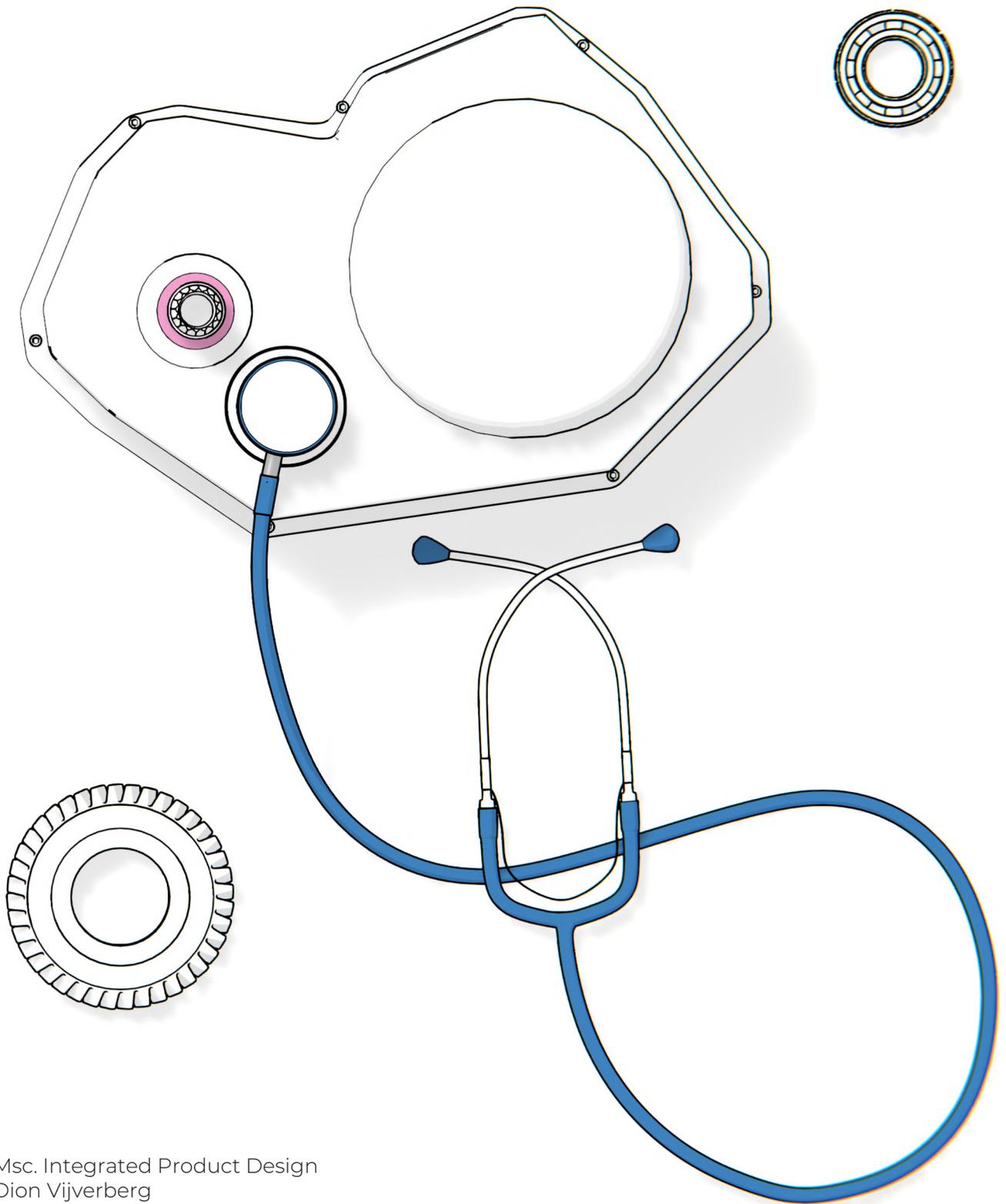


# DEVELOPING A NON-INTRUSIVE DIAGNOSTIC TOOL TO ASSESS THE CONDITION OF E-BIKE MOTORS.



## MASTER THESIS

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# PREFACE.

Hi, i'm Dion Vijverberg and I am a practically oriented IPD student who enjoys understanding how products work by taking them apart. Outside my studies, I spend a lot of time working on technical projects. One example is my old Zündapp moped that I bought when I was eighteen. At the time, I had little knowledge of how a two-stroke engine worked, but over the years, I have spent far more time maintaining and repairing the moped than actually riding it. What I find interesting is that a machine built more than fifty years ago can still be repaired with relatively simple tools and knowledge.

This interest in repair and technical construction of products was further developed during my education, for example during the elective Repair & Recycle. In this course, together with a fellow student, I worked on the disassembly and analysis of a camera. Despite the complexity of the product, I enjoyed mapping its construction and thinking about ways to improve its repairability. This course motivated me to look for a graduation project related to repair and recycling of complex technical products.

The project described in this report focuses on the refurbishment of e-bike motors and the use

of vibration analysis to assess motor condition. E-bike motors are compact products that are often replaced when problems occur, rather than repaired. This project explores whether vibration data can be used to distinguish between healthy motors and motors with internal defects, without opening the motor. The aim is to investigate whether existing measurement technologies can support better diagnostics and, in the long term, improve repairability.

The project was carried out as an individual graduation project, but involved close collaboration with refurbishment companies, bike mechanics, and technical experts. The work combined hands-on prototyping and testing with exploratory research, which fits well with my practical approach.

I hope this report shows that repairability is an important and relevant topic in the design of modern products. Replacing products has become common practice, even when repair could be possible. If mechanical systems (such as a moped) could be maintained and repaired decades ago, it is reasonable to question why this has become so difficult for modern e-bike motors.



Figure 0.1: My 50-year-old Zündapp, still in use and repairable with simple tools and basic knowledge.

# ACKNOWLEDGEMENT.

This project would not have been possible without the support, guidance, and contributions of many people.

First, I would like to thank my supervisory team. My chair, Sonja, for her active involvement, helping establish key contacts and collaborations, and for her insightful feedback throughout the project. My mentor, Ruud, for his valuable and critical perspective, which greatly improved the quality of my work.

I am grateful to the experts, employees and owners from revision companies, bike mechanics, and other industry partners who shared their time, knowledge, and access to motors. Disassembling and performing tests on motors would have been impossible without their help and willingness to collaborate.

I also want to thank my fellow students, particularly Pablo. At the start of the project, we

worked closely together; gathering information, conducting interviews, and reaching out to experts, bike mechanics, and refurbishment companies. The insights and data we collected together were crucial for the rest of my project, and I could never have gathered nearly as much information on my own.

Additionally, I would like to acknowledge the support from everyone at the TU Delft, especially from the PMB and Applied Labs, for their guidance, ideas, and insights at various stages of the project.

Finally, I would like to note that AI tools, including ChatGPT and Gemini, were used as sparring partners and to help improve and refine the text.

**To everyone who contributed in any way: thank you!**

# ABSTRACT.

The increasing adoption of e-bikes has resulted in a growing number of electric motors being produced, used, and eventually discarded. These motors are high-value components, yet they are often poorly repairable. When a motor fails, it is usually replaced rather than repaired, even though more than half of the failures are caused by mechanical components that are theoretically repairable. It is not viable for bike mechanics to open or repair motors themselves, but they play an important role in monitoring and diagnosing problems. At the same time, their ability to assess the internal condition of e-bike motors is limited by closed systems, software-based diagnostics, and a lack of mechanical insight.

This project explores how bike mechanics could be better supported in the transition towards a more circular e-bike motor system. The research combines expert interviews, system analysis, technical teardowns, disassembly mapping, and exploratory testing to understand current barriers to repairability and identify opportunities for improvement. The findings show that mechanical failures, particularly in bearings and gears, occur frequently and are often technically repairable. However, limited ability to detect and diagnose the right signals means that motors

are often not, or only at a late stage, referred to revision specialists.

Based on these insights, a non-invasive, vibration-based diagnostic concept was developed. The proposed tool enables bike mechanics to measure vibration signals from the outside of the motor and compare them with baseline data from healthy motors. In doing so, it supports mechanical diagnosis and helps mechanics make more informed decisions about follow-up actions. Prototyping and testing demonstrated a proof of principle that vibration analysis can be used to distinguish between healthy and defective motors.

The project also highlights important limitations of the proposed concept. It depends on the availability of reliable baseline data, a well-developed revision infrastructure, and clear responsibility for software and data management. Rather than presenting a final solution, this project provides a research direction, a technical proof of principle, and a system-level perspective on the role of diagnosis in improving e-bike motor repairability. It offers a foundation for further research and development towards a more circular e-bike motor system.

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# TERMINOLOGY.

## Amplitude

The magnitude or severity of a vibration signal, indicating 'how hard' something is vibrating.

## Baseline

A reference set of vibration data from a known healthy motor, used for comparison to detect defects.

## Frequency

The number of vibration cycles per second (measured in Hertz), indicating 'how fast' something is vibrating. Used to identify the source of a vibration.

## Frequency domain

A representation of a signal showing how much of the signal's energy lies within each frequency (spectrum).

## Hub motor

An electric motor integrated into the center of the bicycle wheel (front or rear).

## Mid-drive motor

An electric motor located at the bottom bracket (crank) of the bicycle, driving the chain.

## Nyquist frequency

The highest frequency that can be accurately sampled by a digital system (half the sampling rate).

## Remanufacturing

The process of returning a used product to at least its original performance and warranty status.

## Refurbishment/Revision

Bringing a product back to a satisfactory working condition, by repairing defects and cleaning (in this report, refurbishment and revision are used interchangeably and refer to the same process.).

## Repair

Fixing a specific fault or defect to restore functionality, without a full overhaul.

## Revision company

Existing businesses that refurbish e-bike motors. They typically operate on a small scale and serve consumers directly (B2C).

## Revision hub

A proposed future organization that refurbishes e-bike motors at a centralized, industrial scale, serving bike mechanics through a business-to-business (B2B) model.

## Revision expert

A collective term used in this report to refer to both revision companies and revision hubs.

## Time domain

A representation of a signal (such as vibration) as it changes over time (waveform).

## Walk assist

A function on e-bikes that drives the motor at a constant, low speed (~6 km/h) without pedaling.

# ABBREVIATIONS.

## B2B

Business-to-Business

## B2C

Business-to-Consumer

## CO<sub>2</sub>e

Carbon Dioxide Equivalent

## E-bike

Electric bicycle

## EU

European Union

## FFT

Fast Fourier Transform

## IPD

Integrated Product Design

## OEM

Original Equipment Manufacturer

## PCB

Printed Circuit Board

## R2R

Right to Repair

## RMS

Root Mean Square



## 1.1 CONTEXT

E-bikes are rapidly transforming personal mobility in Europe. They are often presented as a sustainable alternative to cars, especially for short to medium commutes of 10–20 kilometres. E-bikes reduce emissions, improve health, and require far fewer materials than cars over their lifetime (Huang et al., 2022). As cities become denser and transport policies focus on low-carbon travel, e-bikes have gained a central role in sustainable mobility strategies. In the Netherlands and Germany, for example, more than half of all new bicycles sold in 2024 were electric (Van Dijk, 2024; CONEBI, 2024). This trend is expected to continue, driven by technological improvements and shifting attitudes toward everyday cycling.

Despite their sustainable image, e-bikes are not always as durable as they seem. Their key components, particularly the battery, motor and display, often fail long before the rest of the bicycle wears out. According to a 2024 survey in Germany (WERTGARANTIE, 2024), 40.9% of all e-bike technical failures involve the battery, 28.6% the display, and 24.2% the motor (figure 1.1a). While batteries are relatively easy to replace, motor failures are more complex, costly, and decisive. A survey among 464 e-bike users found that 178 of them owned a previous e-bike, and 33% of this group had experienced a motor failure, after an average distance of around 15,000 kilometres. For frequent riders, this means replacing a motor every two to four years, much sooner than expected for such a central component.

The environmental impact of e-bikes is largely determined by their production phase, especially when considered over their functional lifetime. As the total impact is typically expressed in emissions per kilometre, the number of kilometres a bicycle covers strongly influences its overall sustainability performance. De Bortoli (2021) estimates that approximately 76% of an e-bike's total CO<sub>2</sub> footprint originates from production, based on a reference case of 20,000

## 1.2 RESEARCH QUESTIONS

The main design assignment addressed in this thesis is therefore as follows:

“Explore and support the potential role of bike mechanics in the transition towards a more circular e-bike motor system.”

In order to do this as comprehensively as possible,

kilometers ridden in France (figure 1.1b).

To illustrate, the production of a 20 kg aluminum bicycle (excluding electric assistance) manufactured in China emits around 181 kg CO<sub>2</sub>e for the frame, 20 kg CO<sub>2</sub>e for the battery, and 37 kg CO<sub>2</sub>e for the motor (figure 1.1c) (De Bortoli, 2024). This highlights both the significant impact of the motor's production and the importance of ensuring that it does not become the limiting factor for the overall lifespan of the bicycle.

Research by Erdmann (2023a) further emphasizes that remanufacturing and repair consistently result in lower environmental impact compared to full replacement. Extending the operational life of motors through repair or remanufacturing could therefore substantially reduce the overall footprint of e-bikes.

