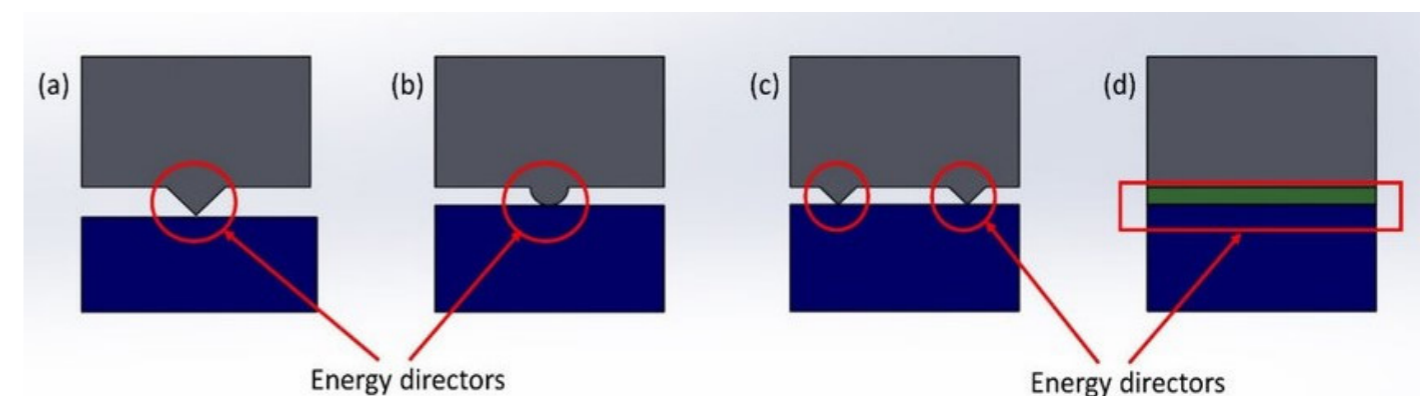


Figure 8.14. Examples of energy directors.

8.5.4 Motor Body: Thixomoulding

Integrating the cartridge requires adapting the existing lightweight magnesium motor casing (such as the Brose reference model) to feature a female thread and a flat sealing face. Adjusting the mold to include a cavity for the cartridge is highly feasible: consultation with remanufacturer 5 confirmed that this modification poses no structural issues and actually reduces the total

volume of magnesium required. The threading can then be tapped during standard post-processing. The Process (Figure 8.15): Thixomoulding is a semi-solid metal casting process. Magnesium chips are heated into a thixotropic (slushy) state and injected into a die under high pressure, blending the principles of plastic injection moulding with metal casting.

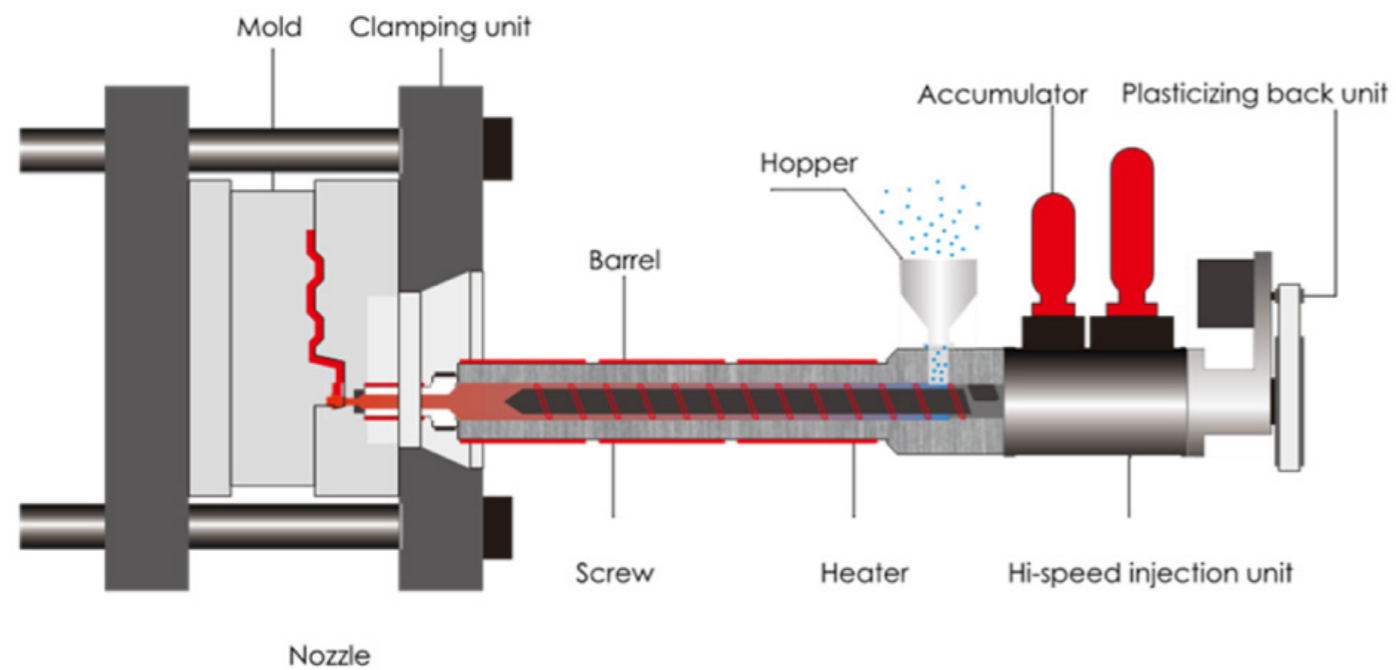


Figure 8.15. Schematic of thixomoulding (Bole Intelligent Machinery, 2025).

To integrate the cartridge into the motor body, the existing lightweight magnesium casing must be adapted. Because thixomoulding is the production method currently used to manufacture modern mid-drive motor casings, integrating the cartridge requires specific DFM considerations early in the development phase.

DFM-RQ 6 (CNC Post-Processing): In line with current manufacturing standards for mid-drive motors, the complex female threads required to secure the cartridge cannot be easily molded. Instead, the small holes and threads must be tapped during a secondary CNC post-processing stage.

DFM-RQ 5 (Mold Integration): The cavity and flat sealing face for the desiccant cartridge must be integrated into the thixomoulding die at the very beginning of the motor's design process.

8.6 Conclusion

Chapter 8 outlines the strategic transition from passive moisture prevention to active internal climate management. Through an evaluation of design strategies, "Absorption" was selected as the most effective method to neutralize the thermodynamic pressure differentials that cause the "breathing cycle."

By leveraging the physical properties of vapor pressure and dew point, 10 grams of color-indicating Silica Gel was sized to actively maintain internal relative humidity below condensation levels for a two-year maintenance interval.

The embodiment of this strategy resulted in the "All-in-One Cartridge", a disposable unit utilizing a threaded compression mechanism and a nitrile O-ring to ensure an IP68-rated seal against external liquid water, closed with a sintered polycarbonate membrane to enable vapor absorption.

Finally, the design was validated for production through specific Design for Manufacturing (DFM) principles, confirming that components can be reliably produced via injection moulding, thixomoulding, and ultrasonic welding.

Injection Moulding: The tooling must incorporate a side-action core to successfully mold the undercuts of the thread and the O-ring groove.

Ultrasonic Welding: The sintered disc will be made from Polycarbonate and the cartridge requires an energy director to fuse the parts.

Thixomoulding: The die for thixomoulding must be changed early in the design process and the thread must be tapped during the CNC post-processing stage.

By establishing and meeting these strict manufacturing requirements, this chapter demonstrates that the Desiccant Cartridge is not only a functionally effective solution for extending motor durability, but a highly scalable and viable product ready for real-world industry integration.

9. Final Concept

This chapter introduces the Desiccant Cartridge, a modular solution to extend motor durability through active internal humidity management. The concept addresses the thermodynamic

“breathing cycle” by maintaining internal humidity below the dew point to prevent condensation. Detailed are the concept’s technical architecture, maintenance flow, and manufacturing feasibility.

9.1 Concept Overview

The proposed solution to extend e-bike motor durability is the Desiccant Cartridge: a modular, retrofittable unit designed to regulate internal humidity. Unlike current solutions that attempt to hermetically seal the motor against pressure differentials, this concept embraces the thermodynamic “breathing cycle.” It prevents moisture damage by maintaining the internal relative humidity below the dew point, thereby preventing condensation from forming on electronic and mechanical components.

The final design consists of a screw-in cartridge integrated directly into the motor housing (Figure 9.1). The unit is composed of three primary elements: an injection-molded transparent Polycarbonate (PC) cartridge body, a 10-gram filling of color-indicating Silica Gel, and a sintered Polycarbonate disc lid that is securely attached using ultrasonic welding. The full list of requirements can be found in Appendix B.

This configuration is built around a two-year maintenance interval utilizing an “All-in-One” replacement strategy. When service is required, the entire cartridge unit is swapped for a new one.

This approach guarantees O-ring seal integrity and optimal desiccant performance without requiring the user or a mechanic to open the main motor body or use specialized tools. The cartridge is designed for intuitive use: consumers can perform the replacement themselves by simply unscrewing the old unit and hand-tightening the new one into place.

To facilitate this user-friendly maintenance, the transparent Polycarbonate body allows the user to clearly see the color-indicating silica gel inside. As the silica absorbs moisture over time, it transitions through different color stages from orange (unsaturated) to green (saturated) (Figure 9.2). Once the gel has fully discolored, it provides a visual cue that the cartridge has reached saturation and requires replacement.

Finally, this complete “All-in-One” unit provides significant value to Original Equipment Manufacturers (OEMs). Because every replacement utilizes a factory-sealed cartridge complete with fresh, unsaturated silica gel and a brand-new O-ring, OEMs can confidently maintain and guarantee the motor’s waterproof warranty after maintenance is performed.



Figure 9.1. Photo of the motor with the desiccant cartridge.



Figure 9.2. Different cartridge saturation cues.

9.2 User Interaction

A requirement for this concept is ensuring that maintenance can be performed confidently by non-expert e-bike owners, bypassing the need for an authorized dealer. The user experience (UX) flow is designed around visual feedback and fail-safe installation.

The user interaction is structured into three clear phases:

Packaging & Preparation: To ensure the silica gel does not absorb ambient moisture while on the shelf or during shipping, replacement cartridges are delivered in sealed plastic packaging. The user opens a new, unsaturated cartridge, which is visually confirmed by the orange color of the silica gel.

Visual Monitoring: Because the face of the cartridge is made of transparent polycarbonate, the user can easily monitor the status of the desiccant without removing the motor cover. Over time, as the motor breathes and the desiccant absorbs internal moisture, the silica beads will slowly change color from orange to green (Figure 9.3). The cartridge is fully saturated and ready for replacement when the beads turn completely green.

Extraction & Fail-Safe Replacement: To begin the service procedure, the user unscrews the saturated cartridge by hand. The user then inserts the fresh cartridge and twists it along the threads. To prevent under- or over-tightening, which could compromise the waterproof seal, the cartridge features tactile and visual indication lines. The user simply applies torque until the lines on the cartridge and the motor body align, ensuring perfect O-ring compression.



Figure 9.3. Saturation levels of Silica Gel.



Figure 9.4. UX flow of replacing the cartridge.

9.3 Design for Manufacturing

9.3.1 Technical Integration

The desiccant cartridge is designed to be highly for integration into modern e-bike motor architectures. Using the Brose motor as a reference model, the unit's dimensions were optimized to sit within the magnesium housing. This sizing ensures there is no interference with internal gears or the printed circuit board (PCB),

9.3.2 Manufacturing Methods

To ensure viability, the product is engineered for production utilizing established industrial processes (Figure 9.5). The manufacturing is defined by the following methods:

Injection Moulding: The main polycarbonate cartridge body is injection molded. This process holds the tolerances required for the external threads and the O-ring groove, for a reliable fit.

Thixomoulding & Post-Processing: The motor casing die for thixomoulding is adapted to account for the cartridge. The threads are tapped into the magnesium housing during a secondary CNC post-processing stage.

while successfully maintaining direct contact with the internal air volume. Furthermore, this geometry accommodates the required 10 grams of silica gel, ensuring the absorption rate is fast enough to actively counteract the occurrence of condensation.

Ultrasonic Welding: To enclose the desiccant, the semi-permeable sintered polycarbonate membrane is ultrasonically welded to the top of the cartridge. This provides a permanent seal that secures the silica beads while allowing water vapor transmission.

Packaging: As a final manufacturing step, the assembled cartridges are sealed in plastic packaging to preserve the silica gel's unsaturated state during shipping and storage.