However, repair and refurbishment of e-bike motors are rarely carried out by bike mechanics. Instead, specialized revision companies handle most maintenance and repair tasks. The role of bike mechanics in this system is limited and largely unclear; they currently contribute little to extending the motor's operational life. Understanding how mechanics could play a more active role in this circular system is therefore an important focus of this research.

Little is known about how e-bike motors fail and how they could be repaired or remanufactured. Most research focuses on battery performance or energy efficiency, while motor repairability and remanufacturing receive little attention. Current information is fragmented and largely based on manufacturer data or user experiences. Understanding the barriers that prevent repair, such as lack of access to parts, tools, or knowledge, is therefore essential to design more circular e-bike systems. This research aims to explore those barriers and identify opportunities for bike mechanics to contribute to extending the lifespan of e-bike motors.

the following research questions have been formulated:

- What is the current situation of e-bike motor maintenance and repair?
- What developments could support a shift towards circular e-bike motor systems?
- How can bike mechanics diagnose motor issues to decide on repair or replacement?

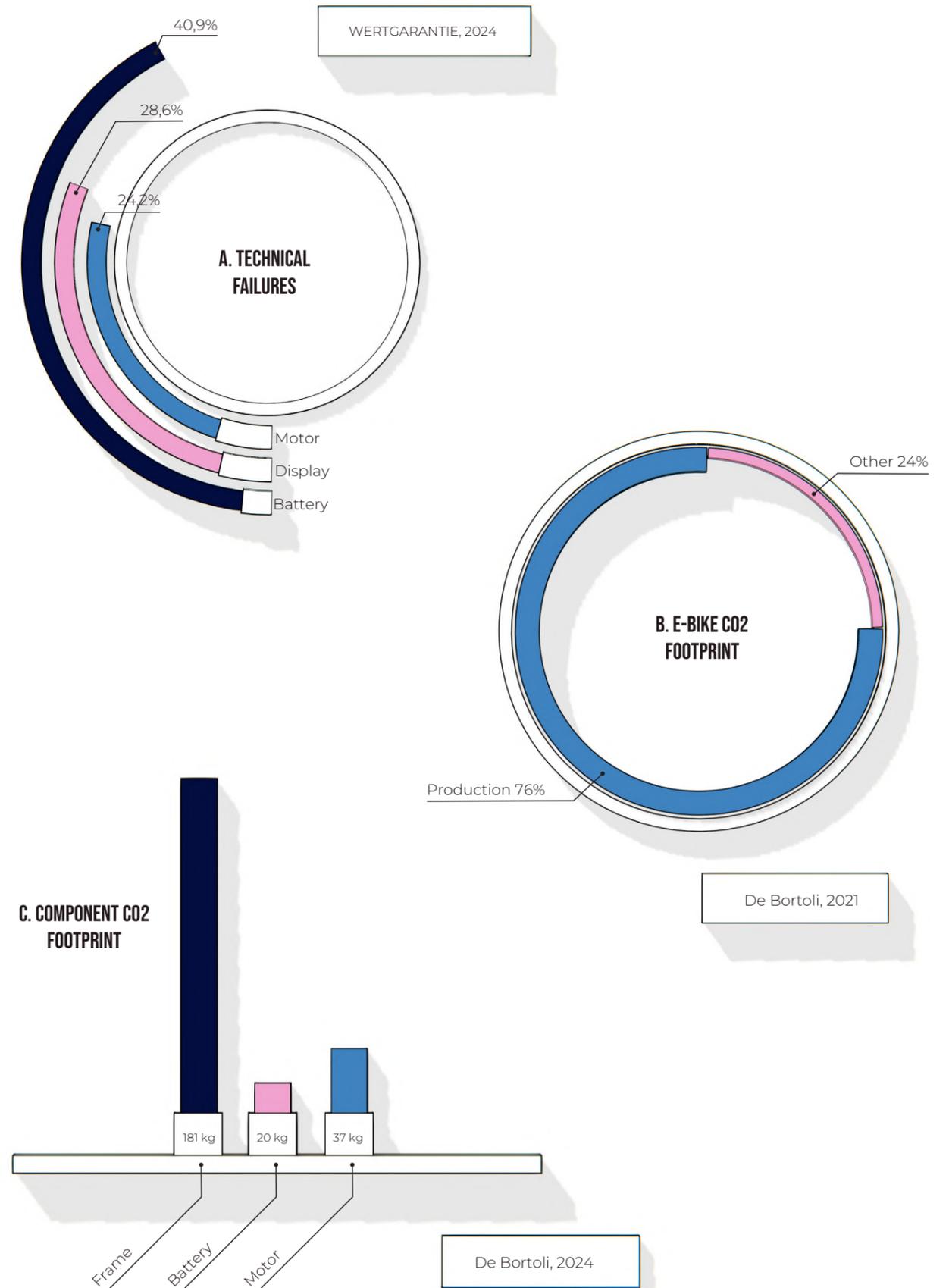


Figure 1.1: A.) diagram showing which e-bike components break down most often. B.) diagram showing the main activity within the carbon footprint of e-bikes. C.) diagram showing the carbon footprint of the components with the highest carbon emission.

## 1.3 APPROACH

To provide a clear overview of the research and design process, this project follows the Double Diamond method (figure 1.2), structured into four phases:

- **Discover:** Gathering information and conducting research to understand the current situation, user needs, and existing challenges.
- **Define:** Analysing the research results to identify key insights, takeaways, and opportunities for design.
- **Develop:** Translating insights into design ideas, concepts, and prototypes.
- **Deliver:** Refining and finalising the chosen design concept.

Although the chapters in this report are presented in a linear order, the process was iterative in practice. Insights from later stages often led to revisiting earlier findings and refining design directions. To provide a clear overview of the research and design process, the work is structured into the following chapters:

Chapter 02 provides essential background information. It explains how an e-bike system works, describes the main motor types and brands, and outlines relevant regulations regarding warranty and the Right to Repair.

Chapter 03 outlines the research methodology used throughout the project. It details how data was gathered through literature review, expert interviews, and technical motor teardowns. This chapter serves as the central reference for the methods used in the subsequent research chapters.

Chapter 04 analyses the current situation of e-bike motor repair. Based on expert interviews, it identifies the barriers and challenges faced by mechanics and revision companies, and maps the most common motor failures.

Chapter 05 explores the potential for a circular future. It introduces the concept of a centralized revision hub and analyses how the role of the bike mechanic changes within this new system.

Chapter 06 focuses on the technical construction of the motor. Using data from teardowns and disassembly mapping, it identifies critical components (such as bearings and gears) and investigates current diagnostic practices and possibilities.

Chapter 07 summarizes the main findings from the research phase. It translates these insights into a design vision and a list of requirements for the solution.

Chapter 08 describes the concept ideation process. It explains how the focus was narrowed down to technical diagnosis, introduces a diagnostic protocol, and substantiates the choice of vibration analysis as the diagnostic method.

Chapter 09 covers the prototyping and testing phase. It describes the development of the test setup and the experiments conducted to validate whether vibration analysis can distinguish between healthy and defective motors.

Chapter 10 presents the final concept, which is developed based on the insights from all previous chapters. This chapter explains how the concept works, who is involved, and how it can be used in practice. The concept is also evaluated on feasibility, viability, and desirability.

The thesis ends with a general discussion (Chapter 11) and a conclusion (Chapter 12). These chapters reflect on the main results of the project and place them in a broader context. A personal reflection on the project process is included as well.

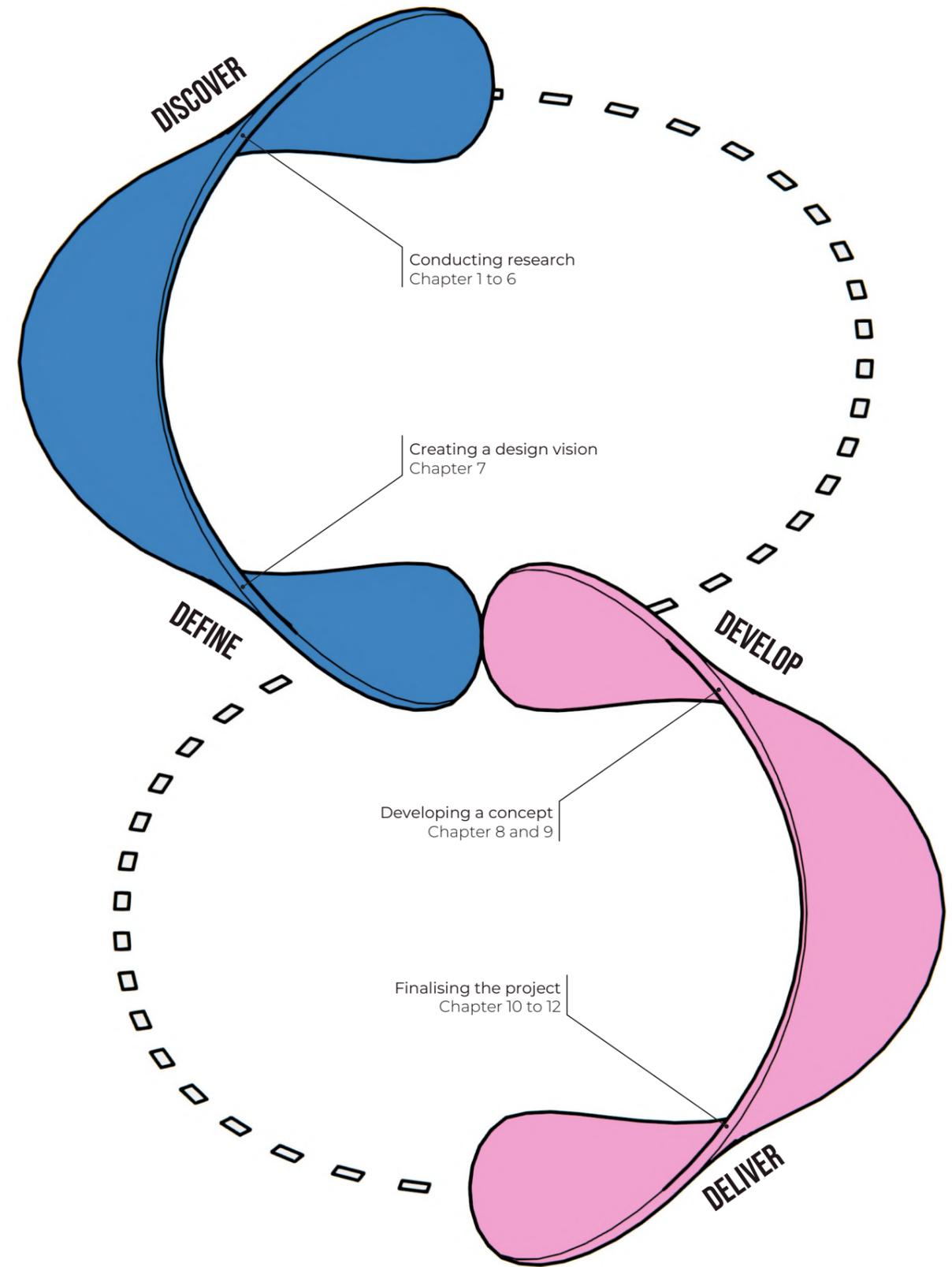
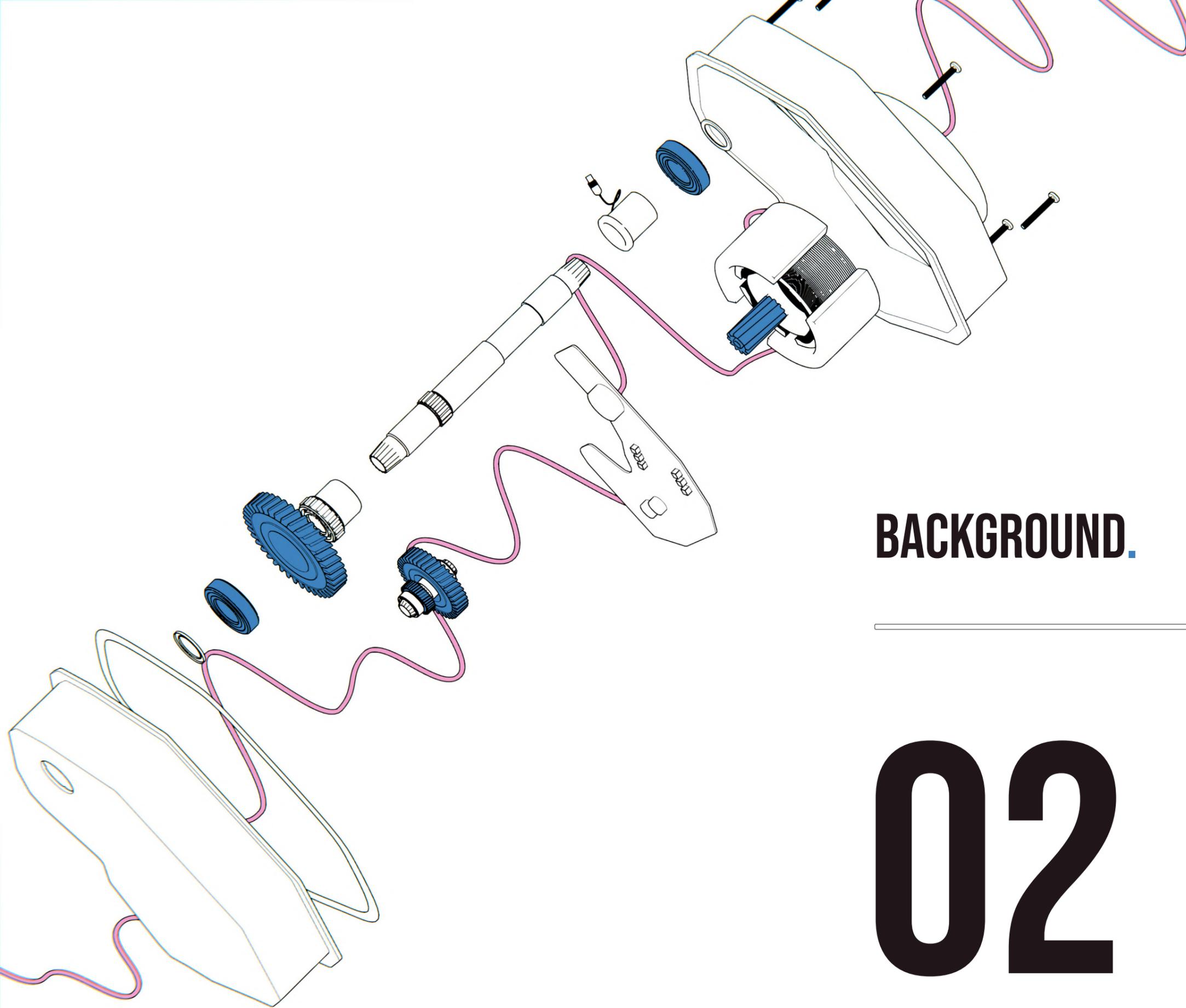


Figure 1.2: A schematic representation of the double diamond process and its phases. Although the chapters in this report are presented in a linear order, the process was iterative in practice (as indicated by the dotted line).



## BACKGROUND.



# 02

This chapter provides essential background information to understand how e-bikes work, the different types of motor systems, and the main brands and their market shares. It also introduces the new Right to Repair directive and explains its implications for e-bike motors.

- 2.1 E-bike system
- 2.2 Type of e-bike motors
- 2.3 E-bike motor brands
- 2.4 Right to repair

## 2.1 E-BIKE SYSTEM

The motor is the heart of an e-bike. It provides the power that turns a normal bicycle into an electrically assisted one. Together with the battery and the display or control unit, it forms the “drive system” (figure 2.1), which determines how the bike performs, how reliable it is, and how easy it is to use. When the motor works well,

the system gives smooth support and a pleasant riding experience. But if the motor fails, the value of the bike drops immediately. Technically, the bicycle can still be pedaled, but most riders no longer see it as usable, since motor assistance is the main reason to buy an e-bike and it loses the majority of its value.

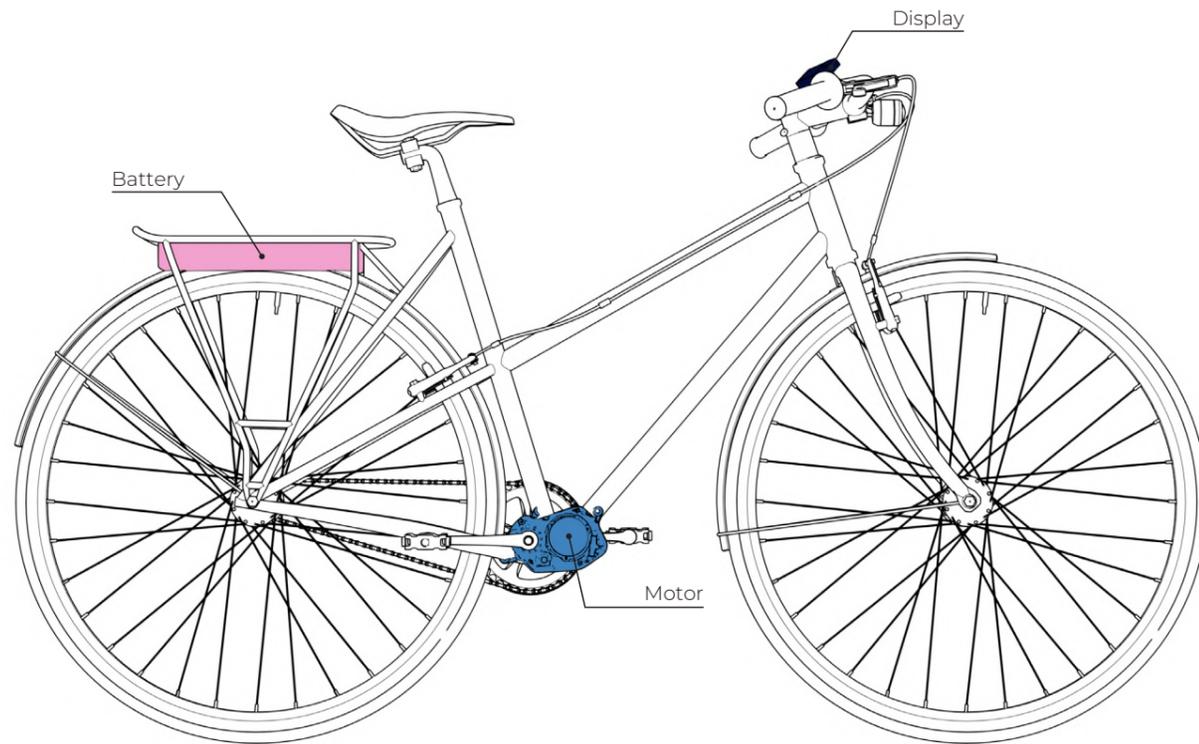


Figure 2.1: Overview of a typical e-bike system

## 2.2 TYPE OF E-BIKE MOTORS

There are two main types of e-bike motors: hub motors and mid-drive motors (figure 2.2). Hub motors are built into the wheel hub and directly drive the wheel. They are simpler in design, usually more durable, and easier to maintain. Mid-drive motors are located at the bottom bracket and send pedaling forces through the motor into the chain. This design gives better weight balance and handling, which explains why mid-drive systems dominate the European market, especially in mountain bikes.

The downside is that mid-drive motors put more strain on the chain, cassette, and bearings, and they are more vulnerable to heavy loads and

water. Experts note that hub motors are often more durable, because in mid-drive systems, the combined forces of the pedals, motor, and chain meet at the crankshaft, causing significant wear on bearings and gears. However, most consumers still prefer mid-drive motors for their riding advantages (Contò & Bianchi, 2022) (Tjandra et al., 2025).

Mid-drive motors currently account for more than half of both the Dutch and the global e-bike drive unit market, and therefore, this thesis will focus on mid-drive motors (Fact.MR, z.d.) (Mordor Intelligence, 2025).

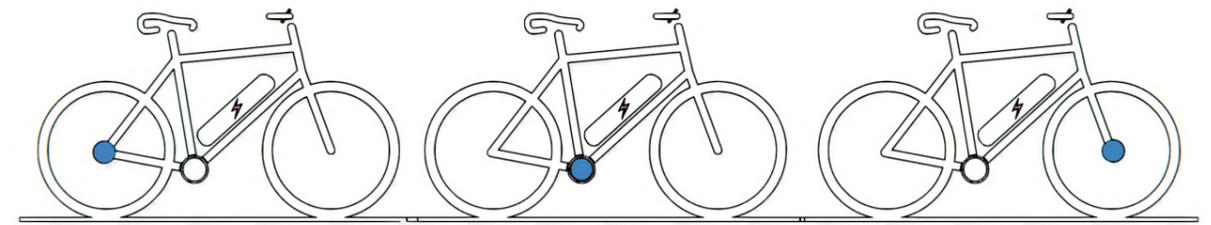


Figure 2.2: The three motor types; (a) Rear wheel hub motor (b) Mid drive motor (c) Front wheel hub motor

## 2.3 E-BIKE MOTOR BRANDS

The European motor market is dominated by Bosch, Shimano, Bafang, and Brose, with Bosch holding the largest share at about 50% (figure 2.3) (Brust, 2024). Warranty policies are similar across brands: two years of full coverage, often followed by a third year of goodwill (Kamp, 2025). If a motor fails within this period, the retailer sends it back to the manufacturer, who then supplies a new one to be installed.

After the warranty ends, customers face a difficult choice. Buying a new motor is expensive, the motor alone often costs more than €600, not including labour, and still leaves the risk of battery failure. Some specialized companies

offer refurbishment services, but they are rare, cannot guarantee success, and do not remove the risk of further breakdowns in the system. As a result, many customers decide to buy a new bike instead of repairing the motor.

Bike mechanics are also limited in what they can do. Failed motors have no value to them, and the cost of replacing both the motor and the battery is a major investment (around €1,000–€1,500). The refurbished second-hand e-bike will not sell for enough to recover these costs. As a result, bike mechanics usually decide not to repair these bikes, and many of them are simply discarded.

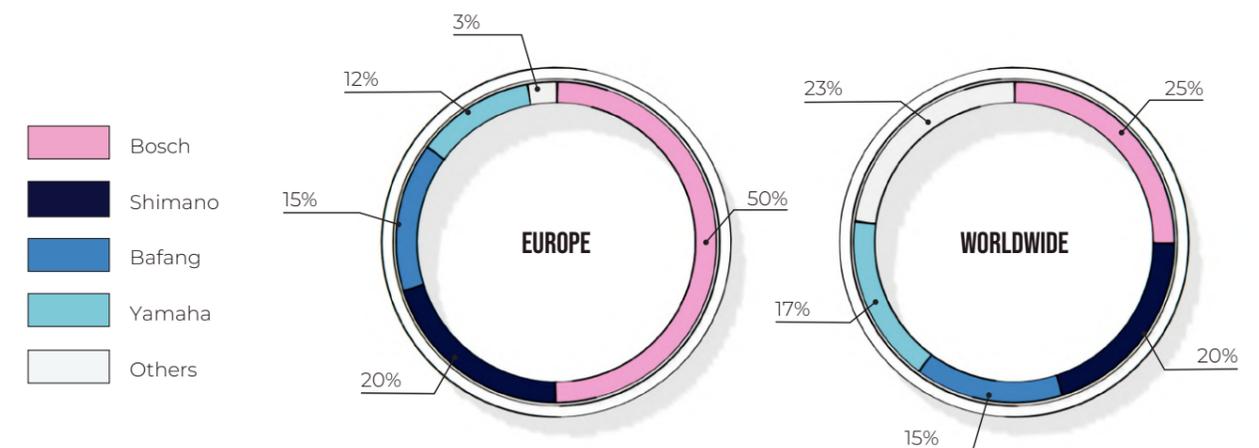


Figure 2.3: The main brands in the e-bike motor industry and their market shares. Figure made with data from Brust (2024)

## 2.4 RIGHT TO REPAIR

The lack of repairability is increasingly recognized as a growing problem. The upcoming Right to Repair directive for e-bikes, which is planned to come into effect in the coming years, will require manufacturers to provide spare parts and repair information for certain components, such as batteries and displays.

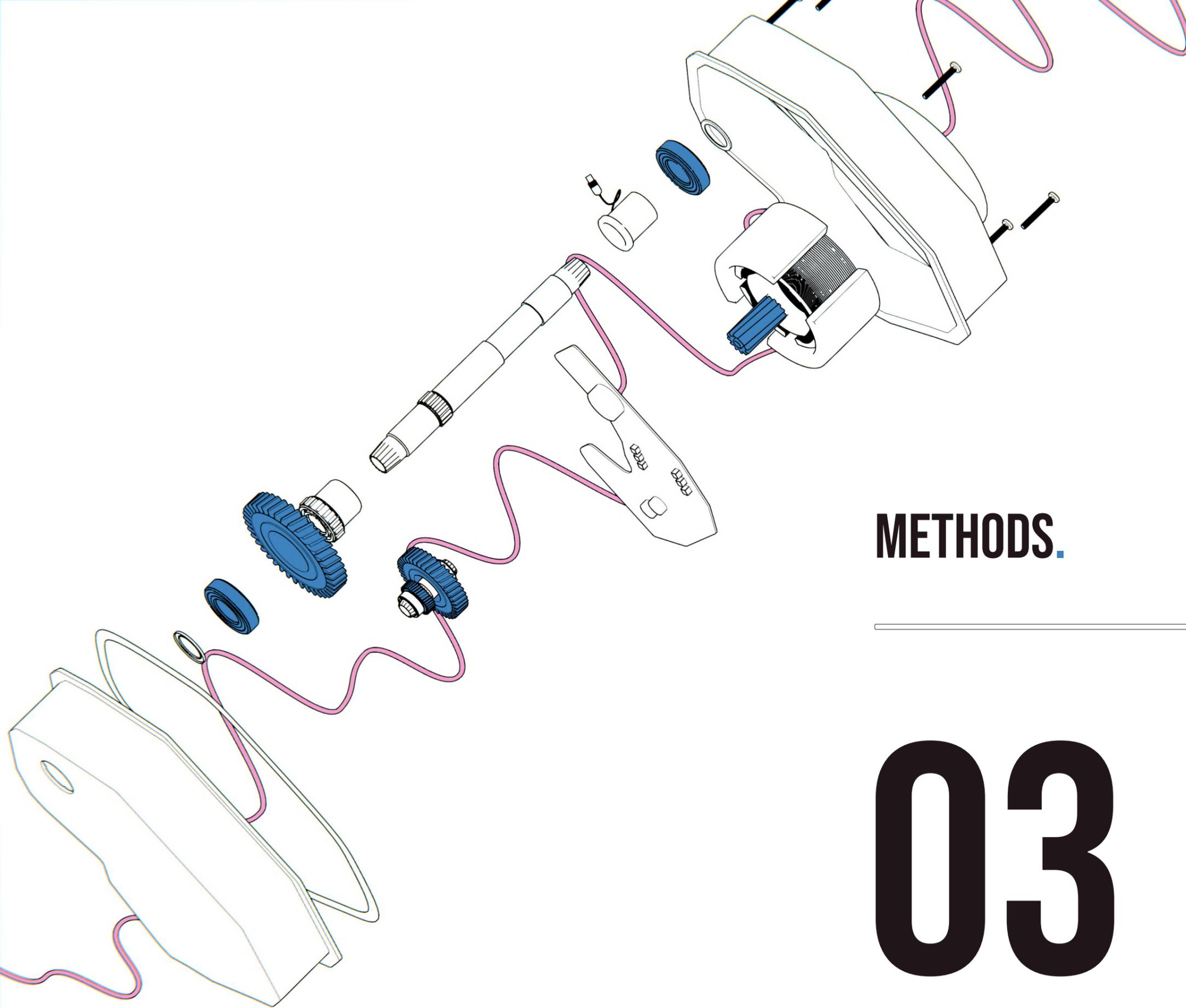
However, e-bike motors are not (yet) included in this regulation (Right to Repair Europe, 2025). This means that even as other parts of the bicycle

become easier to repair, manufacturers of the motor, one of the most complex and expensive components, do not have to comply with these regulations in the coming years.