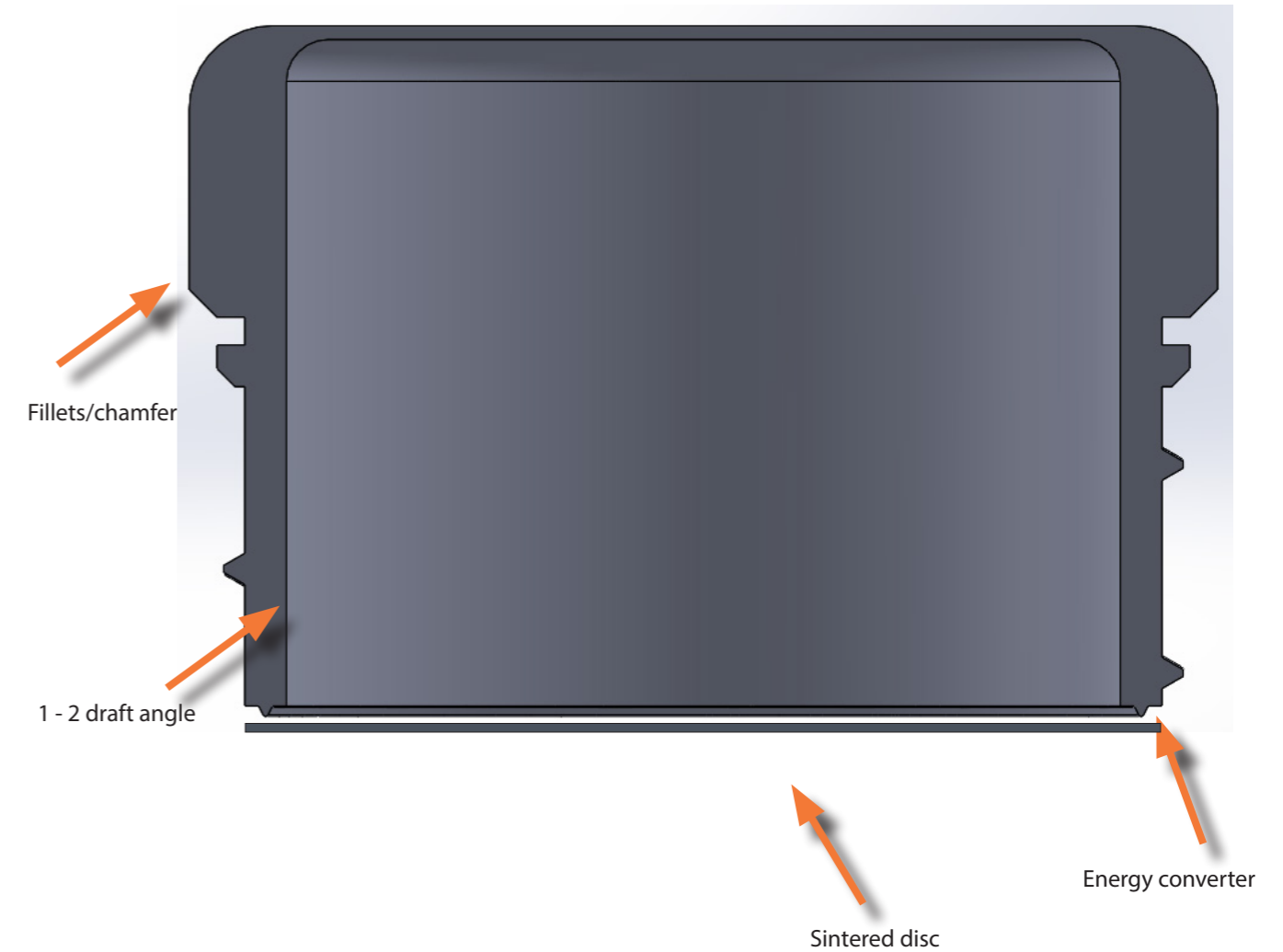


Figure 9.5. Cartridge drawing with annotations.

9.4 Regulatory Alignment & Costs

9.4.1 Regulatory Alignment

The desiccant cartridge concept aligns with the European Union's expanding "Right to Repair" directive. Currently, e-bike owners and repair mechanics are not able to perform maintenance on internal components that require breaking factory seals, which voids the manufacturer's warranty. This design moves the failure-

prevention mechanism to an accessible exterior port on the motor casing, where consumers can perform maintenance themselves. They can actively extend the life of their motor without ever opening the main casing, thereby preserving the OEM warranty and responding to the Right to repair regulations.

9.4.2 Costs

While specific unit costs will decrease as order quantities scale, the baseline cost of an injection-molded polycarbonate cartridge and a sintered disc is low. For the consumer, the total cost of ownership (incorporating the cartridge cost, retail margin, and shipping) is low when compared to replacing out-of-warranty motors. This maintenance bypasses high hourly labor rates of authorized mechanics, as the user can complete the swap themselves in minutes.

The product's scalability is secured through a combination of manufacturing, streamlined distribution, and its "All-in-One" disposable architecture. From a production standpoint, injection molding ensures that the unit cost decreases as production volume increases, making it economically scalable.

Logistically, the compact and lightweight nature of the cartridge guarantees high availability; new replacement units can be shipped directly to consumers.

9.5 Conclusion

The Desiccant Cartridge represents a shift in e-bike motor design, prioritizing preventative climate control over reactive, high-cost repairs. Through its "All-in-One" replacement strategy, the concept offers a low-cost, scalable, and user-friendly maintenance that can be performed by non-experts, bypassing breaking up the whole system without specialized tools required. By

utilizing a factory-sealed unit with integrated visual cues, the solution allows Original Equipment Manufacturers (OEMs) to have confidence and guarantee waterproof integrity with every new cartridge, while making able for the consumers to make an effort in extending their motor's service life toward the 100,000 km target.

10. Discussion

This chapter discusses on the physical and systemic implications of the research, evaluating the Desiccant Cartridge against the initial durability goals. It addresses the limitations of the study, such as the reliance of gathered data and the lack

of long-term physical testing. Finally, it provides recommendations for future testing, focusing on user experience and the industry reforms needed to bypass current closed-ecosystem barriers.

10.1 Discussion

This study aimed to identify causes of premature e-bike mid-drive motor failures and to conceptualize a design intervention capable of extending their service life toward a 100,000-kilometer target. To address this, the research proposes the active Desiccant Cartridge, a hardware solution designed to actively manage the motor's internal climate. By maintaining relative humidity safely below the dew point, this system is calculated to prevent internal condensation for a two-year maintenance cycle. However, while this design theoretically prevents condensation, validation remains limited by the testing timeframe. Consequently, it cannot be proven that integrating this cartridge will achieve a 100,000-kilometer service life.

The implications of this research are discussed in three themes: the physical mechanisms of failure, supply chain inefficiencies, and active internal climate management.

The findings establish that the mechanism driving premature motor failure is not mechanical fatigue, but is the thermodynamic "breathing cycle", as discussed in Chapter 4. Current approaches within the e-bike industry focus on moisture ingress prevention through radial shaft seals and gaskets. Thermal expansion and contraction during motor operation create pressure differentials of up to 200 mbar. This is enough for humidity to pass the seals into the housing, supporting existing

literature that states (Stiemcke et al., 2024) that dynamic seals leak under a pressure difference of 50-100 mbar.

As the motor cools multiple cycles, accumulation of moisture builds, and condensation causes oxidation of bearings (Figures 4.10, 4.11) and PCB short-circuits. This insight extends current literature, by defining why motors fail. This means that prevention of condensation within the motor must be addressed and taken into account by manufacturers early in the design stage.

The closed supply chain model restricts remanufacturing and repair of failed motors outside of the warranty period. Currently, e-bikes mid-drive motors are excluded from the "Right to Repair" directive applied to other consumer electronics. This study aligns with broader product design literature that products should be designed with repair, remanufacturing, and recyclability in mind. While mid-drive motors are complex and may not require full consumer repairability, a different framework could be developed. The industry should focus on empowering mechanics and/or remanufacturing companies to repair high-wear parts without compromising system integrity to improve service life. They could develop more opportunities as an example the Pinion E1.12 discussed in Chapter 6.2.2, where the consumer is able to do preventive maintenance by refreshing the oil every 10.000km, which normalizes user-performed maintenance.

In the absence of repair legislation and open supply chains, the desiccant cartridge (Chapter 9) serves as a workaround. It extends current literature by exploring active internal climate management as an alternative to relying on existing sealing for waterproofing.

10.2 Limitations

Although the proposed design inspires a different look on improving motor durability by management of moisture ingress, several constraints limit the generalizability of these findings.

Due to the lack of data from OEMs, the results cannot confirm a statistical breakdown of industry-wide motor and component failure rates. The reliability of these data is impacted by reliance on qualitative interviews and third-party survey data to understand failure numbers and causes, which detailed technical insights but not statistical certainty. This means that it is hard to have an understanding of the scale of the problem on mid-drive motors failures, where newer generations have less problems than older ones, which makes it difficult to design solutions for specific failures.

The final desiccant cartridge could not be tested and validated based on its actual performance within a running motor. Due to the lack of physical testing data on the prototype, the results cannot confirm the actual impact of actively dehumidifying the motor internals. Currently, the lifespan (desiccant saturation) has only been theoretically calculated based on ideal gas laws and assumed ingress rates. It is beyond the scope of this study to conduct lengthy physical testing, such as running the prototype in a climate-controlled environment, which would be necessary to observe the saturation rate of the solution over time.

It gives consumers the possibility of a tool-free maintenance procedure (Figure 9.4) to replace the desiccant. Furthermore, this solution acts as a failsafe for degrading seals. The saturation rate of the desiccant can serve as a diagnostic monitor, potentially indicating when the motor's seals have degraded if the silica gel saturated quicker than expected.

The result is limited by the conditions used for thermodynamic calculations. The sizing of the 10-gram silica payload was calculated with KNMI data reflecting the absolute humidity of the Netherlands, coupled with an assumption of heavy commuter usage. Different conditions of absolute humidity, weather conditions, e-bike usage and rate of sealing degradation impact the sizing of silica needed for the requirement of only needing maintenance every 2 years.

The Brose mid-drive motor was used as a reference model and limits the use of the results for the architectural variation across other motor brands. Disassembly mapping revealed varied internal layouts, such as different PCB placements (top versus bottom mounted, Figure 4.15), gearing systems and types of sealing strategies across brands. Due to these differences in motor architecture, these results may not universally apply to all mid-drive units and brand specific adjustments have to be made. Furthermore, it is beyond the scope of this study to evaluate the use of this solution to hub motor configurations.

10.3 Recommendations

To advance the Desiccant Cartridge from conceptual validation to commercial deployment, future research and development must prioritize the following themes:

Future studies should conduct UX testing to validate the intended "maintenance-free" operational model. This research must assess the interpretability of the silica gel's visual saturation cues (orange to green) by non-expert users and ensure that the threaded installation mechanism reliably prevents improper installation, such as under- or over-torquing. Additionally, understanding if the target group has the confidence to perform DIY maintenance on an e-bike motor.

The cartridge assembly must undergo ISO 4210 vibration testing to verify long-term mechanical retention. Furthermore, dynamic Ingress Protection (IP) testing should be executed using artificially aged and abrasive-worn crankshaft seals (replicating the grit degradation shown in Figure 4.2) to quantify the desiccant's performance as external moisture ingress naturally increases over the motor's lifecycle.

Future efforts should extend beyond hardware development into systemic industry reform. Industry stakeholders should find a way to include the e-bike motor into the European Union's "Right to Repair" directives to motivate more supply chain connections and open remanufacturing opportunities for failed e-bike motors with expired warranty.

Finally, OEMs should develop a tool (physical or digital) to identify and predict when component failure occurs. With this information, future designs could aim to construct the architecture of the motor in a way that these components are modular, accessible sub-assemblies based on these failure predictions. With the goal of improving the durability by lowering the repairability threshold.

11. Final Conclusion

The final chapter summarizes the research findings and answers the design assignment of extending e-bike motor life to 100,000 km. It concludes with a personal reflection structured by

the Gibbs Reflective Cycle, describing experiences, feelings, and evaluation of the design process, and discussing future development.

11.1 Conclusion

This research aimed to develop a durable, low-maintenance e-bike mid-drive motor capable of achieving a 100,000-kilometer operational lifespan. Through disassembly mapping, thermodynamic analysis, and systemic evaluation, this study concludes that reaching this durability target requires a shift from passive moisture exclusion to active internal climate management.

The primary cause for premature motor failure was identified as the thermodynamic "breathing cycle." Standard dynamic seals cannot withstand the negative pressure differentials generated during motor cooling. This leads to moisture ingress, internal condensation, and component failure. To counteract this, this study proposes the Desiccant Cartridge, a modular, injection-moulded polycarbonate unit integrated into the motor housing. Utilizing 10 grams of indicating silica gel, the cartridge absorbs ingressed moisture to continuously maintain the internal relative humidity below the condensation threshold. The design allows non-expert users to execute a simple, tool-free replacement every two years. The unit provides a factory-fresh O-ring upon every replacement, it guarantees the motor's watertight integrity without ever requiring the main casing to be opened.

Beyond these mechanical findings, this research highlights systemic barriers that currently accelerate the cycle of premature motor disposal. Closed OEM supply chains and legislative voids work against repair. For the industry to progress, OEMs must look beyond a singular reliance on seals and adopt broader, proactive design strategies to resolve moisture issues. Furthermore, the findings lay out that current policy is ineffective in this sector; it could be beneficial that e-bike mid-drive motors be incorporated into the European Union's "Right to Repair" directives.

Ultimately, the insights generated by this study offer direct value to both policymakers and industry stakeholders. Regulators can utilize these findings to formulate stricter guidelines on the repairability and manufacturability of e-bike motors. While testing constraints currently limit the validation of the 100,000-kilometer target, managing internal humidity is a requirement for achieving the 100,000-kilometer target. By neutralizing the "breathing cycle," the proposed Desiccant Cartridge removes one of the causes that prevent motor durability. Therefore, OEMs should further develop and validate the proposed desiccant technology. By continuing to explore solutions to internal condensation, the industry could enhance motor durability and reduce e-bike motor e-waste.

11.2 Personal Reflection

11.2.1 Introduction

Within this project, I researched why e-bike mid-drive motors are failing prematurely and looked to find a solution that could improve their overall durability. This reflection is about my Master's thesis journey, evaluating both the project and personal growth experienced throughout the project.

11.2.2 Gibbs Reflective Cycle

The initial phase of this project involved collaborating with Dion, to conduct research on premature e-bike motor failures. Because we were entering an unfamiliar topic, we tackled the research phase together, collaborating on motor teardowns and expert interviews. Having a partner during this early stage felt energizing. It lowered the barrier to interviewing industry experts and felt less intimidating as a duo.

Evaluating this phase, a benefit was the ability to keep each other motivated and critically discuss each other's perspectives. The collaboration succeeded because we shared an open mind regarding the scale of the problem and complementary interviewing skills. I believe this improved the quality of our initial research. The experience validated the value of co-designing, mixing ideas, and brainstorming collectively. In future design assignments, I plan to implement this collaborative approach to early-phase research, to make sure I have different types of inputs when mapping out the context of a new problem.

The project brief stated that e-bike motors were failing prematurely, likely due to water ingress, but lacked specific data on the how, when, and why. The first objective was to explore causes and develop a universal solution for current motors without redesigning the entire architecture.

Using the Gibbs Reflective Cycle, I have structured my reflection around six themes: collaboration, ideation, methodology, learning objectives, time management, and my future career. The cycle moves through description, feelings, evaluation, analysis, conclusion and future actions within the themes.

However, the lack of a client and the absence of component failure data from Original Equipment Manufacturers (OEMs) made ideation challenging. I found it hard without a client dictating feasibility or OEM data pinpointing to a failing component. I felt anxious that the scope was too small to yield an innovative solution and I felt lacking in technical knowledge to make decisions. Furthermore, I experienced tension: as a designer, I want to create a highly impactful solution, but I felt that changing industry regulations would have a bigger impact than a physical product tweak. This resulted in some wasted time early in the design phase and slow decision-making. The midterm deadline and guidance from my coaches helped me in focussing on the durability aspect. I learned that in these situations, I must start making decisions to see what happens. Moving forward, I will be setting my own project requirements earlier, to make easier and faster decisions.

To investigate the motor failures, Dion and I used the methods: literature reviews, disassembly mapping with motor teardowns, and interviews with both repair mechanics and revision companies. Using these methods gave me a sense of confidence, as they were the obvious methods to acquire more information. However, this was coupled with the insecurity about whether we would actually get some usable findings.

In evaluating the methods, the interviews gave mixed results: local repair mechanics offered somewhat flat, repetitive answers, whereas specialized revision experts provided valuable, qualitative insights. The motor teardowns were interesting for understanding architecture, but it was practically impossible to pinpoint the exact root causes of failures just by taking the motors apart. While the methods were appropriate, the lack of transparent data from OEMs regarding their newer motor iterations left a blind spot in our research. We still do not know how big the problem is with the newer generation of e-bike motors. I learned that when literature is limited, mapping the problem relies on speaking to stakeholders and experts. For future research assignments, I will replicate this approach to stakeholder interviewing.

At the start of the thesis, I set several learning objectives: utilizing CAD (SolidWorks) and rapid prototyping, applying the theoretical framework from the 'Repair & Recycling' course, improving structured decision-making, and enhancing my visual communication and technical presentation skills. Initially, I felt confident about achieving these, though the learning objectives were broad since the project's exact trajectory was unknown. Looking back, applying the 'Repair & Recycling' theory during the motor teardowns was a success, helped out with a structured setup, and I successfully broadened my knowledge of production techniques. However, I fell short on my visual communication goals.

This happened because making the final report consumed more time than anticipated and needed my full attention. Additionally, my CAD objectives were lighter than expected simply because my final design solution required less complexity than I originally envisioned. To conclude that while not every objective was met, the shift in focus was appropriate for the reality of the project. In the future, I will treat my learning objectives as iterative goals, revisiting and adjusting them mid-project to better align with the evolution of the project.

Managing my time while balancing a full-time thesis with the responsibilities of a part-time job as a sous-chef was a challenge. I am normally quite capable of having a high workload and responsibility, so I was surprised and stressed when I found myself falling behind on my intended thesis hours. At times it felt overwhelming and that made the stress and pressure higher than I wanted.

To overcome this I turned to literature like *Hyperfocus* and *Atomic Habits*. I evaluated my working style and implemented time-blocking, focus modes to eliminate distractions, and tracked my productivity to see when I worked most efficiently. My initial procrastination came from the ideation struggles mentioned earlier, not knowing where to start made it easier to get distracted. However, by intentionally scheduling "deloading" time to recover from study and work, I found a better balance, which made it easier to put in the work when it mattered. I realized that having and scheduling intentional free time made me more efficient and have a more free relaxed feeling. In the future, I will step back and organize my time with intention and make a healthy balance in work and free time.

One of the discoveries of this thesis was the realization that I am not a "diehard" Integrated Product Design (IPD) detail-oriented designer. Instead, I discovered that I value the design-thinking mindset to complex problems, mapping stakeholders, and framing solutions.

Initially, this felt a bit weird because I thought I wanted to work for a design agency, but I am excited for other opportunities that are ahead. Through talking to experts and attending the Delft Career Days, I evaluated my skills and realized that companies value designers who can think broadly, analyze systemic problems, and facilitate solutions without necessarily having the deepest technical engineering knowledge.

The interactive part of my thesis research proved that I thrive when meeting stakeholders and working practically, rather than being strictly desk-bound. As I look towards my future, I am going to seek roles that allow me to merge my

11.2.3 Conclusion

In conclusion, my thesis on e-bike motor durability was not just a test of my academic and design capabilities, it was a journey of personal and professional growth.

Through the Gibbs Reflective Cycle I reflected on six themes.

design strengths with my personal passions. The ultimate dream is to find a career crossover between design and the culinary world, or design and the bike industry.

I faced some challenges, from defining my scope, writing a report to managing my time alongside a part-time job as a sous-chef. I learned how to collaborate doing research, getting the information necessary from stakeholders and doing activities with intention.

These skills will help me in my future career and find the crossover job between design and the culinary world or the bike industry.

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Appendix A Project Brief



Name student **Pablo Geraedts** Student number **4,882,016**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title **The E-bike motor that lasts 100.000km.**

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The e-bike is upcoming rapidly in sustainable mobility, with sales in Germany and the Netherlands now accounting for more than half of all new bicycles sold (1). The e-bike could challenge the car for commuting from home to work as green alternative, but the e-bikes is being undermined by the short lifespan of their motors. Frequent commuters cycle 5,000-10,000 km per year, motors often fail around 15,000 km, necessitating replacement every 1.5 to 4 years. This contrasts with the 5-10 year warranty on quality frames and the long-lived nature of electric motors in other industries.

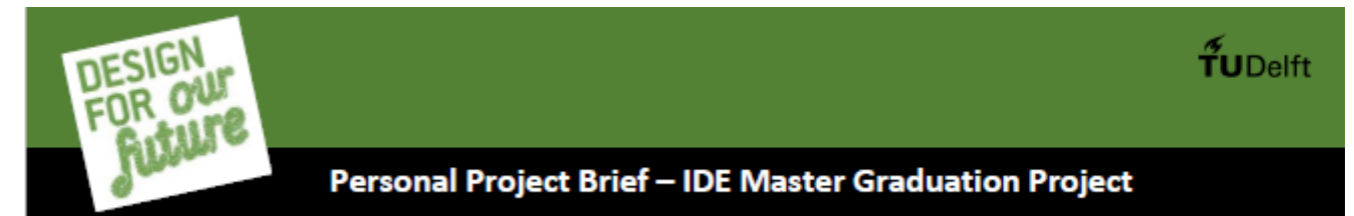
A 2024 survey identified the motor as the cause of 24.2% of all technical e-bike failures. The primary causes for these failures are often wear and water ingress. This leads to premature disposal of functional e-bikes, which contain critical raw materials, due to high replacement costs. Research shows that e-bike motors have repair and remanufacturing potential(2).

The stakeholders involved make for a complex situation: users want a reliable, low-maintenance bike that lasts, while repair shops need serviceable motors with clear instructions and available parts to build a sustainable business model. Manufacturers must balance production costs with durability to protect brand reputation, as regulators push for higher sustainability standards.

The opportunity lies in redesigning e-bike motors to enhance repairability and extend their lifespan. Limitation are navigating the design trade-offs, such as achieving robust water resistance while allowing for easy maintenance access, and developing a motor with 5-10 lifespan within realistic cost constraints.

Sales figures for 3 major markets over 2024: 450,000 e-bikes sold per year in the NL, 2.05 million e-bikes sold in Germany (Total number of e-bikes in circulation Germany: 11 million for 2023), 570,000 e-bikes sold in France Erdmann, J. G., Koller, J., Brimaire, J., & Döpfer, F. (2023). Assessment of the disassemblability of electric bicycle motors for

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Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

The problem is two-faced: a design flaw in e-bike motors and a significant lack of detailed research into their specific failure modes. Before a solution can be created, it is necessary to research and categorize common failures—such as water ingress and component wear—and understand their consequences in relation to the product lifespan. This initial analysis will paint a clearer picture of causes, revealing design opportunities to improve repairability and extend the motor's lifespan.

Currently, motors are not build to last (durable) or be repaired or remanufactured. A preliminary survey shows that while 51% of users would be willing to repair a motor, 39% would likely replace the entire e-bike if the motor fails. This causes bikes to be discarded earlier than necessary, while most parts of the product are in good condition.

The manufacturers' business model makes it cheaper to sell a new motor than to repair a broken or out of warranty one. This creates a tension with consumers, who want more durable and circular products. The challenge is how to make a long-lasting motor that helps the consumer and the planet, while still being profitable enough for the manufacturer to sell.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a durable e-bike motor concept to extend the lifetime expectancy to 100.000km, while being maintenance free, for consumers.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This project will follow the Double Diamond design methodology to navigate from problem to a validated solution. The first diamond is focused on understanding the problem. In the Discover phase, I will investigate causes of motor failure through interviews with repair mechanics, hands-on product teardowns and analyzing existing research through literature review. This research will converge in the Define phase, with a clear problem statement and a detailed set of user and technical requirements for a durable motor.

The second diamond explores solutions. The Develop phase will involve ideating a range of concepts using principles of Design for Durability, with a key focus on creating solutions that are durable, while being maintenance free. The concept that fits the requirements best will be delivered as a CAD model and a physical model. This final design will be validated with repair shops to test its effectiveness.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	2 sept 2025
Mid-term evaluation	12 nov 2025
Green light meeting	21 jan 2026
Graduation ceremony	26 feb 2026

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	<input type="checkbox"/>
For how many project weeks	<input type="text"/>
Number of project days per week	<input type="text"/>

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My motivation for this project comes from a technical interest in cycling mechanics and a focus on sustainable design. In addition to my hobby of riding and servicing my own roadbike. I see a challenge in the current lifecycle of e-bike motors, which limits their potential as a sustainable mobility solution. This project provides an opportunity to address this gap between the e-bike's promise and its practical durability.

I intend to apply my developed competencies, including CAD modelling (SolidWorks), rapid prototyping, and the theoretical framework from the 'Repair & Recycling' course.

For my personal development. I want to improve my structured decision-making in the design process and the ability to justify design choices. Additionally, I plan to enhance my visual communication skills through rendering techniques and further develop my ability to present technical information clearly.

Appendix B List of Requirements

	The cartridge must be able to be integrated into existing motor architectures.
RQ 1.1	The body design change must be able to be made with existing manufacturing methods.
Wish1.1.1	The cartridge should be able to be integrated without major redesigns of the casing.
Wish 1.1.2	The cartridge should be able to be manufactured with accessible manufacturing methods.
RQ 1.2	The desiccant must comply with standards and regulations that the motor meets.
RQ 1.3	The cartridge and its locking mechanism must withstand vibrations and shocks of e-bike usage (ISO 4210 standards (ISO, 2023)) without rattling, loosening, or causing the desiccant beads to damage internal components.
RQ 1.4	Desiccant must be in contact with the internal air.

	The cartridge must facilitate serviceability and maintenance for mechanics and non-expert users.
RQ 2.1	The motor must be maintenance free for a minimum of 2 years.
RQ 2.2	The maintenance must be able to be done by mechanics and e-bike owners.
Wish 2.2.1	The service time should be as short as possible.
RQ 2.3	The cartridge must be able to be removed with a standard bike maintenance tool.
RQ 2.4	The saturation level of the desiccant must be visible without removing the motor cover.
RQ 2.5	The waterproofness of the product must be maintained when swapping the saturated desiccant.
RQ 2.6	The cartridge must not be able to be installed incorrectly.
RQ 2.7	The locking mechanism must provide feedback that it is installed correctly.
RQ 2.8	The cartridge locking mechanism must be able to be used multiple times.
Wish 2.8.1	The locking mechanism of the cartridge should not lose its waterproof quality when opened and closed multiple times.
Wish 2.9.1	The cartridge should be as cheap as possible.