This thesis therefore focuses on exploring how the lifespan of e-bike motors can be extended and premature replacement reduced, without depending on manufacturer-controlled repair systems.



Figure 2.4: Bicycles have long been considered repairable products. However, the increasing complexity of electric bicycles challenges this.



## METHODS.



# 03

This chapter outlines the research methods used to explore the reparability of e-bike motors, identify barriers for bike mechanics and remanufacturing companies, and develop a diagnostic solution. The research approach combines qualitative methods with technical analysis.

- 3.1 Literature review
- 3.2 Expert interviews
- 3.3 Product selection
- 3.4 Motor teardown
- 3.5 Disassembly mapping
- 3.6 Motor comparison
- 3.7 Hotspot mapping

### 3.1 LITERATURE REVIEW

To gain insight into existing research on e-bike motor diagnosis and remanufacturing, a literature review was conducted in October 2025. The aim was to identify what is already known about diagnostic practices and remanufacturability of electric bicycle motors.

The search was performed in the academic databases Scopus and Google Scholar, using the

keywords shown in table 3.1. It started broadly to capture a general overview of research related to e-bike motors. However, many of the initial results focused on topics such as motor design, control systems, or energy efficiency rather than maintenance. Therefore, additional search terms were gradually added to narrow the scope and find publications specifically related to maintenance, repair, and remanufacturing.

Table 3.1: Overview of the search terms used during literature review in both Scopus and Google Scholar (Note: the search terms in Google Scholar are slightly different, as the W/3 proximity operator cannot be used in this database)

Search term	Reasoning	Number of results in Scopus	Number of results in Google Scholar
"Electric* W/3 bicycle* W/3 motor*" OR "Electric* W/3 bike* W/3 motor*" OR "E-bike* W/3 motor"	To get an overview of the total amount of research related to e-bike motors.	477	16700
"Electric* W/3 bicycle* W/3 motor*" OR "Electric* W/3 bike* W/3 motor*" OR "E-bike* W/3 motor*" AND "maintenance"	To narrow the search to studies that focus on maintenance or servicing aspects.	15	6680
"Electric* W/3 bicycle* W/3 motor*" OR "Electric* W/3 bike* W/3 motor*" OR "E-bike* W/3 motor*" AND "re-manufacturing"	To explore research on reusing or restoring electric motor components for extended lifespan.	3	236
"Electric* W/3 bicycle* W/3 motor*" OR "Electric* W/3 bike* W/3 motor*" OR "E-bike* W/3 motor*" AND "diagnosis"	To find research highlighting diagnosis of electric bicycle motors.	1	2580
"Electric* W/3 bicycle* W/3 motor*" OR "Electric* W/3 bike* W/3 motor*" OR "E-bike* W/3 motor*" AND "repair"	To identify research discussing repairability or failure recovery.	0	3620

### 3.2 EXPERT INTERVIEWS

To understand the real-world context of e-bike motor repair, expert interviews were conducted with key stakeholders in the repair chain. Given the limited availability of academic research on this specific topic, these interviews were essential to identify barriers, understand current workflows, and validate potential solutions.

In total, 12 experts were interviewed across three categories:

- Bike mechanics: To understand the daily reality of the workshop and the current diagnostic process.
- Revision companies: To gain technical knowledge about motor failures.
- System experts: To explore future business models and the feasibility of centralized hubs.

Table 3.2 lists the interviewees and their specific focus.

Table 3.2: Overview of interviewed experts and their area of expertise.

Category	Number	Role and focus of interviewee
Bike mechanic	M1	Owner, retail and repair
	M2	Employee, repair
	M3	Employee, repair
	M4	Owner, retail and repair
	M5	Owner, retail and repair
	M6	Owner, retail and repair
	M7	Owner, retail and repair
Revision company	R1	Owner, remanufacturing of all motor brands
	R2	Owner, remanufacturing of Bosch and Brose motors
	R3	Owner, remanufacturing of Shimano motors
	R4	Owner, remanufacturing of all motor brands
Circular system expert	S1	Circular system expert and maker

The interviews were conducted in semi-structured sessions covering three main phases of the research:

#### Current repair practices

The initial interviews with mechanics (M1-M7) and revision companies (R1-R4) focused on identifying why repairs are rarely performed. Topics included:

- Motor failures: Lifespan, common defects, and causes.
- Repairability: Accessibility, spare parts availability, and manufacturer support.
- Barriers: Why mechanics choose replacement over repair.

#### Circular system development

To explore the concept of a centralized revision hub, specific interviews were held with the owner of a revision company (R3) and a circular system expert (S1). These discussions focused on the

logistics, feasibility, and stakeholder mapping of a B2B refurbishment hub.

#### Diagnostic opportunities

To refine the final design direction, follow-up sessions were held with a revision specialist (R2) and a bike mechanic (M1). These focused on:

- Weak spots: Verifying the most frequent mechanical failures (bearings and gears).
- Diagnostic signals: Mapping how these failures manifest (sound, vibration) and establishing a diagnostic protocol.

During all interviews, notes were taken and, where possible, conversations were recorded. Key insights were synthesized and compared to identify patterns and discrepancies between the bike mechanics and the specialized experts. See appendix C for the interview preparations and summaries.

### 3.3 PRODUCT SELECTION

To analyse the disassembly process and explore the reparability of e-bike motors, a series of motors were taken apart. As mentioned in Chapter 2, the focus was on mid-drive motors, as these are the most common in the market. Motor selection depended on accessibility and

availability through collaborating partners, while ensuring a broad representation of brands.

A total of nine motors were analysed, covering the three largest European brands as well as additional manufacturers (table 3.3).

Table 3.3: The motors used for the teardown analysis

Brand and model	Year of first production	Picture
Ananda M81	2021	
Bafang M210	2020	
Bosch BDU 250	2018	
Bosch BDU 350	2021	

Brand and model	Year of first production	Picture
Brose Specialized 3.1	2022	
Gobao P101	2023	
Shimano DU-E5000	2019	
Shimano DU-EP600	2022	
Shimano DU-E6110	2020	

### 3.4 MOTOR TEARDOWN

As described in section 3.3, a selection of motors was taken apart to analyse disassembly and repairability. This process was done while following a structured procedure:

1. Open the motor: split the two casing parts to access internal components.
2. Initial analysis without removing parts: observe seals, electronics, gear materials, and “water management” (if water entered the casing, where would it go). Notes were taken on paper using a standardised format (see appendix B) and photos were captured.
3. Disassembly process: components were carefully removed (figure 3.1). Attention was given to the required tools (e.g., for bearing removal), bearing dimensions, and other critical aspects. Notes were taken throughout the process.

4. Simultaneous mapping: a second researcher created the disassembly map in real time, with continuous discussion to ensure an accurate representation of the motor structure.
5. Layout and documentation: all parts were laid out neatly and photographed.
6. Reassembly: motors were reassembled after documentation.

The outcome of each teardown consisted of detailed photos, a complete disassembly map, and notes on key observations. These results provided insights into component accessibility, potential maintenance steps, and challenges for repair.



Figure 3.1: One of the photos that have been taken during the disassembly of the Brose Specialized 3.1

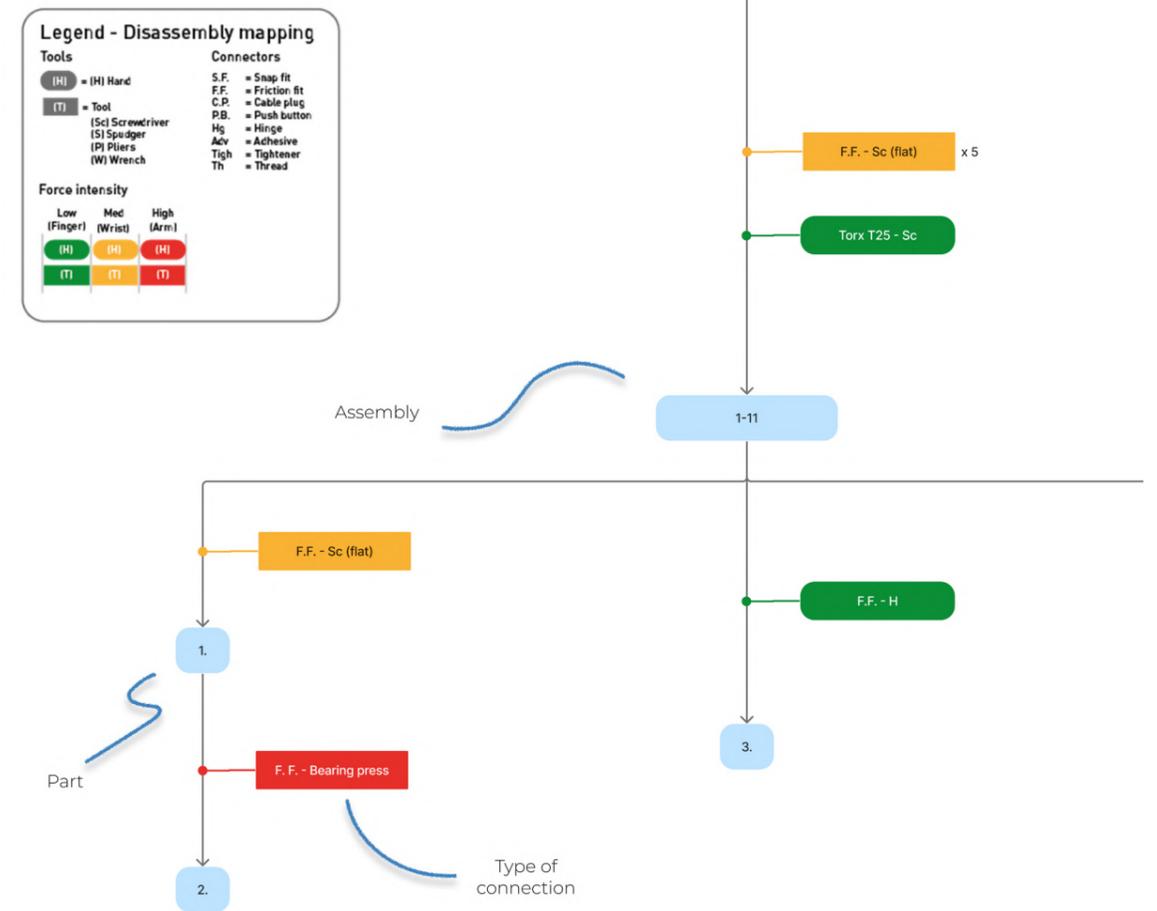


Figure 3.2: Explanation of the component of a disassembly map

### 3.5 DISASSEMBLY MAPPING

Disassembly mapping is a method to visually represent the product architecture and the disassembly process of a product (De Fazio, 2021). A disassembly map shows how components are connected, which parts need to be removed first, the required tools, and critical observations for maintenance or repair (figure 3.2). While the teardown focused on physical access and removal, the disassembly map provided the structured documentation of this process. Each component is represented as a block in the map, with links illustrating assembly hierarchy and dependencies.