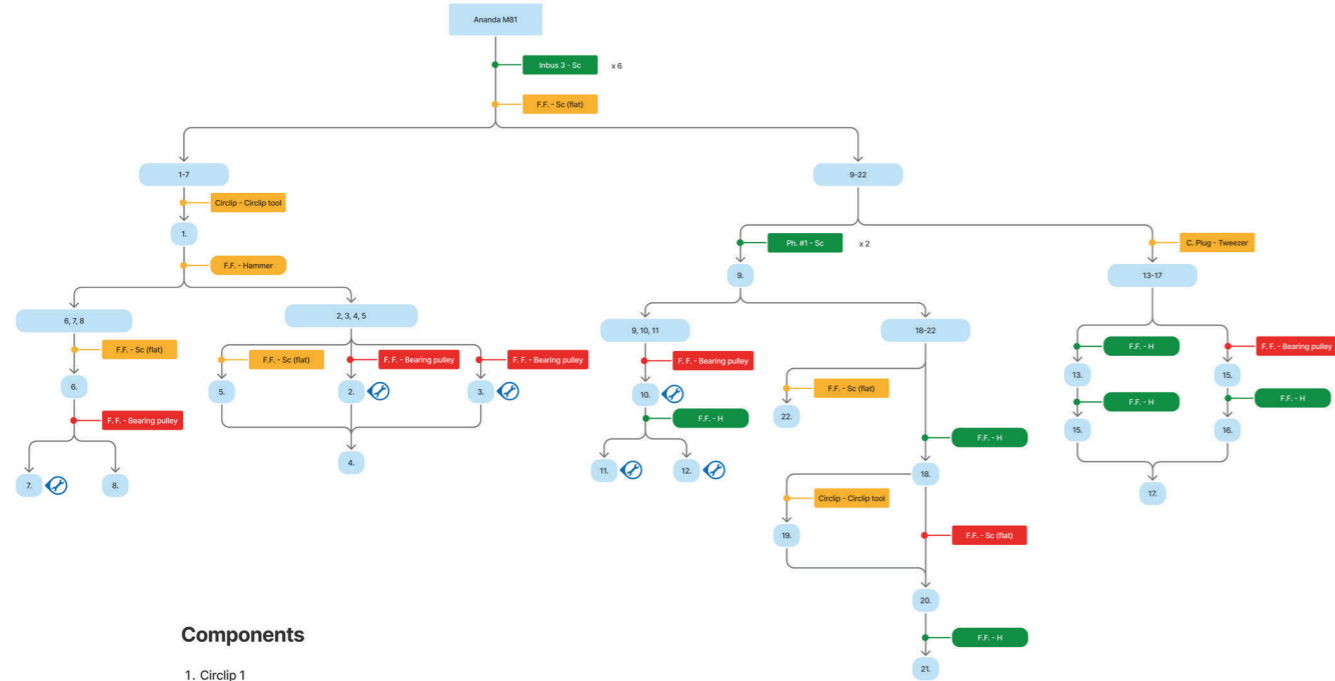
	The desiccant must regulate the humidity level within the motor housing to prevent condensation.
RQ 3.1	The desiccant must be able to reduce relative humidity inside the casing from [X]% to [Y]% within [Z] minutes (response time).
RQ 3.2	The desiccant must be able to be used multiple times.
Wish 3.2.1	The desiccant should be able to be regenerated for a minimum of 5 times.
RQ 3.3	The moisture must not be able to evaporate out of the desiccant under a minimal temperature of 90 °C.
Wish 3.3.1	The desiccant material expansion should be as minimal as possible.
Wish 3.3.2	The absorption to weight ratio should be as high as possible.
Wish 3.3.3	The volume needed for the desiccant should be as minimal as possible.

	The desiccant and cartridge must be durable.
RQ 4.1	The cartridge housing material must withstand the operating temperature range of the motor (often -20°C to +80°C).
RQ 4.2	The external face in the insert must be resistant to common bicycle maintenance chemicals (degreasers, chain lube, soap) the internal motor environment and road grit.
RQ 4.3	The body of the cartridge must allow the desiccant to only adsorb moisture internally and not externally.
RQ 4.4	The cartridge must allow the desiccant to be regenerated.
Wish 4.4.1	The cartridge should lead to the least waste possible.
Wish 4.4.2	The cartridge should be made from sustainable materials as much as possible.

	Requirements O-ring Specifications
RQ 5.1	The design restricts O-ring stretch to a maximum of 5% and compression to 3% to prevent material fatigue over the two-year maintenance cycle.
RQ 5.2	The cross-sectional (CS) area of the groove needs to be at least 15% larger than the CS area of the O-ring.
RQ 5.3	The material must withstand motor operates in temperatures from 20 °C to 80 °C and exposure to petroleum-based bike greases and chain lubes.
RQ 5.4	Corners must be chamfered during seal installation to limit damage and reduce wear and tear, stress, and maintenance issues.
RQ 5.5	The O-ring must have a squeeze of at least 0.1 mm to ensure its waterproofing.

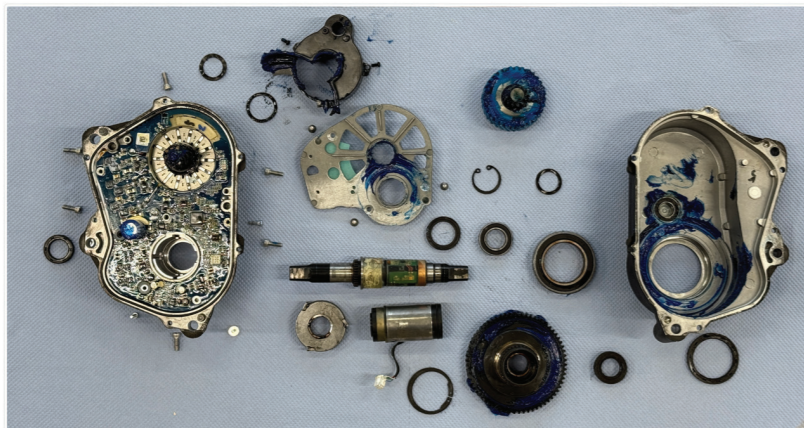
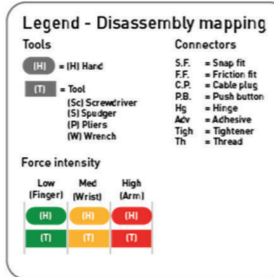
Appendix C Disassembly Mapping

Ananda M81

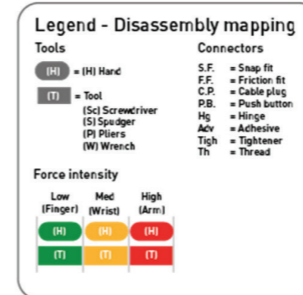
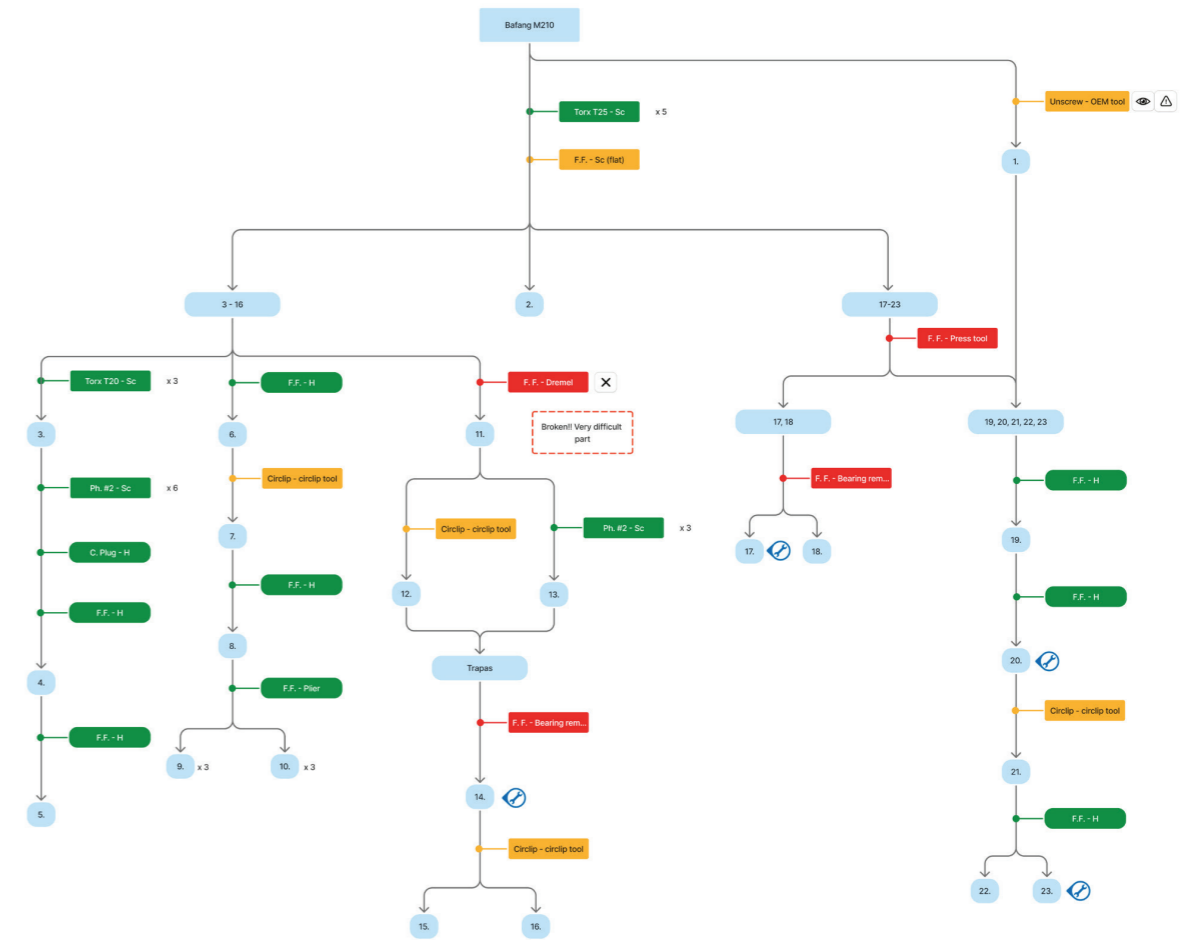


Components

1. Circlip 1
2. Bearing 6907RS (CHL)
3. Bearing 6901RS (CHL)
4. Kartelheft links
5. Seal ring
6. Seal ring
7. Bearing 61903RS (C&U)
8. Gear ring
9. Plastic gear protection
10. Bearing 6901RS (CHL)
11. Nylon gear
12. Metal gear
13. Springring
14. Freewheel mechanisme
15. Rubber ring
16. Torque sensor
17. Crankshaft
18. Springring
19. Circlip 2
20. Metal cover
21. Spring ring
22. Seal ring

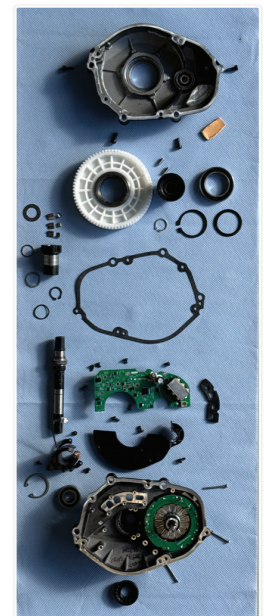


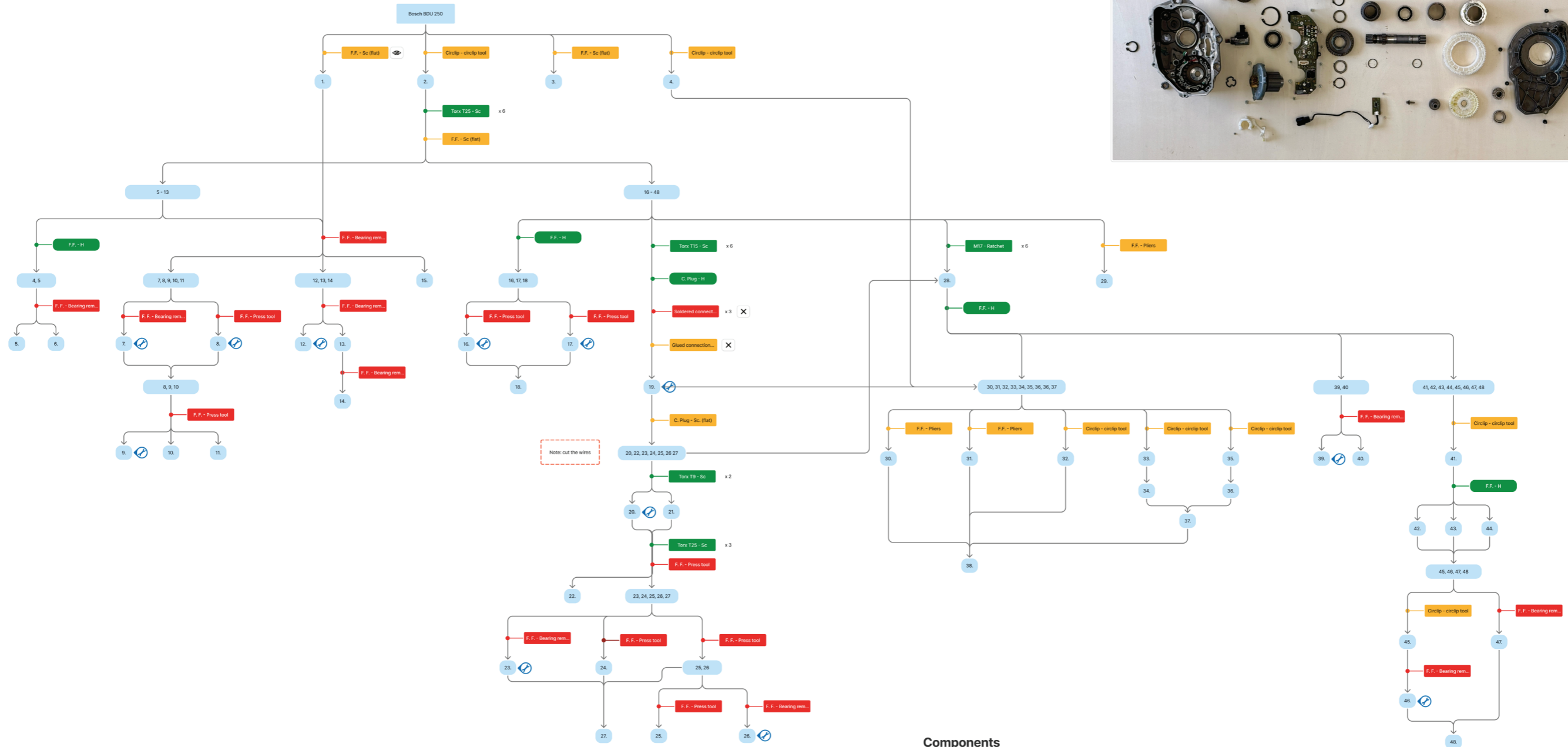
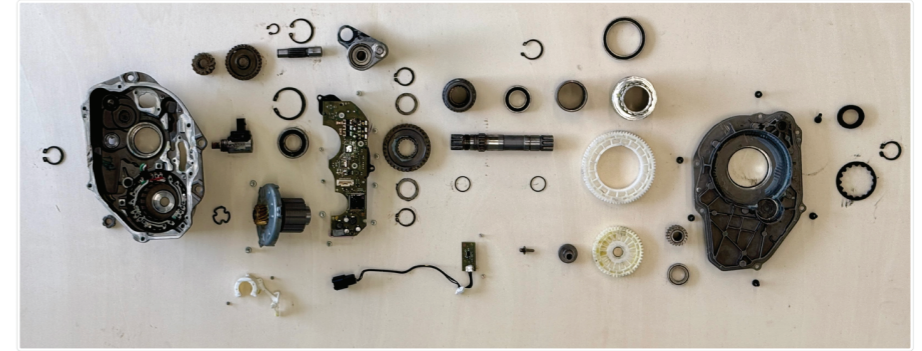
Bafang M210



Components

1. Chainring
2. Water seal
3. Motherboard cover
4. Motherboard
5. Rubber connector protector
6. Trapas-ring 1
7. Circlip 1
8. Trapas-ring 2
9. Freewheel stop
10. Freewheel stop spring
11. Torque sensor
12. Circlip 2
13. Plastic cover
14. Bearing 6008 RS
15. Circlip 3
16. Crankshaft
17. Bearing 629RS
18. Casing right half
19. Seal ring
20. Bearing 6907RS1
21. Circlip
22. Freebody sub-assembly (incl. needle bearings)
23. Nylon Gear





Legend - Disassembly mapping

Tools

- (H) = (H) Hand
- (T) = Tool
- (Sc) = Screwdriver
- (Sp) = Spudger
- (P) = Pliers
- (W) = Wrench

Connectors

- S.F. = Snap fit
- F.F. = Friction fit
- C.P. = Cable plug
- P.B. = Push button
- Hg = Hinge
- Adv = Adhesive
- Tigh = Tightener
- Th = Thread

Force intensity

Low (Finger)	Med (Wrist)	High (Arm)
(L)	(M)	(H)

Penalties

- Product manipulation
- Low visibility/identifiability
- Uncommon tool
- Non-reusable connector

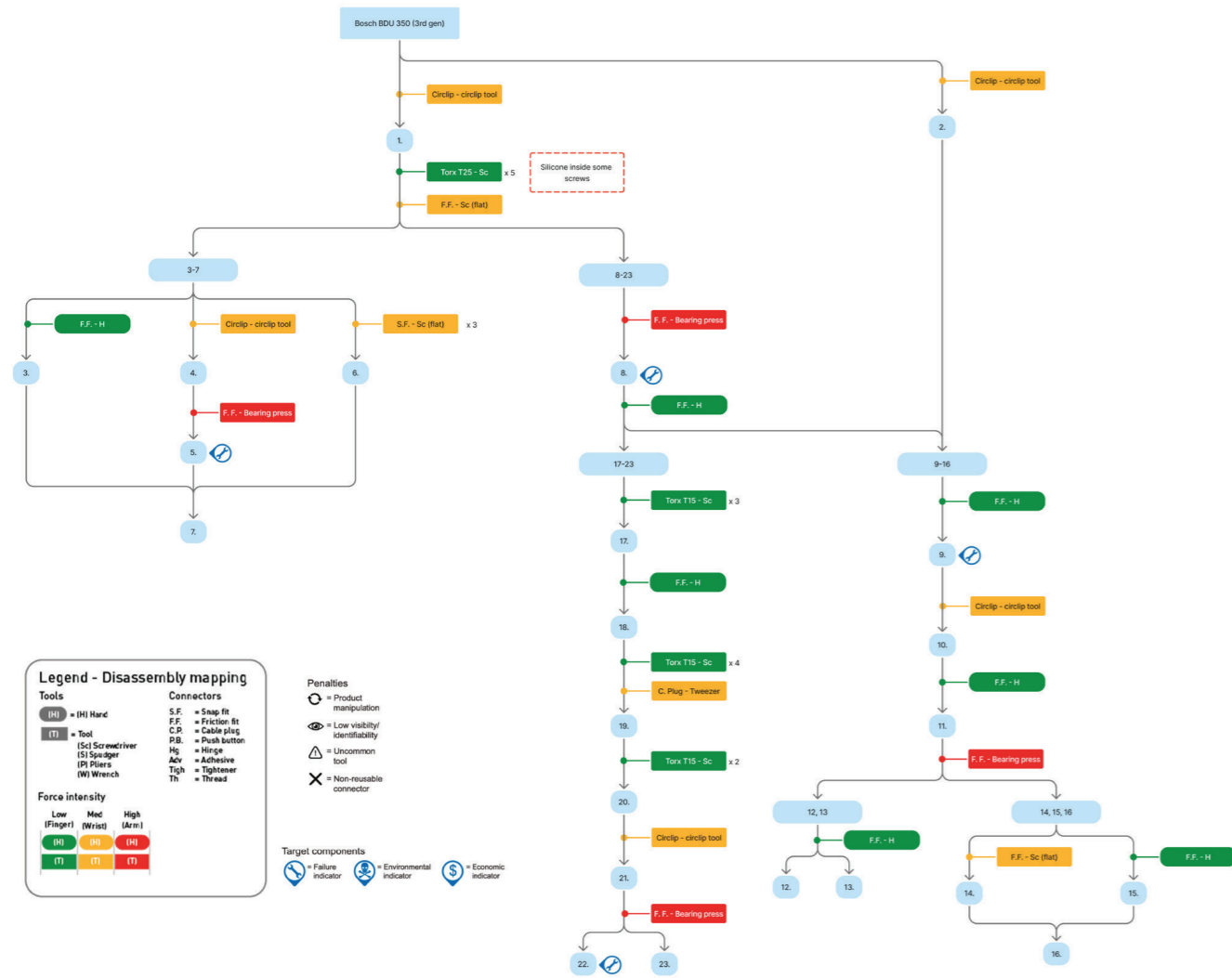
Target components

- Failure indicator
- Environmental indicator
- Economic indicator

Components

- | | | |
|----------------------|-----------------------|-----------------------------------|
| 1. Plastic protector | 17. Bearing 4 | 33. Circlip 4 |
| 2. Circlip 1 | 18. Metal base 2 | 34. Metal ring 2 |
| 3. Foam ring | 19. Motherboard | 35. Circlip 5 |
| 4. Circlip 2 | 20. Hall sensor | 36. Metal ring 3 |
| 5. Needle bearing 1 | 21. Plastic holder | 37. Metal gear 4 |
| 6. Metal gear 1 | 22. Metal ring 1 | 38. Crankshaft |
| 7. Bearing 1 | 23. Bearing 5 | 39. Bearing 7 |
| 8. Large nylon gear | 24. Metal gear 3 | 40. Right half casing incl. coils |
| 9. Bearing 2 | 25. Motor top cover | 41. Circlip 6 |
| 10. Needle bearing 2 | 26. Bearing 6 | 42. Metal axle |
| 11. Metal base | 27. Rotor | 43. Metal gear 5 |
| 12. Bearing 3 | 28. M17 bolt | 44. Metal gear 6 |
| 13. Metal gear 2 | 29. Gear locator bolt | 45. Circlip 7 |
| 14. Needle bearing 3 | 30. O-ring | 46. Bearing 8 |
| 15. Left half casing | 31. O-ring | 47. Needle bearing 4 |
| 16. Small nylon gear | 32. Circlip 3 | 48. Gear assembly holder |

Bosch BDU 350



Legend - Disassembly mapping

Tools		Connectors	
(H) = (H) Hand	S.F. = Snap fit	S.F. = Snap fit	S.F. = Snap fit
(T) = Tool	F.F. = Friction fit	F.F. = Friction fit	F.F. = Friction fit
(S) = Screwdriver	C.P. = Cable plug	C.P. = Cable plug	C.P. = Cable plug
(IS) = Spreader	Hg = Hinge	Hg = Hinge	Hg = Hinge
(PI) = Pliers	Adv = Adhesive	Adv = Adhesive	Adv = Adhesive
(W) = Wrench	Tgh = Tightener	Tgh = Tightener	Tgh = Tightener
	Th = Thread	Th = Thread	Th = Thread

Force intensity

Low (Finger)	Med (Wrist)	High (Arm)
(L)	(M)	(H)

Penalties

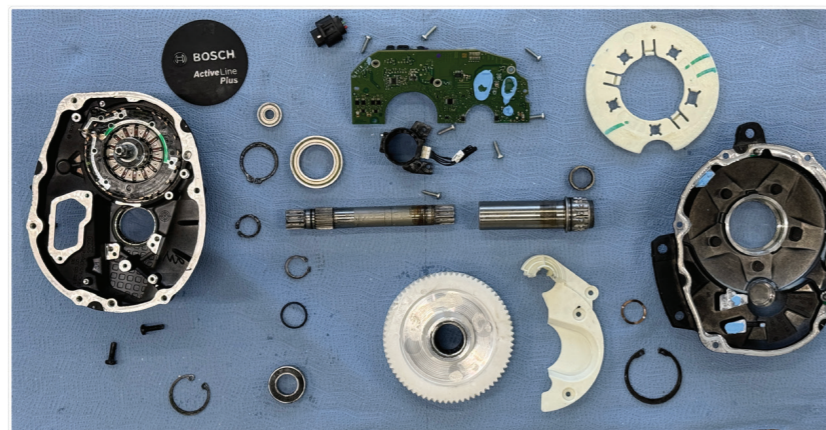
- Product manipulation
- Low visibility/identifiability
- Uncommon tool
- Non-reusable connector