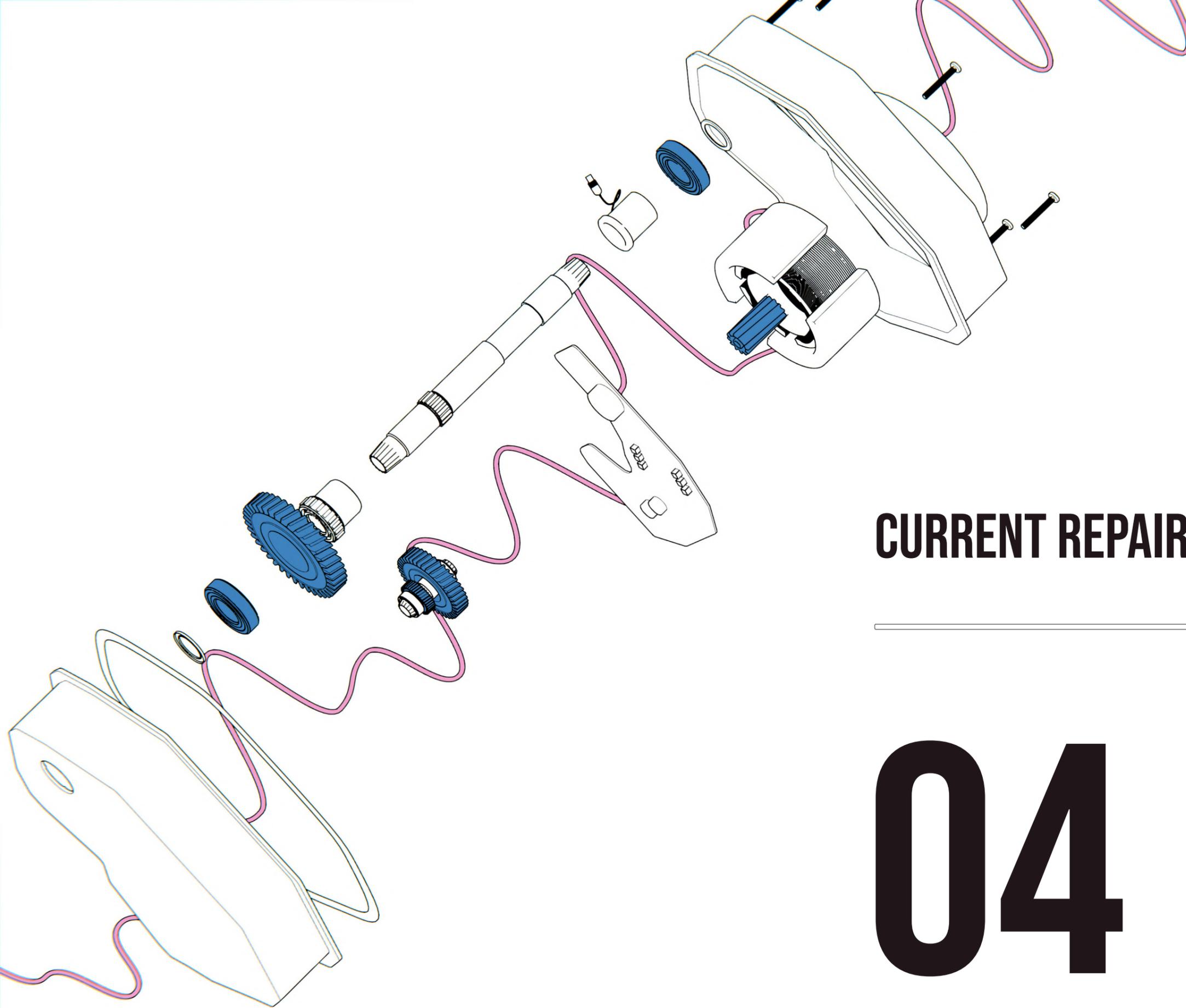
In this study, disassembly mapping was used to create a clear overview of the motor's product architecture, the steps in the disassembly process, and the tools or equipment required. This allowed analysis of pain points in terms of accessibility, complexity, and repairability, and helped identify which components could realistically be maintained.

Following the procedure described in section 3.4, the disassembly map was created simultaneously with the teardown. Normally, a video of the disassembly is made and later used to create the map. In this case, the map was created directly during the teardown because:

- Two people were working together (one performing the disassembly, the other creating the map), which made real-time mapping easier.
- The teardown process often took a long time, producing a large amount of data that would have required extensive review time if a video was used.

This approach was compensated for by taking many photos of components and observations. The result was a visual representation of the motor's architecture and challenges for disassembly and repair.





## CURRENT REPAIR PRACTICES.



# 04

This chapter examines the current situation of e-bike motors, with a specific focus on repair and remanufacturing. Drawing on the expert interviews described in section 3.2, this chapter explores what prevents mechanics and revision companies from opening, repairing, or remanufacturing motors, as well as the most common types of motor failures. The chapter concludes with an overview of the main takeaways from this chapter.

- 4.1 Results
- 4.2 Conclusion

## 4.1 RESULTS

### 4.1.1 BARRIERS AND CHALLENGES

The analysis of interviews with bike mechanics (M1-M7) and specialized revision companies (R1-R4), as detailed in section 3.2, reveals similar reasons why repairs on e-bike motors are rarely carried out. An overview of the main barriers and challenges for both groups is shown in figure 4.1. During the first two to three years (depending on the manufacturer), opening the motor is almost never done. Legally, EU regulations do not allow

manufacturers to void a warranty solely because a product has been opened (European Union, 2022), but in practice mechanics mentioned that manufacturers can attribute any failure to the fact that the motor was opened. Therefore, when a defect occurs, retailers simply return the motor and the manufacturer provides a replacement unit, a process most mechanics describe as efficient and customer-friendly.

After the warranty expires, all seven interviewed bike mechanics (M1-M7) stated they still avoid opening motors. For them, repair is blocked by a combination of factors, including lack of spare parts, absence of service manuals, and the compact and complex internal design. Even when faults can be identified, repair is often not possible due to missing components or diagnostic tools.

A less frequently mentioned but underlying barrier, mentioned by two of the seven bike mechanics, is the lack of a viable business model for motor repairs. Motor issues occur relatively rarely, and repairing a motor is time-consuming and costly, requiring removal, disassembly, and troubleshooting without any guarantee of success. Because of all these factors combined, most bike shops choose not to offer motor repairs at all.

Specialized revision companies face similar issues, but to a different extent. They do open motors after the warranty period and manage to bypass certain barriers, for example by sourcing third-party components. However, all four interviewed companies indicated they remain limited by restricted access to diagnostic software and electronic components. One company, for instance, explained that Bosch divides its software into several layers: the first layer contains user-level data visible on the display, the second layer includes diagnostic information accessible to certified dealers, and the third and deepest layer is reserved for Bosch engineers only. It is unclear whether other manufacturers apply a similar structure, but this example illustrates the broader challenge. Overall, while mechanical repairs are sometimes feasible, electronic failures and limited access to diagnostic information remain the biggest obstacles.

#### Takeaway

Good manufacturer service ensures that any problems with the motor are resolved by the manufacturer within the warranty period.  
→ Focus on post-warranty repair and remanufacturing

#### Takeaway

Identified barriers and challenges for both bike mechanics and revision companies.  
→ Not feasible for regular bike mechanics to repair e-bike motors.

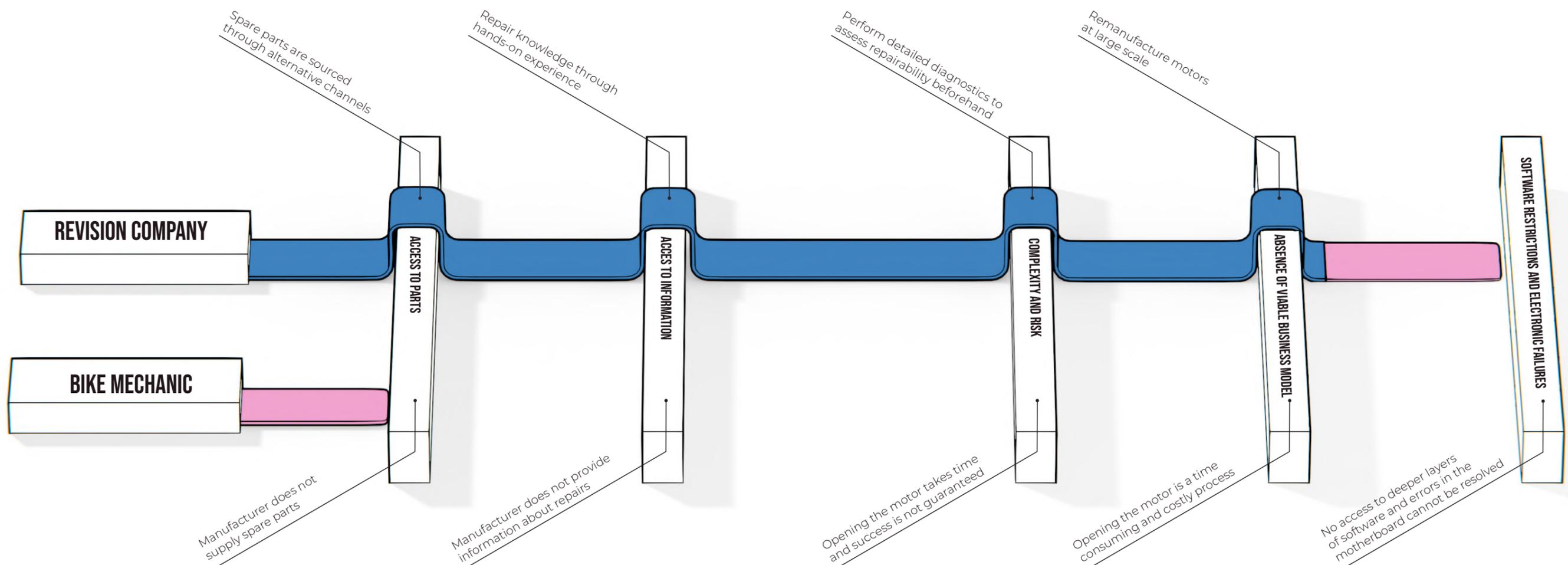


Figure 4.1: Overview of the barriers and challenges in repair of e-bike motors for both bike mechanics and revision companies

#### 4.1.2 COMMON FAILURES

The failure modes of e-bike motors differ between brands, but interviews with repair specialists reveal clear patterns. Three out of the four interviewed revision experts (see section 3.2) indicated that motor failures can be grouped into three main categories (figure 4.2). The fourth expert chose not to share detailed data, as this information is considered commercially sensitive.

Around half of all failures are caused by worn bearings. Bearings are essential to the motor because they connect static parts with rotating parts (or link rotating parts together) and carry high loads, especially in mid-drive systems. Due to constant rotation and force, they are also vulnerable to water and dirt. They indicated that when bearings wear out, the motor starts to feel rough, often makes noise, and eventually fails completely.

About 25% of failures are linked to the electronic system, most often due to moisture ingress that damages printed circuit boards (PCBs) or connectors. These failures are especially difficult to handle because they require diagnostic tools and software that are only available to manufacturers. Without these, repairs are very challenging and sometimes simply impossible.

The remaining 25% of failures are other mechanical issues, such as gear wear or structural defects like cracks in the housing. These failures are less predictable and depend on motor design and usage context. For instance, motors with nylon gears often suffer from broken or partly broken gear teeth, often caused by a sudden impact (such as the crank hitting a curb). These types of failures are brand-specific and will be further discussed in Chapter 5.

Revision companies also highlight that failure patterns vary strongly between brands. One company noted that Bosch (2nd and 4th generation) motors have poor sealing around the crankshaft, allowing water to enter the motor through this part, while early Brose motors often suffer from worn drive belts after five to six years. Despite these brand-specific differences, the general picture is clear: bearings, electronics and (nylon) gears are the main weak points across the market.

As mentioned, even for revision companies, repairing electronics and software remains very challenging. Therefore, the focus of the remainder of this thesis will be on the mechanically critical components.

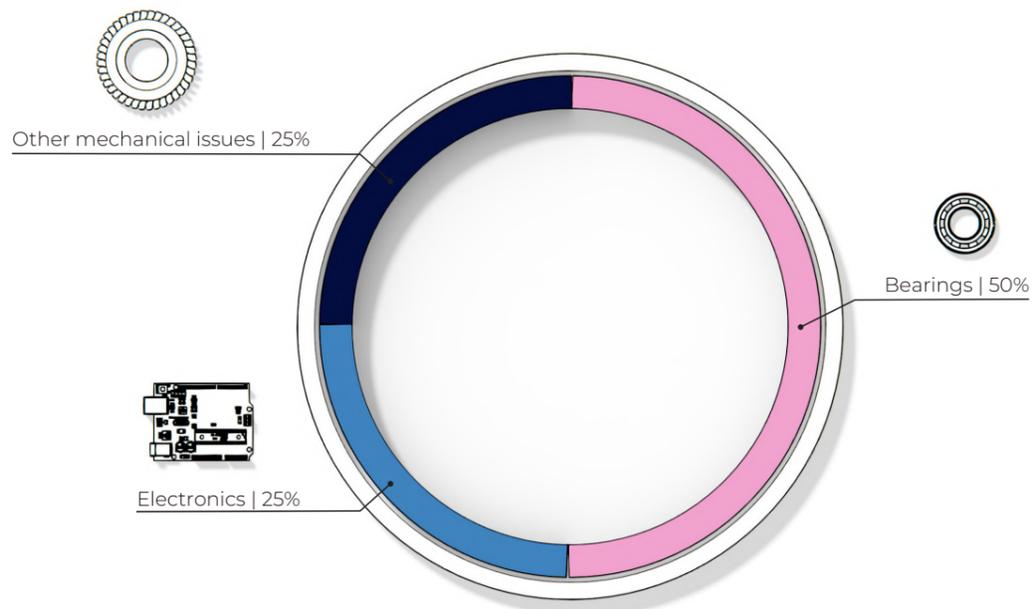


Figure 4.2: The three main points of failure in e-bike motors

#### Takeaway

~50% bearings, ~25% electronics, ~25% other mechanical.  
→ Focus on the mechanically critical parts.

#### 4.1.3 MOTOR MANUFACTURERS ATTITUDE TOWARDS REPAIR

As mentioned earlier, manufacturers are generally not very cooperative when it comes to repair and remanufacturing. The interviewed revision companies interviewed (R1-R4) together cover the four largest motor brands. Figure 4.3 combines their insights and shows how each

brand approaches repair and remanufacturing.

Overall, these attitudes reflect a gradual but uneven shift towards greater openness and the potential for preventive maintenance in the future.

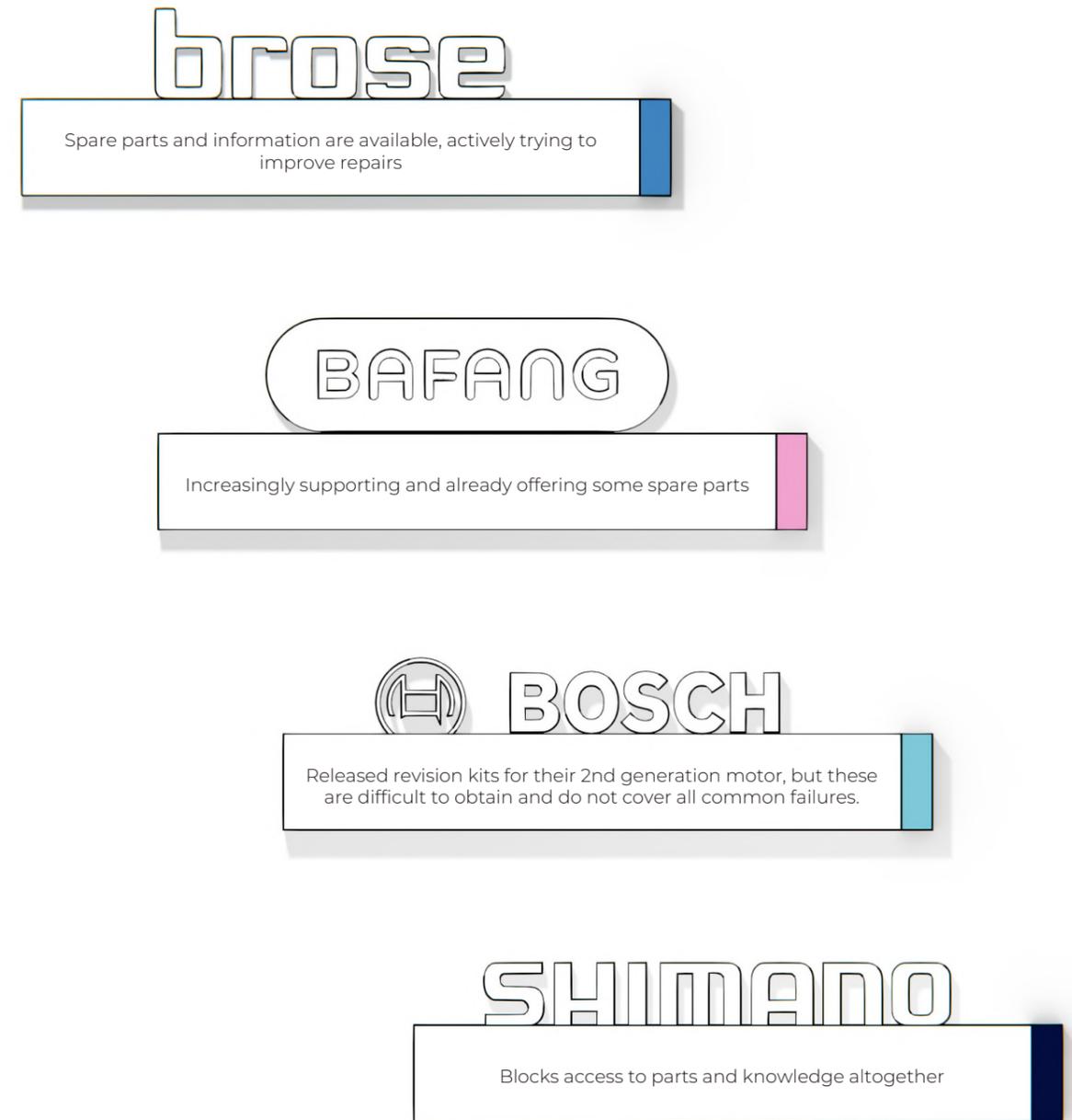


Figure 4.3: Overview of the four largest e-bike motor brands in Europe and their attitude towards repair and remanufacturing, ranked from supportive (top) to restrictive (bottom), based on insights from expert interviews.

## 4.2 CONCLUSION

The findings show that during the warranty period, repair beyond the manufacturer is almost never done, and after it ends, both bike mechanics and revision companies face serious barriers. The lack of spare parts, manuals, and diagnostic tools makes it hard to repair motors in a reliable and affordable way. At the same time, the compact design and high costs mean that replacing the motor is usually faster and easier than attempting repair.

The technical weak points of motors are also clear. Bearings account for about half of all failures, while electronics make up another quarter, and

both are difficult or impossible to repair without manufacturer support. Other failures, such as gear wear or housing cracks, are less common but still contribute to premature breakdowns. These patterns, combined with the lack of repair options, explain why many e-bikes with failed motors are discarded rather than repaired. This situation highlights both the urgency and the potential of enabling preventive maintenance as a means to extend motor lifespan.

Figure 4.4 describes the main takeaways from this chapter.

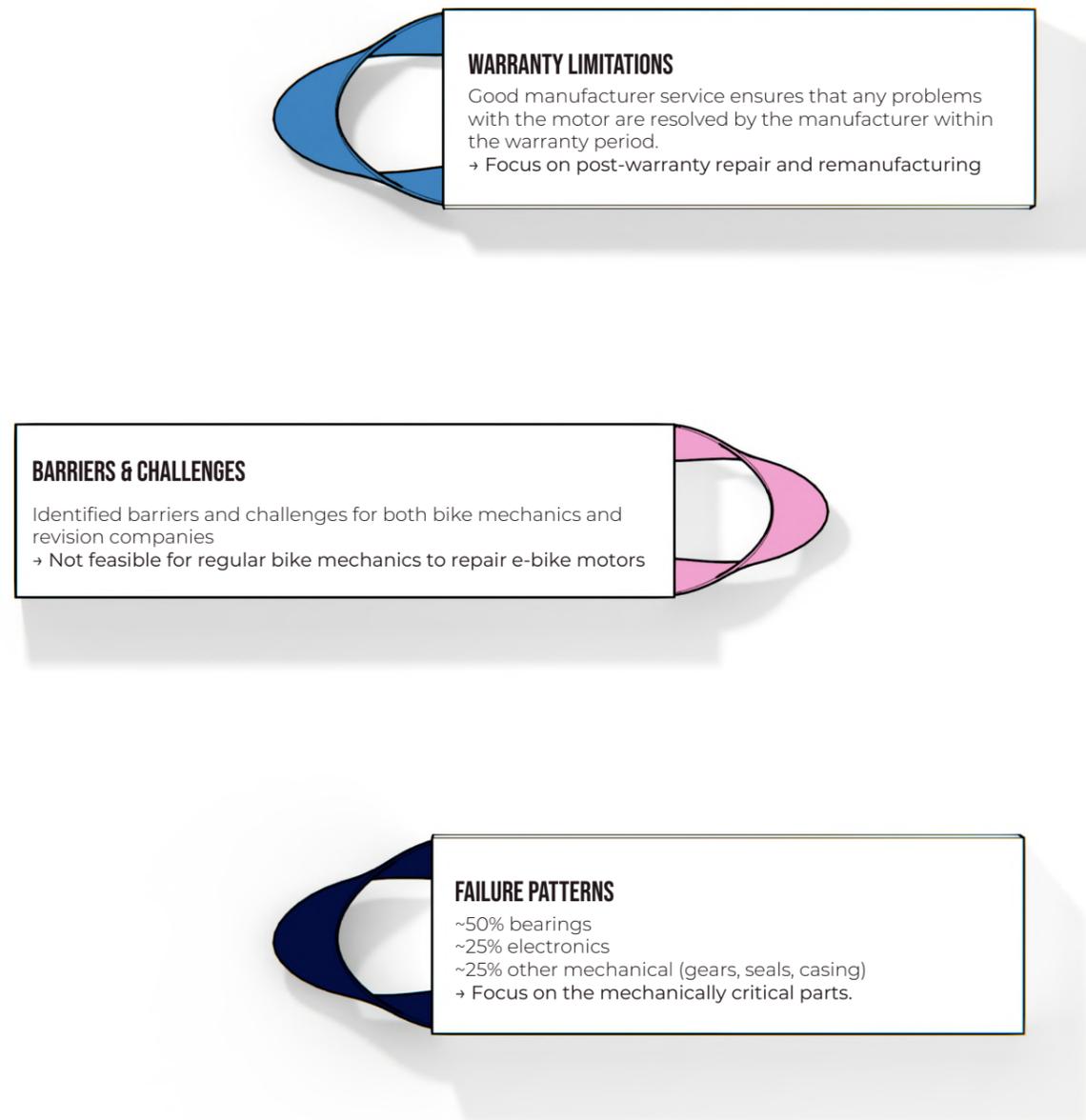
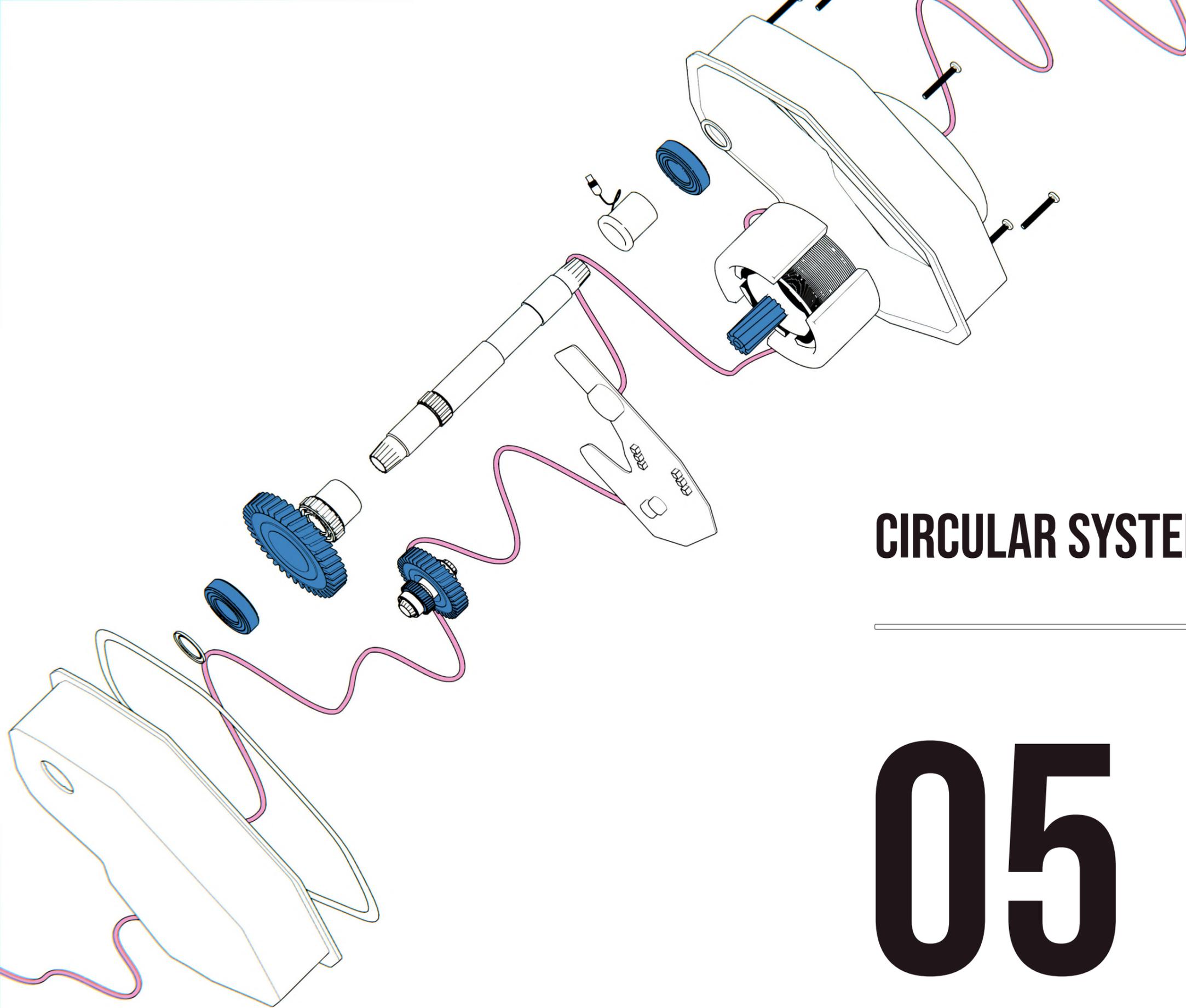


Figure 4.4: The main takeaways from this chapter



# CIRCULAR SYSTEM DEVELOPMENTS.



# 05

The previous chapter showed that bike mechanics are not the ones to perform e-bike motor repairs. As a result, when motors fail outside warranty, replacement rather than repair is still the norm. This chapter explores new and emerging developments that could change this situation. It outlines the current system, reviews insights from literature, and introduces the concept of a central refurbishment hub. Finally, it analyses how the role of the bike mechanic may evolve within this future system. The chapter concludes with a summary and a set of key take-aways.