Target components

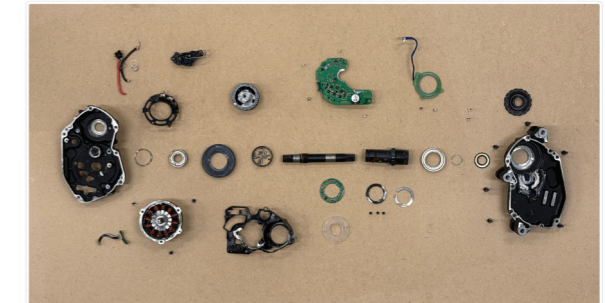
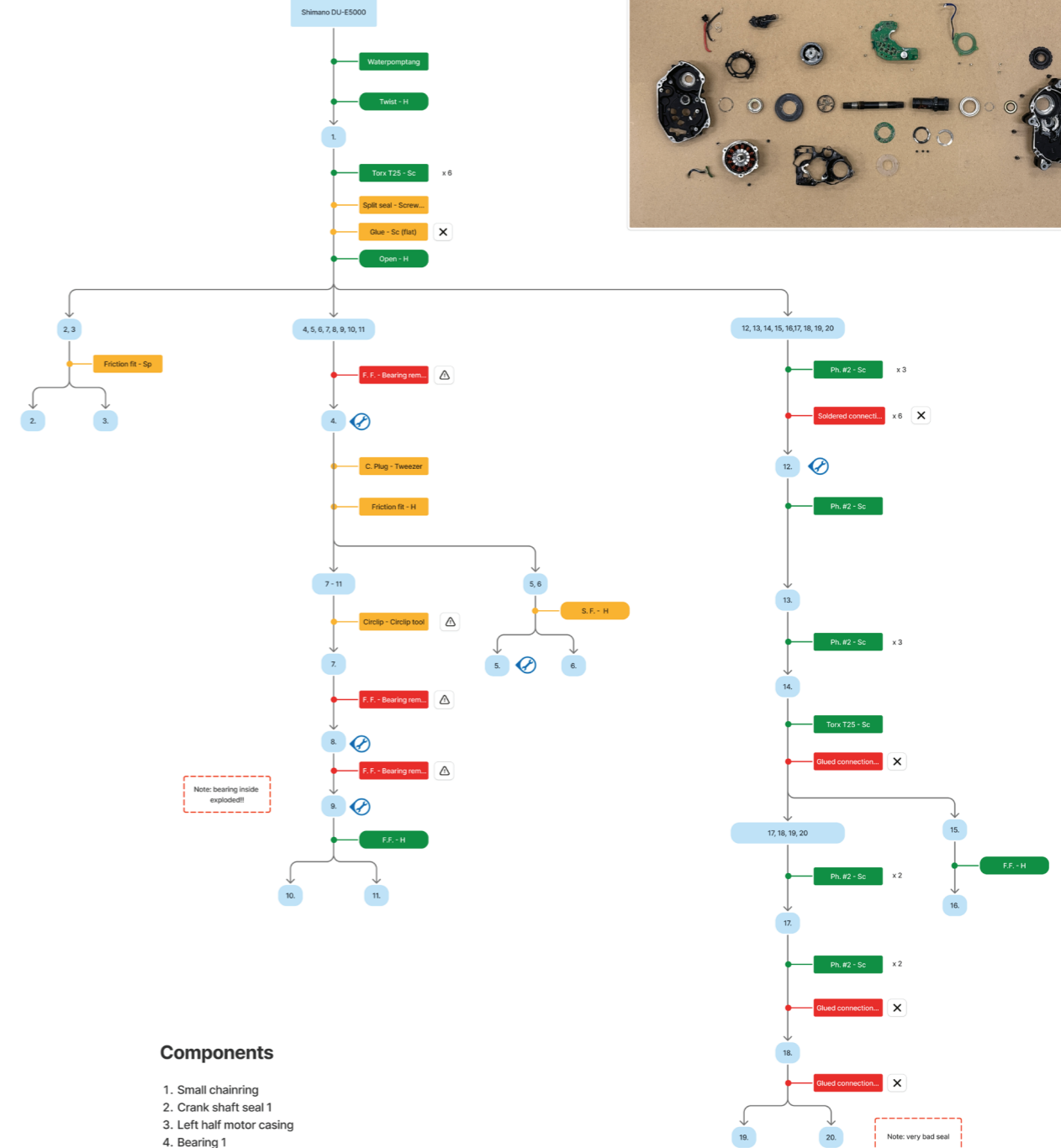
- Failure indicator
- Environmental indicator
- Economic indicator

Components

- Circlip 1
- Circlip 2
- Spring ring
- Circlip 3
- Bearing 6906-ZV (CW)
- Plastic cover part
- Casing half
- Bearing 608-Z (CW)
- Nylon gear, incl. freewheel mechanism
- Circlip 4
- Rubber ring
- Rubber ring
- Inner crankshaft
- Rubber ring
- Water seal
- Outer crankshaft
- Plastic motherboard protector
- Connector plug
- Motherboard
- Torque sensor assembly (incl. plug)
- Circlip 5
- Bearing 18*33*8-ZV (CW)
- Casing half



Shimano DU-E5000



Components

- Small chainring
- Crank shaft seal 1
- Left half motor casing
- Bearing 1
- Sensor
- Plastic sensor mount
- Circlip
- Bearing 2
- Bearing 3
- Gear (with exploding bearing inside)
- Crankshaft
- Main PCB
- Round sensor
- Plastic motor cap
- Metal casing
- Electromotor
- Small sensor
- Cable connector 1
- Cable connector 2
- Right half motor casing

Legend - Disassembly mapping

Tools		Connectors	
(H) = (H) Hand	S.F. = Snap fit	S.F. = Snap fit	S.F. = Snap fit
(T) = Tool	F.F. = Friction fit	F.F. = Friction fit	F.F. = Friction fit
(S) = Screwdriver	C.P. = Cable plug	C.P. = Cable plug	C.P. = Cable plug
(IS) = Spreader	Hg = Hinge	Hg = Hinge	Hg = Hinge
(PI) = Pliers	Adv = Adhesive	Adv = Adhesive	Adv = Adhesive
(W) = Wrench	Tgh = Tightener	Tgh = Tightener	Tgh = Tightener
	Th = Thread	Th = Thread	Th = Thread

Force intensity

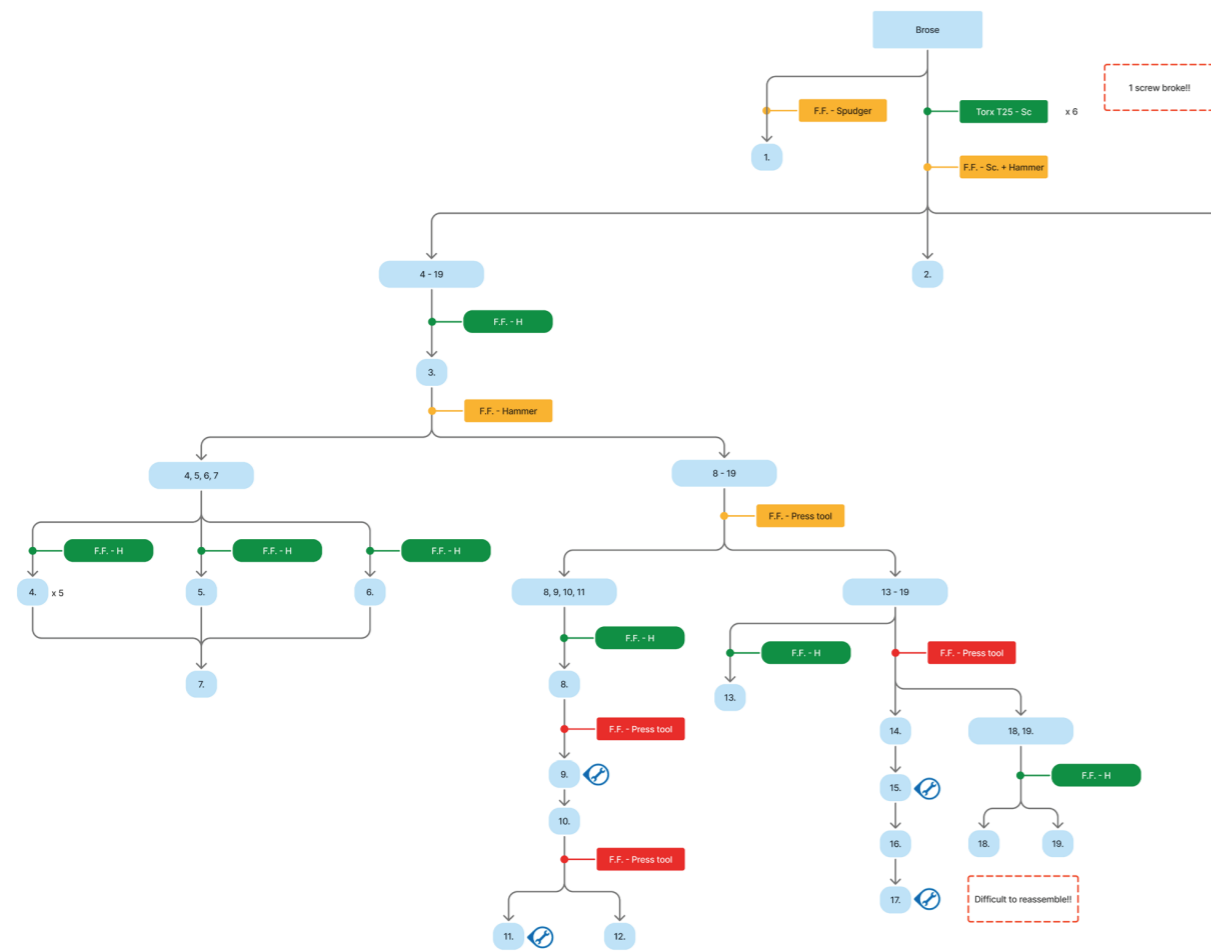
Low (Finger)	Med (Wrist)	High (Arm)
(L)	(M)	(H)

Penalties

- Product manipulation
- Low visibility/identifiability
- Uncommon tool
- Non-reusable connector

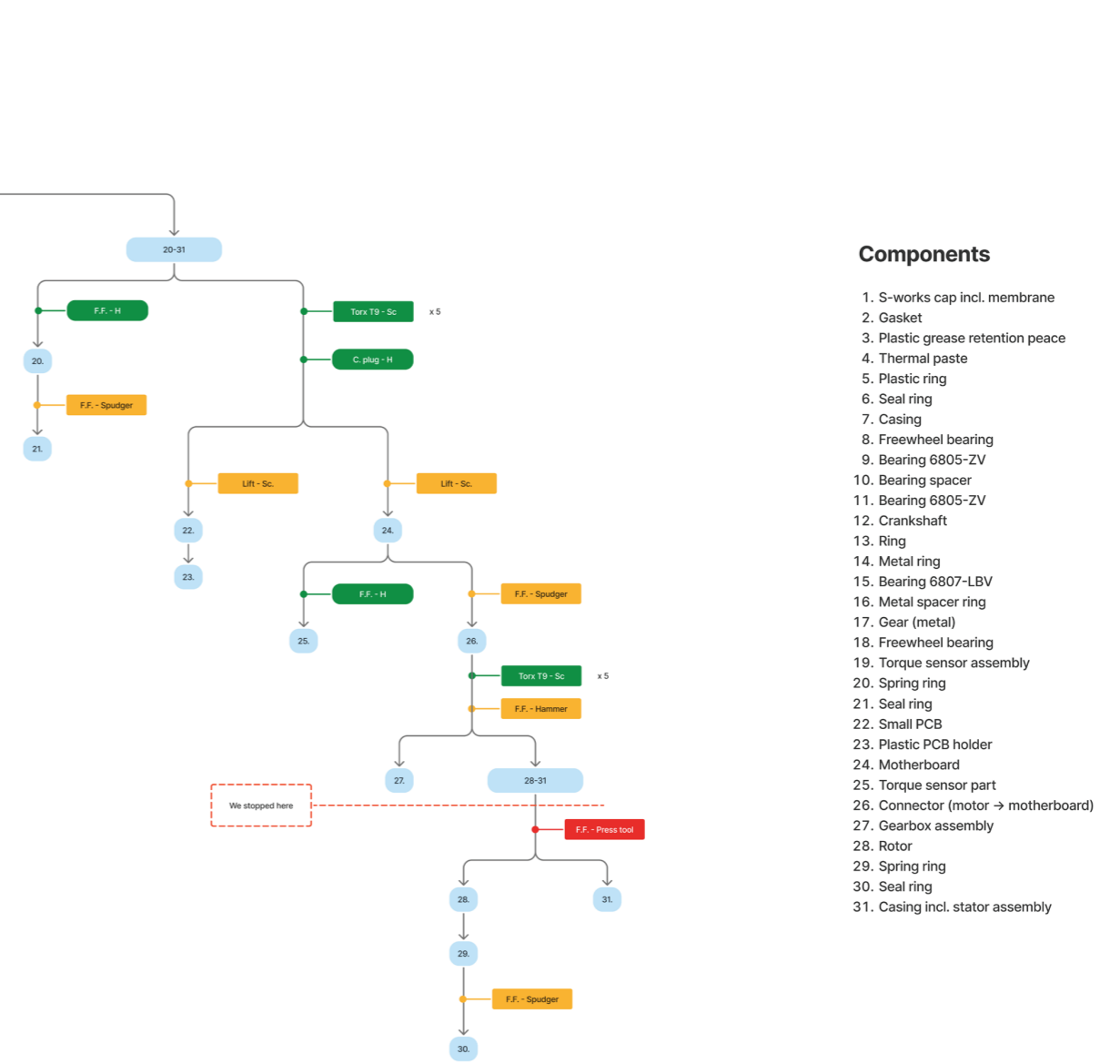
Target components

- Failure indicator
- Environmental indicator
- Economic indicator



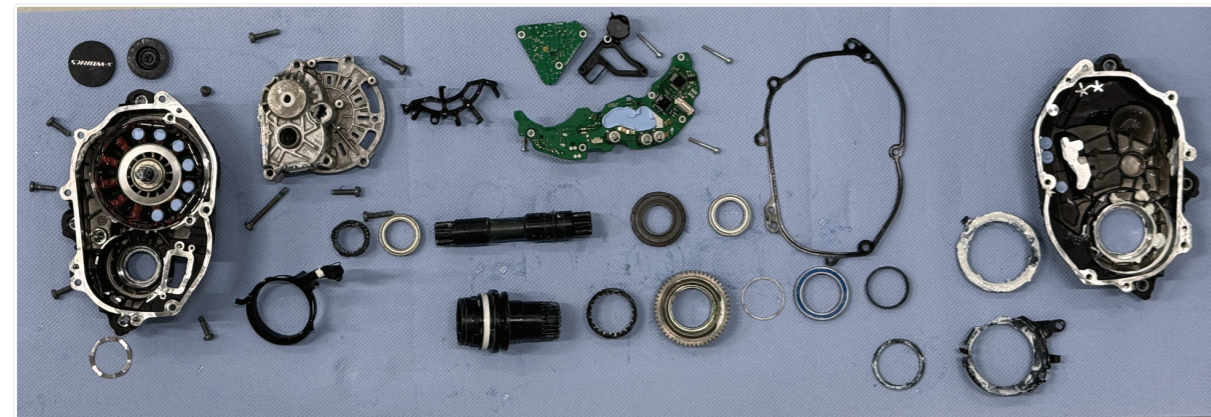
1 screw broke!!