5.1 Results

5.2 Conclusion

## 5.1 RESULTS

### 5.1.1 CURRENT SYSTEM

Figure 5.1 shows the current system through a value exchange map. In this map, the bike mechanic plays a central role. Mechanics often also act as retailers: they sell the bicycle to the customer and take care of its maintenance over time. This makes them the first point of contact when motor problems occur. The map also includes the existing revision companies. These companies refurbish motors directly for consumers and therefore operate mainly in a

business-to-consumer (B2C) model. Although they offer an alternative to buying a new motor, their position in the wider system is still small.

Even with these companies refurbishing motors, the current system does not function in a circular way. As mentioned in the introduction, motors, and sometimes complete bicycles, are still thrown away early because of motor issues. This means the motor system remains mostly linear.

Interview results (M1-M7 and R1-R4, see section 3.2) support this. None of the mechanics interviewed had ever sent a motor to a revision company. This shows that the link between mechanics and revision companies is often missing. The mechanics and revision companies mentioned several reasons for this. First, the repair process at revision companies takes time and brings uncertainty. A motor must be shipped without knowing whether it can be repaired. The mechanic then has to wait for the result and reinstall the motor afterwards. This is considered inefficient, time-consuming, and risky.

Second, the number of revision companies is still small, and their operations are relatively limited. The broader infrastructure needed, such as streamlined logistics and stable communication

with mechanics, is not yet in place. As a result, these companies operate more as separate service providers instead of being part of a larger, circular system.

Third, as discussed earlier, when a motor fails outside the warranty period, there is a real chance that the battery will fail within a short time as well. Repairing or replacing both components is a considerable investment, which sometimes leads mechanics to advise customers to buy a new bicycle instead.

Together, these factors prevent the current system from remanufacturing e-bike motors at scale. This gap between mechanics and revision companies forms a clear barrier to achieving circularity in e-bike motor systems.

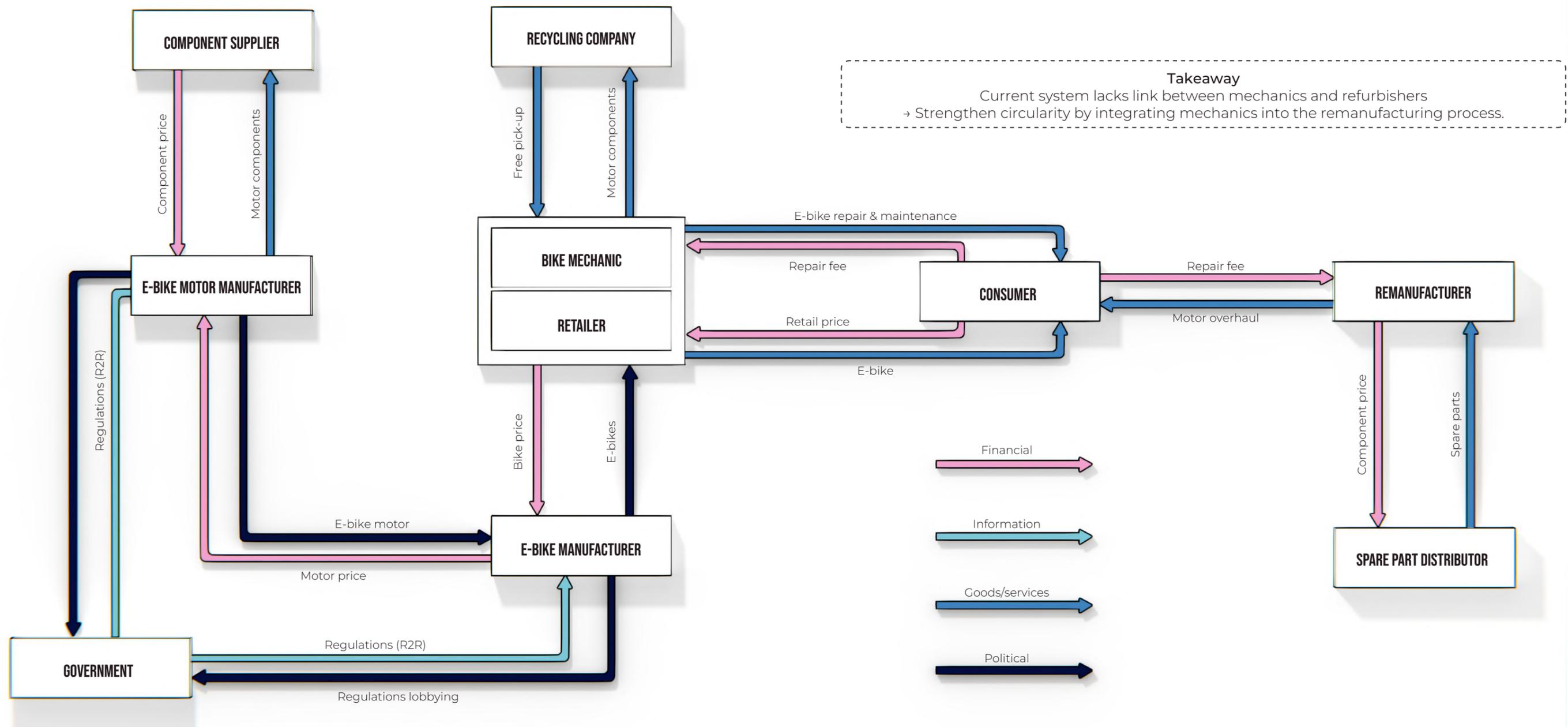


Figure 5.1: A value exchange map of the current system

### 5.1.2 IMPROVING CIRCULARITY

As mentioned before, the e-bike sector functions largely in a linear way: components are replaced rather than repaired. Circular business models have the potential to extend the lifetime of parts, reduce waste, and lower material use. Although most studies found during the literature review (see Section 3.1) focus on e-bike remanufacturing in general, the principles can be directly applied to e-bike motors.

Koop et al. (2021) discuss circular business models and remanufacturing in e-mobility, including e-bikes. They highlight that, despite challenges due to rapid innovation and lack of standards for components like motors and batteries, users are generally open to sustainable models that allow for remanufactured parts and longer product lifetimes. Motors and batteries are identified as the most promising components for remanufacturing because of their high value, common defects, and importance for usability. The study also emphasizes that effective circular models require close collaboration among value chain partners, including sharing information about repair options, hazardous materials, and component availability to make remanufacturing economically viable.

Schlesinger et al. (2021) present a five-step strategy for implementing remanufacturing of e-mobility components, validated with a case study on a mid-drive e-bike motor. The steps are described as follows:

1. **Product analysis:** this step determines whether a component is suitable for remanufacturing. For e-bike motors, the analysis in Schlesinger et al. (2021) confirmed that the motors meet the necessary criteria and are suitable for remanufacturing.
2. **Market research:** this step identifies the actors in the current remanufacturing market. Three

main types exist: OEMs (Original Equipment Manufacturers), Contracted Remanufacturers (CR) supported by OEMs, and Independent Remanufacturers (IR). OEMs are often hesitant to implement remanufacturing due to the risk of cannibalization, where sales of remanufactured products could reduce new product sales. The study also highlights that bike mechanics rarely repair motors themselves.

3. **Remanufacturing technology analysis:** this step assesses which parts can be reconditioned and which need replacement. Wear-sensitive parts, such as bearings and gears, are often replaced. Additive manufacturing could be applied to produce a wide variety of gears for different motor models.
4. **Remanufacturing process design:** a structured sequence of actions is defined, known as the enhanced Remanufacturing Process Step Model (eRPSM). The process includes: entrance diagnosis of the product, complete disassembly, cleaning of all parts, inspection and sorting, reconditioning or replacement of parts, reassembly, and final testing.
5. **Business model development:** insights from the product, market, technology, and process analyses are combined to define a suitable business model. This can include options such as product upgrades or customization to increase value and support sustainability goals.

This strategy shows that e-bike motors have the potential to be systematically remanufactured, which can improve their circularity. However, this is not yet common practice. In the next section, a concrete example is given of a new initiative that is starting to address this.

#### Takeaway

Literature confirms motors are suitable for refurbishment, but it requires collaboration and structured processes.

→ Coordinated B2B refurbishment can improve circularity of e-bike motor system.

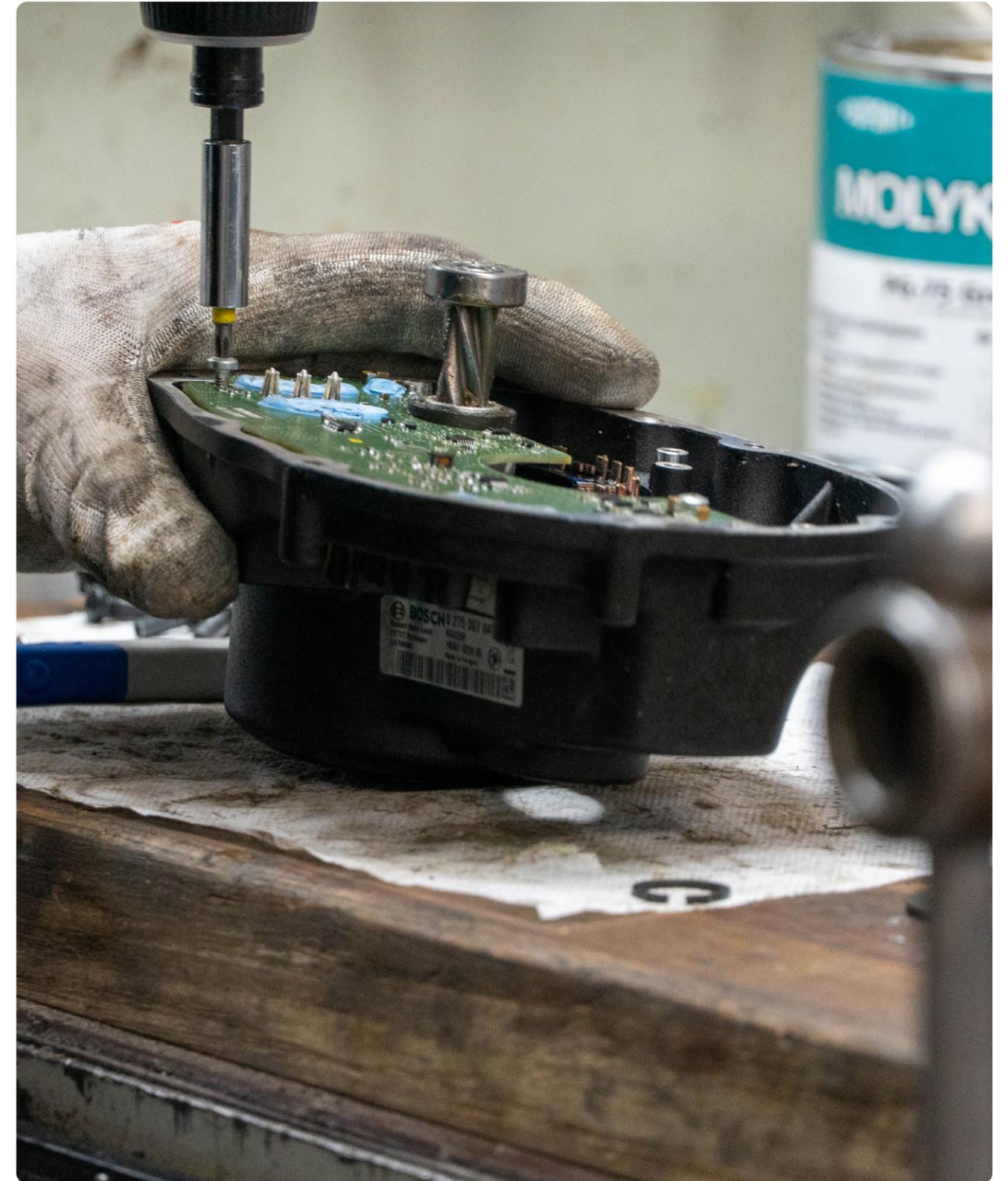


Figure 5.2: Photo taken during the remanufacturing process of a Bosch BDU 350 motor (in the workshop of R2)

### 5.1.3 CENTRAL REVISION HUB

Literature shows that e-bike motor refurbishment is feasible and that B2B models could be more effective than B2C models. In this section, we describe an emerging initiative to illustrate how a central refurbishment hub could work and what lessons can be learned. In the following section, this information will be used to analyze the potentially changing role of the bike mechanic.

The initiative is led by two stakeholders, and both were interviewed (R3 and S1, see section 3.2). They are currently setting up a central refurbishment hub: a company that refurbishes

motors at scale, provides quality assurance, and redistributes motors to the market through B2B channels, mainly via bike mechanics. In practice, this means that when a bike has a motor failure outside the warranty period, the mechanic can order a refurbished motor, and the old motor is sent to the hub for refurbishment.

consumers, and the B2B remanufacturing hub, which works through mechanics. Note: Both parties remanufacture motors, but they use different business models.