Difficult to reassemble!!



We stopped here

- ### Components
- S-works cap incl. membrane
 - Gasket
 - Plastic grease retention peace
 - Thermal paste
 - Plastic ring
 - Seal ring
 - Casing
 - Freewheel bearing
 - Bearing 6805-ZV
 - Bearing spacer
 - Bearing 6805-ZV
 - Crankshaft
 - Ring
 - Metal ring
 - Bearing 6807-LBV
 - Metal spacer ring
 - Gear (metal)
 - Freewheel bearing
 - Torque sensor assembly
 - Spring ring
 - Seal ring
 - Small PCB
 - Plastic PCB holder
 - Motherboard
 - Torque sensor part
 - Connector (motor → motherboard)
 - Gearbox assembly
 - Rotor
 - Spring ring
 - Seal ring
 - Casing incl. stator assembly



Legend - Disassembly mapping

Tools			Connectors		
(H)	= (H) Hard		S.F.	= Snap fit	
(T)	= Tool		F.F.	= Friction fit	
(Sc)	= Screwdriver		C.P.	= Cable plug	
(SI)	= Spudger		P.B.	= Push button	
(P)	= Pliers		Hg	= Hinge	
(W)	= Wrench		Adv	= Adhesive	
			Tigh	= Tightener	
			Th	= Thread	

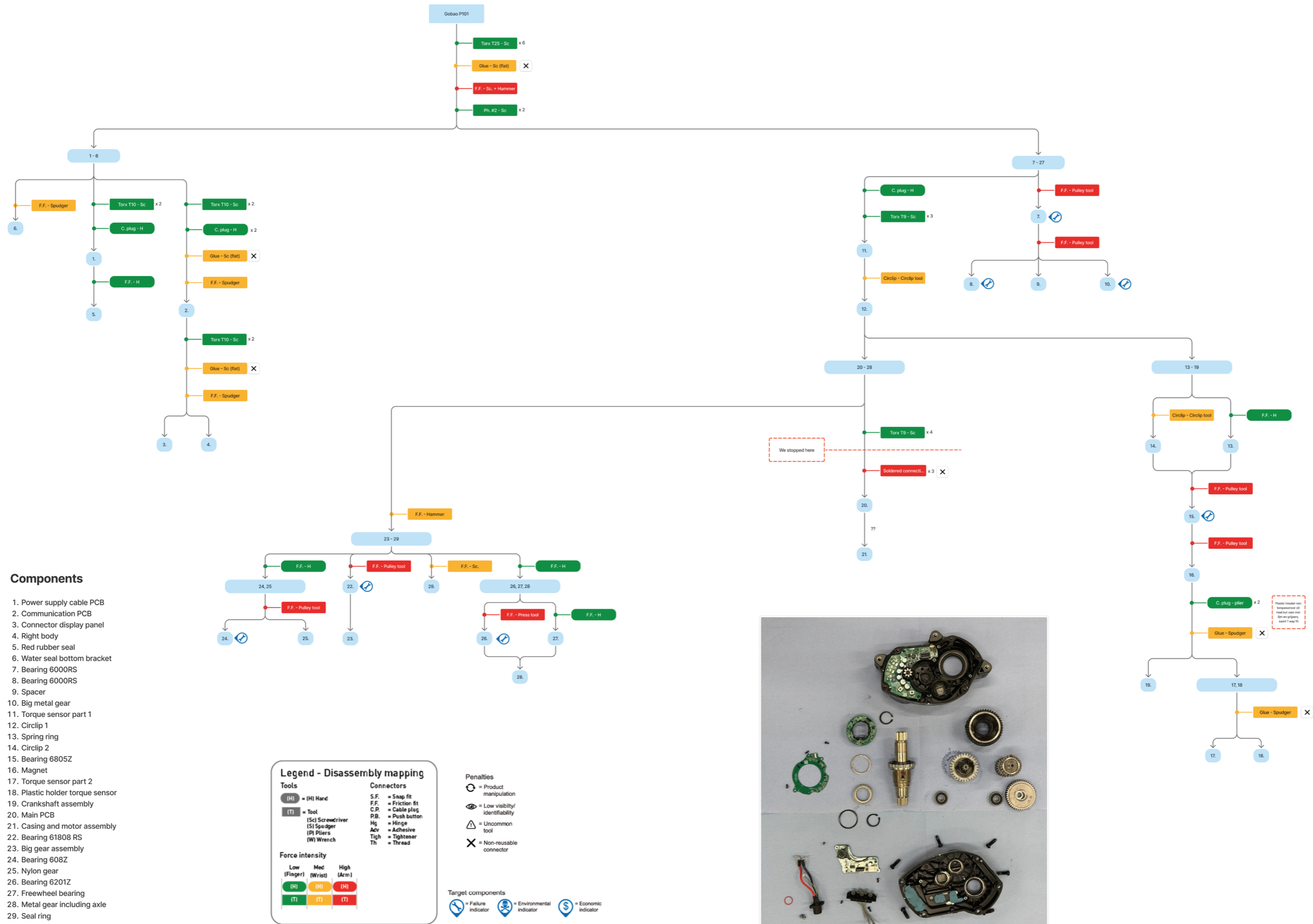
Force intensity		
Low (Finger)	Med (Wrist)	High (Arm)
(H)	(H)	(H)
(T)	(T)	(T)

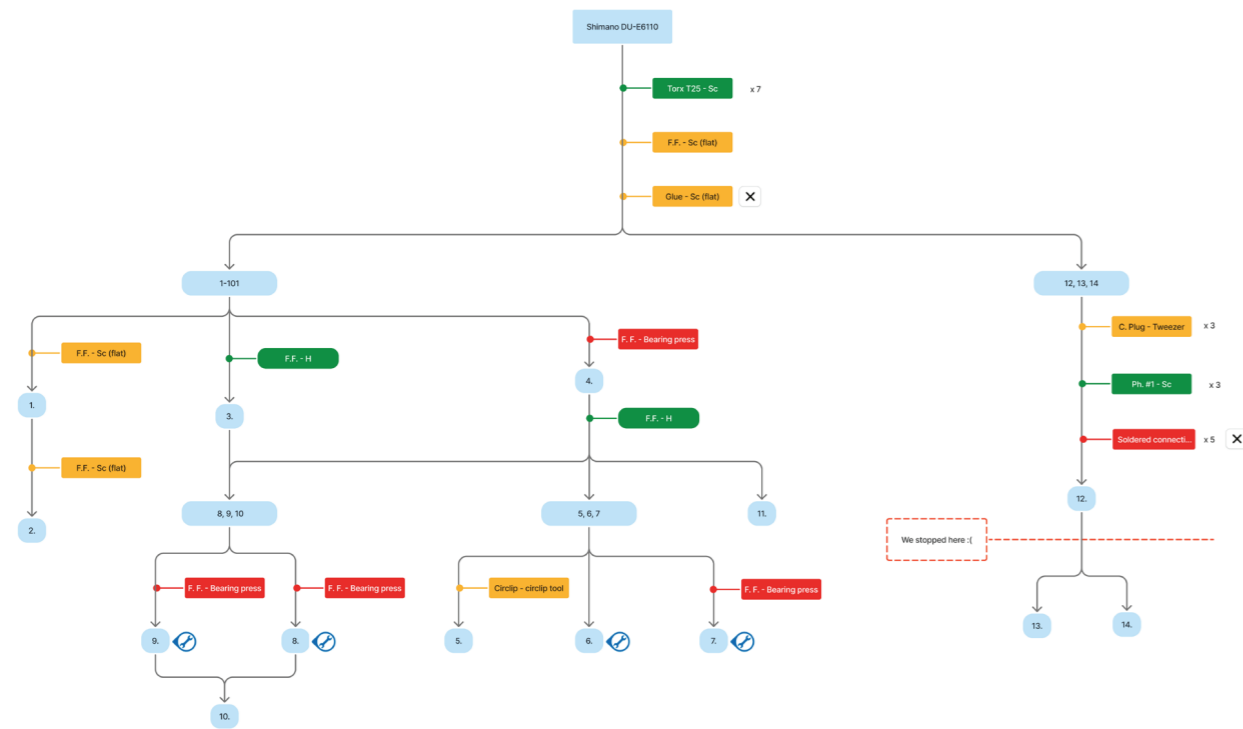
Penalties

- Product manipulation
- Low visibility/identifiability
- Uncommon tool
- Non-reusable connector

Target components

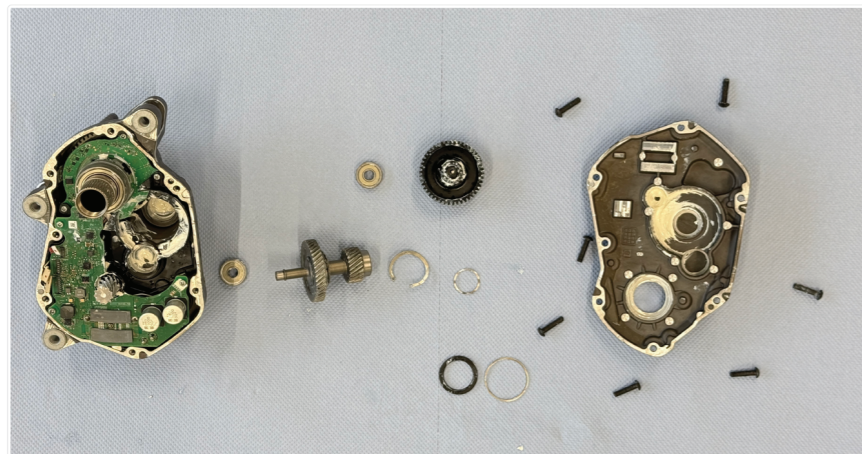
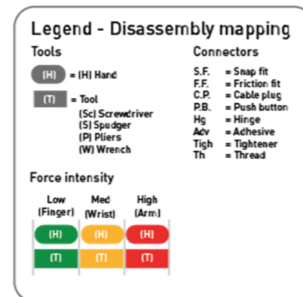
- Failure indicator
- Environmental indicator
- Economic indicator





Components

1. Seal ring
2. Spring ring
3. Small spring ring
4. Bearing 608-Z (NSK)
5. Circlip
6. Double metal gear
7. Bearing 608-Z (NSK)
8. Bearing 608-Z (NSK)
9. Bearing 608-Z (NSK)
10. Freewheel gear assembly
11. Casing half
12. Motherboard
13. Trapas assembly
14. Casing + motor assembly



Appendix D Interview Questions

Interview Questions Bike Mechanics

Introduction

- What percentage of the bicycles you sell/repair are e-bikes?
- What brand of bicycles do you sell?
- What brand of motors do you sell?

Motor Failures

- In your experience, how many kilometers do e-bike motors typically last (examples of short/long lifespan)?
- In your experience, what percentage of e-bikes have motor problems?
- Looking specifically at the motor, what are the top 3 most common failures you see?
- What do you think is the underlying cause of these motor problems? Is it pure wear and tear, moisture damage, software errors, or perhaps improper use by the cyclist?
- How important is the role of software and electronics in motor failures compared to mechanical defects (such as bearings or gears)?
- Is it easy for you, as a bicycle mechanic, to diagnose a problem? What tools (readout equipment) do you use for this?

Repairability

- Suppose a motor is defective. What is the standard procedure? Will the engine be repaired or completely replaced?
- Is it permitted and possible to open an engine yourself, for example, to replace a bearing or gear? Or do the manufacturers prescribe that this is not permitted?
- Are spare parts for the engine readily available?

Manufacturers

- How do you experience the support from the engine manufacturers regarding warranty, technical manuals, and parts delivery?
- Are there any brands that excel in this area, either positively or negatively?

Interview Questions Remanufacturing Companies

Motor Failures

In your experience, how many kilometers do e-bike motors typically last (examples of short/long lifespan)?

What percentage of e-bikes have motor problems, in your experience?

Looking specifically at the motor, what are the top 3 most common failures you see?

What do you think is the underlying cause of these motor problems? Is it pure wear and tear, moisture damage, software errors, or perhaps misuse by the rider?

How important is the role of software and electronics in motor failures compared to mechanical defects (such as bearings or gears)?

Is it easy for you to diagnose a problem? What tools (readout equipment) do you use for this?

Repairability

Suppose a motor is defective. What is the standard procedure? Is the motor repaired or completely replaced?

Are spare parts for the motor readily available?

Reconditioning

Which motors do you work on? What does your overhaul line look like? What does the process entail?

How much does a complete overhaul of a motorcycle cost, both in terms of new parts and time?

Which parts do you replace during an overhaul?

What are some things you frequently encounter during an overhaul?

Manufacturers

How do you experience the support from motorcycle manufacturers regarding warranty, technical manuals, and parts delivery?

Are there any brands that excel in this area, either positively or negatively?

What do you think is wrong with the current e-bike market?

General

Are there any other things you'd like to share?

Open discussion about what we've heard from bike manufacturers.

Appendix E

Interview Answers

Results (summary from notes, generated by AI)

Repair and sales 1 & 11

Bosch's service is really very good and accommodating. If there are any problems, they quickly send a new motor (I have no idea what happens to the old one). "I often see that batteries wear out faster than the motors actually do."

Repair and sales 2 & 9

Satisfied with returning the motor to Bosch/Shimano. Happy with these two major suppliers. In the past, there were many more small suppliers who caused more problems because they all had different working methods. Doesn't think many motors break down. Doesn't open the motors himself, but always sends them back. Because: the warranty expires. There are no spare parts. EU regulations are likely to change. Then something else will have to be devised, he reckons. The reason for replacing a complete bicycle instead of just the motor lies with the customer and is usually budget-related. Replacing the motor takes about an hour.

Repair and sales 3

Motors hardly ever break down; they are simply well constructed. Only uses Bosch motors. Has a maximum of 2-3 broken motors per year. The goodwill arrangement is even longer → 4/5/6 years, you often get a discount. Sends it to Bosch, works really well. They have no idea what happens to the motors that are sent to Bosch. Replacing a motor takes about an hour.

Repair and sales 4

This one also did not open the motors and rarely has broken motors. After 4/5 years, sometimes one breaks down, and then people often opt for a completely new bicycle. The old bicycle simply goes to the scrap metal dealer, who picks it up for free. Replacing a motor takes about an hour. Battery reconditioning has been around for some time, but I don't know anything about motor reconditioning.

Repair and sales 5 & 6

The cost of repairing the motor is too high for what you get in return; it would actually be better to install a new motor. They also refuse to open the motors, as this would void the warranty. Bosch collects the broken motors and sends new ones; they have no idea what happens to them. Older versions of the motors are more prone to error messages. Some brands, such as Bafang, do have replacement parts, but it is unclear exactly how this works.

Repair and sales 7 & 8

Recognised all the barriers mentioned by previous bicycle makers. Open to online discussion about frustrations. May have extra parts/motors to donate.

Repair and sales 10

Has different brands. Does not open electric motors. Electric bicycles are often not worth refurbishing and selling on the second-hand market when the motor breaks down because: first, a new motor must be purchased, often for the same or more money than the bicycle is still worth. Does not understand why they use PCB in the motor. This would solve a lot of problems. Missing parts, etc. are the reason why they are not opened after the warranty expires.

Open to a follow-up interview, preferably in the morning. Has provided two hub motors to take apart.

Remanufacturer 1

The company involved in this project has many years of experience in repairing e-bike motors and has built a large database of failures, causes, and repair solutions. To date, approximately 15,500 motors have been repaired. The repair process is highly circular: many parts are reused from second-hand motors, resulting in very little residual waste.

The relationship with manufacturers differs strongly per brand. Bosch initially provided limited support but does not officially support independent repairers. Brose and Mahle supply parts directly, and Bafang motors are designed to be highly repairable, with all internal components available. Shimano does not cooperate with repair companies and does not provide software or spare parts. On average, a motor repair takes around 2.5 hours. Clean motors with bearing or gear damage can often be repaired in under two hours, while motors affected by water or mud require full disassembly and cleaning and can take up to five hours. Approximately 250 motors are repaired per month. In some cases, electronic components are also repaired and reused.

Failure patterns differ by use case. Motors used on city and road bikes show relatively few failures, while mountain bike motors fail more often due to water, mud, and higher mechanical loads. Water ingress is frequently caused by pressure differences and airflow during transport, rather than by rain. Fully sealed motors reduce water ingress but increase friction and reduce efficiency, which manufacturers tend to avoid. Many motors reach lifetimes of 40,000–50,000 miles without major issues.

According to the repair company, batteries are the main reason e-bikes are discarded. Battery replacement is costly, and failures often occur shortly after the warranty period. Issues include battery management systems disabling the entire pack due to a single faulty cell and deep discharge leading to irreversible damage.

Looking ahead, manufacturers are slowly increasing repairability, partly driven by upcoming right-to-repair regulations. Design changes take time, due to long development cycles. Hub motors are considered mechanically more durable and easier to repair, while mid-drive motors are mainly chosen for market and performance-related reasons.

Remanufacturer 2

The company is a family-owned business founded in 2018, originating from a hobby project after the founder's father suffered a stroke. It started with refurbishing second-hand bicycles and gradually specialised in the revision of e-bike motors, with a strong focus on Bosch systems.

Most motors are received after the warranty period has expired (Bosch: three years, sometimes extended to five years as a goodwill gesture). Bicycle shops typically do not repair motors themselves and instead send defective units to specialised repair companies.

Based on the company's experience, approximately 50% of motor failures are related to bearing damage, which is often predictable per motor type. Around 25% are electrical failures, which are difficult or impossible to repair depending on software restrictions and PCB design. The remaining 25% consist of other issues such as moisture damage, gear wear, and structural failures of the motor housing or mounts.

Several brand-specific weaknesses were identified. Bosch sometimes uses bearings with nonstandard dimensions, which are not freely available. Plastic gears used in Bosch Active Line motors wear or fail faster than the steel gears used in Performance Line motors. In Brose motors, the internal belt typically wears after around six years but is often not replaced preventively.

Bosch provides very limited spare parts and mainly promotes complete motor replacement by bicycle shops. Only a small number of revision kits are available, which do not cover all common failure modes. As a result, spare parts are often sourced through informal networks of bicycle shops. From a market perspective, Bosch dominates the Dutch e-bike market with an estimated share of around 75%. Bafang is growing in the lower-priced segment, particularly among younger users and fat bikes. Brose is mainly used in high-end mountain bikes, such as those from Specialized. Stromer, which focuses on high-end speed pedelecs, still uses rear hub motors, which are considered mechanically simpler and more durable.

From a design perspective, rear hub motors are technically more durable due to fewer wear components and lower mechanical load paths. Mid-drive motors are mainly adopted for market and branding reasons, such as central weight distribution and promotion by major manufacturers. New concepts, such as integrated gearboxes, may offer a compromise between these approaches.

Remanufacturer 3

The interviewed organisation specialises in the repair and refurbishment of industrial electric motors. These motors are typically high in purchase cost, which makes repair economically attractive. The company is currently expanding its activities toward structured refurbishment lines for smaller electric drive units.

The organisation originally started refurbishing motors through a collaboration with an industrial partner, where end-of-life motors were disassembled and components were reused. According to the interviewee, a broader shift in business models is making repair and refurbishment more attractive. Examples include service-based or access-based models, in which manufacturers retain responsibility for maintenance while customers pay for usage rather than ownership.

In this context, the company is developing a refurbishment line for e-bike motors. Preparatory discussions on how to organise this process have been ongoing for several years. At present, approximately 8,000 motors have been collected for refurbishment. Historically, around 70–75% of incoming motors can be successfully refurbished. Once the refurbishment line is fully professionalised and operational, the expected throughput is approximately 5,000 motors per year.

The interviewee indicated that the most common failure mode in the motors currently under consideration relates to sensor failures, which result in specific error codes. Replacement sensors are not commercially available. However, there is potential for third-party production of replacement circuit boards as spare parts in the future.

To professionalise the refurbishment process, the organisation aims to implement an efficient

production line supported by automation, a clearly defined workflow, investments in tooling, and digital quality control and testing procedures. At present, no formal support is provided by original manufacturers in terms of spare or replacement parts. Components are sourced through an internal and informal network.

The company operates exclusively in a business-to-business context and focuses on high-volume refurbishment rather than individual consumer repairs. The long-term goal is to establish a centralised entity where bicycle retailers can purchase refurbished motors at a fixed price, making functional replacement motors more accessible and affordable for end users.

Based on current estimates, the organisation expects that a single motor could be refurbished within 30–60 minutes, corresponding to a refurbishment cost of approximately €100. At present, the refurbishment line is operated by a small team.

Remanufacturer 4

The interviewee is an independent bike mechanic operating a small e-bike-focused workshop. He indicated openness to follow-up contact. His professional background is in the automotive industry, where he previously worked on robot programming. He has formal training in both electrical and mechanical engineering.

According to the interviewee, the motor control PCB is paired with the motor's orientation sensor, meaning that these components cannot be interchanged without recalibration or replacement as a matched set. He noted that Bosch has made progress in repairability by releasing revision kits for second-generation motors. While earlier designs used plastic gears, these have since been replaced with metal components.

The interviewee expressed strong criticism of Shimano, particularly regarding repairability and support for independent repair. He emphasised that user behaviour plays a significant role in motor failures. Inadequate maintenance—often less frequent than the recommended annual or biannual service—contributes substantially to premature wear and failure. From this perspective, motor failure is not always attributable to design flaws alone.

He reported positive experiences with the latest generations of e-bike motors, stating that they show improved durability compared to earlier versions. Water-related damage does occur, but is mainly associated with e-mountain bikes, bicycles transported on vehicle-mounted carriers, and the use of high-pressure cleaning. Newer Bosch motor designs are expected to have a significantly longer service life.

Revising motors using Bosch replacement kits was described as straightforward, typically requiring 30 to 60 minutes. The interviewee identified the battery as a larger long-term issue than the motor itself. Battery technology has not progressed at the same pace as other e-bike components, partly due to external constraints on battery development. Batteries are not designed to withstand prolonged outdoor exposure and temperature fluctuations, and they are often subjected to high power demands and improper user handling.

Finally, he noted a design change in newer motors in which the main PCB is no longer fixed with rigid soldered connections. Instead, spring-loaded contact pins are used, allowing vibrations to be absorbed more effectively and reducing mechanical stress on the electronics.

Appendix F

Refurbishment

Guidelines

The Bosch motor is refurbished and upgraded in the following order (The eBike Motor Centre, 2025) (APA): Motor is disassembled and the complete crankshaft assembly removed.

Self-lubricating plastic crankshaft support bushes are replaced in the torque tube to stabilise crankshaft play.

The original torque tube sealing ring is removed and an Oilite self-lubricating bronze bush is fitted to ensure maximum crankshaft support. This stops crankshaft oscillation and aids sealing.

After the Oilite bush, we fit a single-lip rotary shaft seal, with the lip facing outwards to stop water ingress into the crankshaft and torque tube area. This stops rust damage to the crankshaft bearing surface, premature failure of the crankshaft support bushes, and internal damage to the printed circuit board (PCB) and all other components.

The left hand crankshaft bearing is replaced with a double-sealed bearing to prevent water ingress into or through this bearing.

Waterproof long life grease is packed between outer bearings and motor covers. This helps stop water sitting in these areas and seeping into the outer bearings.

We also remove the PCB and add a silicone coating to the plug assembly gasket seal.

Silicone gasket sealant is also added to the aluminium motor cover gasket. Water ingress into this area corrodes the gasket faces of the magnesium motor cases.

Finally, we treat and coat the motors' electric socket pins to limit corrosion.

The Brose motor is refurbished and upgraded in the following order (eBike Motor Centre, 2025):

Upgraded thicker, stronger, Brose carbon fibre drive belt.

Upgraded heavy duty sprag clutch bearing for the motor drive pulley

Upgraded heavy duty sprag clutch bearing for the crankshaft drive

Single lip rotary shaft seal to stop water ingress into the crankshaft needle roller bearing and beyond (This also stops rust damage to the crankshaft bearing surface and premature failure of the crankshaft needle roller bearing)

Genuine Brose bearing cover seal for the right hand crankshaft ball bearing (Not factory fitted until 2017)

Waterproof long life grease packed between outer bearings and motor covers. (This helps stop water sitting in these areas and seeping into the outer bearings).

We also fit an external X-ring seal each side of the crankshaft to further stop the chance of any water ingress into the motor.

We remove the two ECU cover screws and seal these to stop water ingress into the ECU.

Finally, we treat and coat the motors' electric plugs to stop corrosion and water entering the ECU by capillary action along the wires.

Appendix G

Silica Gel

Calculations

Silica Calculation Appendix

free air volume average = 200 ml air total
50 ml air (refresh)

silica gel 35% moisture absorption
silica gel dichtheid = 0,7
safety factor = 3

① IDEAL GAS LAW

$$P \times V = n \times R \times T$$

① SATURATION VAPOR PRESSURE

$$P_{SAT} = 6.112 \times e^{\left(\frac{17.67 \times T}{T + 243.5}\right)}$$

pressure at freezing
e (EULER) = 2.718
bolton/magnus

② ACTUAL VAPOR PRESSURE

$$P_{act} = P_{SAT} \times \frac{RH}{100}$$

③ ABSOLUTE HUMIDITY

$$AH = \frac{216.7 \times P_{act}}{T + 273.15}$$

molecular weight of water vapor

KNMI DATA

	T(avg)	RH(avg)	AH	ingress (g)
jan	6.1	87	6.4	0.03
feb	7.0	84	6.5	0.027
mrt	10.5	78	7.7	0.036
apr	14.8	73	9.2	0.042
mei	18.3	70	10.9	0.051
jun	20.9	72	13.1	0.059
jul	23.1	74	15.2	0.071
aug	22.9	76	15.4	0.072
sep	19.5	81	13.6	0.061
okt	14.8	84	10.6	0.049
nov	9.8	89	8.3	0.037
dec	6.7	89	6.7	0.031

0.567 g TOTAL / YEAR

④ COMBINED

$$AH = 216.7 \times 6.112 \times e^{\left(\frac{17.67 \times T}{T + 243.5}\right)}$$

$$\text{Silica gel needed} = \frac{0.567 \text{g} \times 3 (\text{sf}) \times 2 (\text{years})}{0.35} = 10 \text{g}$$

⑤ MONTHLY INGRESS

$$\text{Ingress (g)} = AH \times V_{inhale} \times N_{rides}$$

$V_{inhale} = 0.00005 \text{ m}^3$
 $N_{rides} = 100$