The interviews and literature indicate several advantages of this B2B hub model:

- Immediate availability of remanufactured motors
- Economies of scale, allowing lower prices
- Consistent quality and warranty
- Efficient logistics, with the hub managing collection and delivery of motors

Figure 5.3 shows the system with a central refurbishment hub and the corresponding value exchange map, highlighting the differences compared to the current system. For a broken motor, there are now two options: a traditional B2C remanufacturing company, which relies on

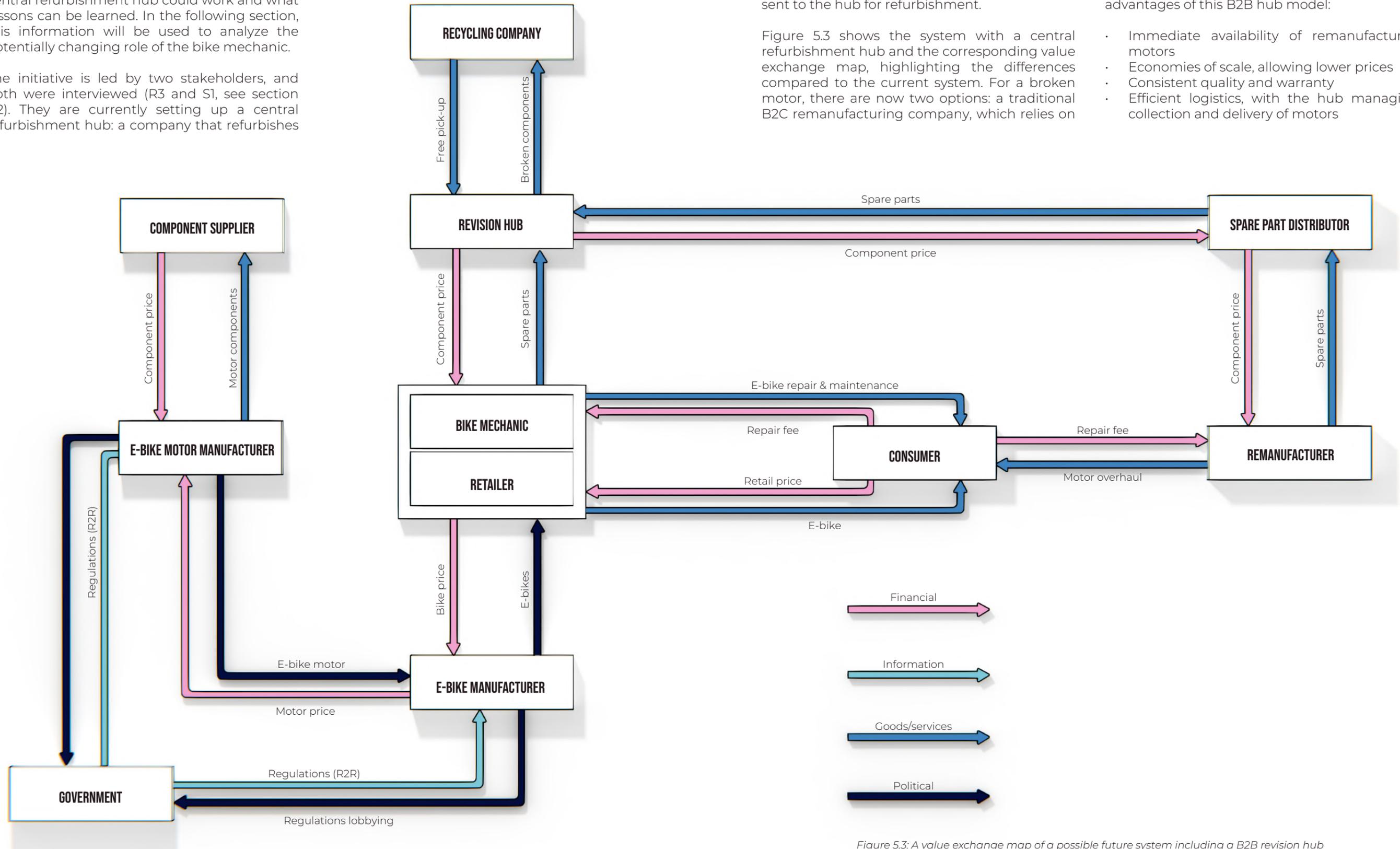


Figure 5.3: A value exchange map of a possible future system including a B2B revision hub

If successful, the hub is expected to launch around 2026. Currently, it is in an exploratory phase, validating whether a financially viable business model can be established and whether a sustainable company can be built. Some uncertainties remain:

- Will there be enough motors to sustain a refurbishment line?
- Which motor models should be prioritized, given the wide variety of types and processes?

- Pricing: what will mechanics and consumers be willing to pay for a refurbished motor?

As mentioned in the previous section, literature supports the idea that both B2C and B2B models can coexist. While they may appear as competitors, the focus should be on collaboration and the overall system. No single company can make the entire e-bike motor value chain fully circular. Communication and cooperation between different players are therefore essential.

**Consideration**

Central refurbishment hubs can provide a reliable, B2B-focused system for motor refurbishment and coexist with existing B2C players.  
 → Encourage collaboration between B2C and B2B actors to create a more circular system rather than treating each other as competitors.

**5.1.4 FUTURE ROLE OF BIKE MECHANIC**

Previous sections have established that bike mechanics do not open or repair e-bike motors themselves. This remains true in both the current and emerging systems.

In the current system, the mechanic's role is limited to monitoring the motor: is there a problem or not? If there is an issue and the motor is under warranty, it is sent back to the manufacturer; if not, there is little the mechanic can do. Due to these limitations, mechanics have little incentive to investigate the exact cause of a problem or determine whether a motor is repairable.

In a future system with a central refurbishment hub (and circular systems in general), the mechanic's role expands. Mechanics not only monitor but also diagnose and link their findings to concrete next steps. They remain the first "sensor in the field," identifying problems early

and enabling remanufacturing opportunities. Timely and accurate diagnosis becomes critical, both for sustainability and economic reasons, to ensure that each motor follows the appropriate path in the system and has the best chance of being successfully remanufactured.

Figure 5.4 illustrates the decision pathways for mechanics in the current and future systems.

This highlights that diagnosing motors and linking diagnoses to the appropriate actions is essential for the system to function effectively. Without the mechanic, early issues may go unnoticed, motors could fail further, and refurbishment potential would be reduced.

While there is research on diagnosing e-bikes in general, there is currently no literature specifically on diagnosing e-bike motors. This gap will be addressed in Chapter 6 through further research.

**Takeaway**

The mechanic gains more options within the system, their role changes and expands.  
 → Support mechanics in diagnosing motor issues and selecting the right follow-up actions.

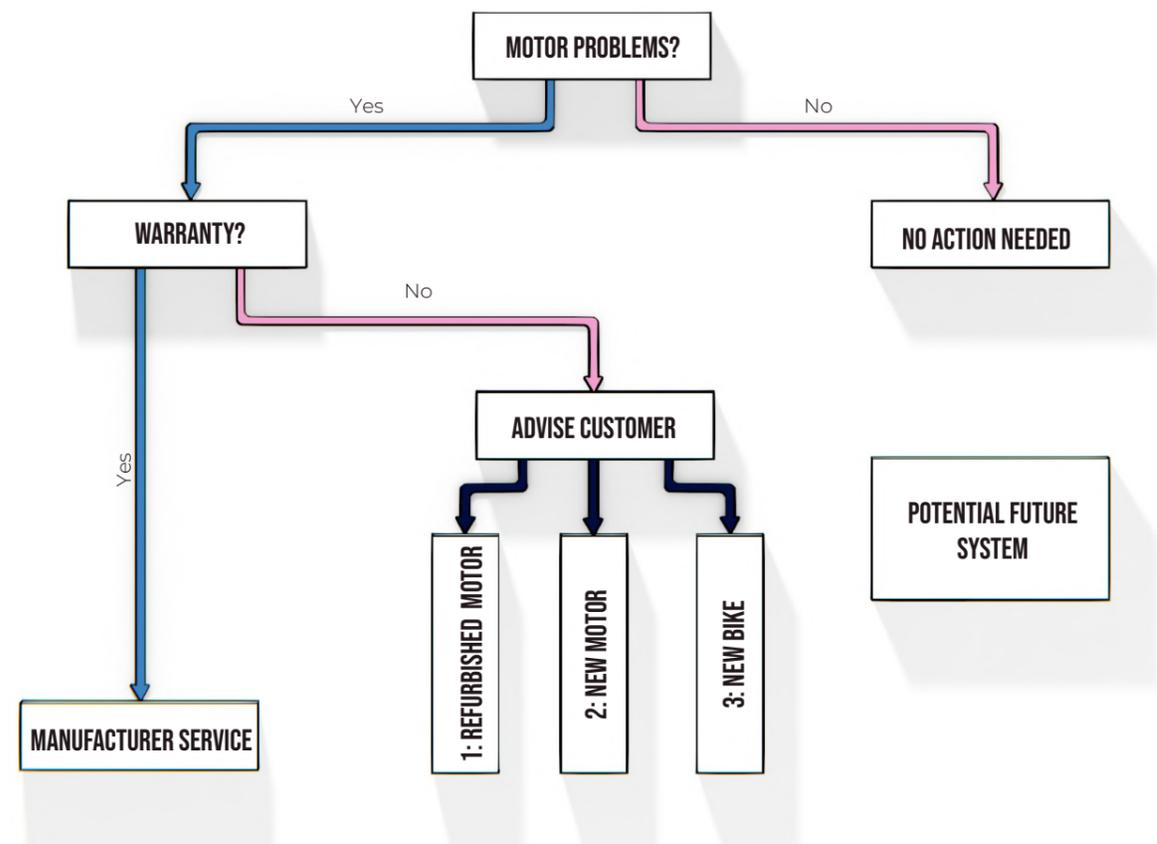
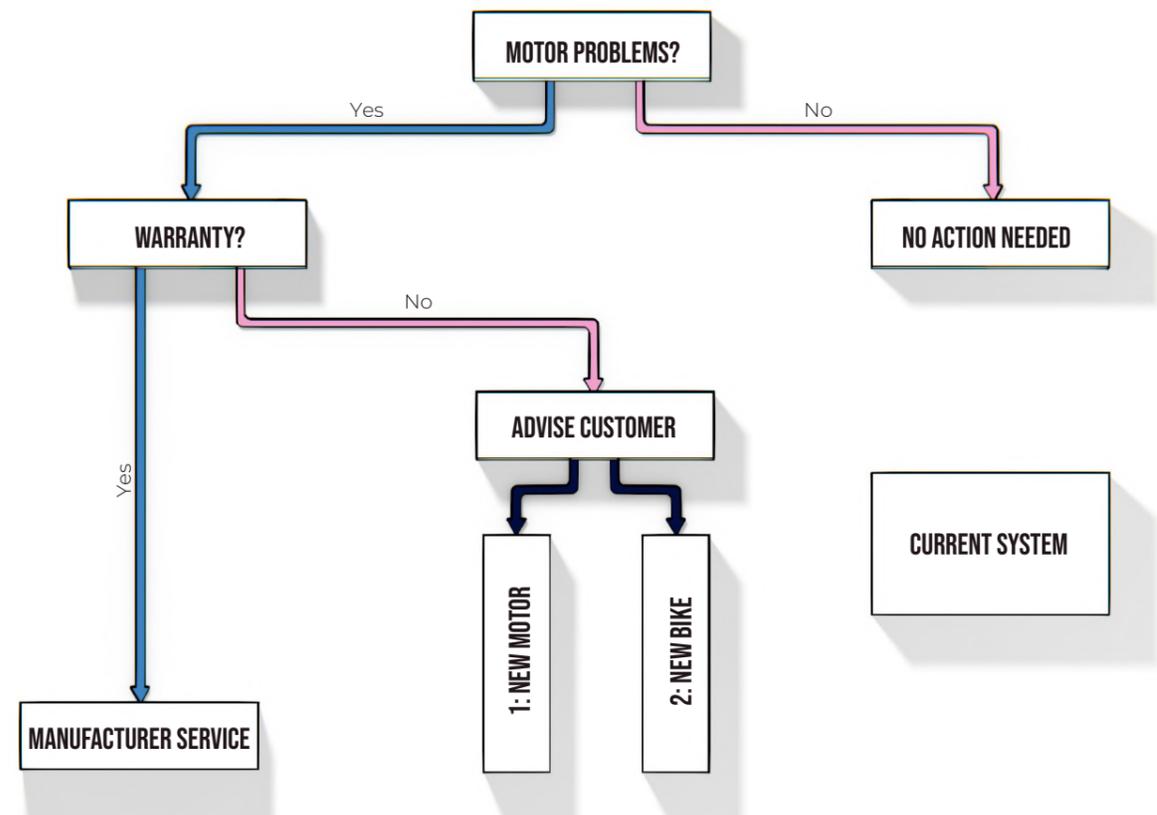


Figure 5.4: The decision pathway for mechanics in the current and potential future systems

## 5.2 CONCLUSION

This chapter examined how the current e-bike motor system operates and how circularity could be improved. The results show that the existing system is still quite linear, with limited collaboration between mechanics and revision companies. Literature confirms that motors are well-suited for remanufacturing and that structured B2B systems have strong potential. The emerging concept of a central

refurbishment hub illustrates how such a system could function and highlights both opportunities and challenges. Within this future system, the mechanic's role becomes more important: from simple monitoring to diagnosing issues and directing motors into the right pathways.

Figure 5.5 describes the main takeaways from this chapter.

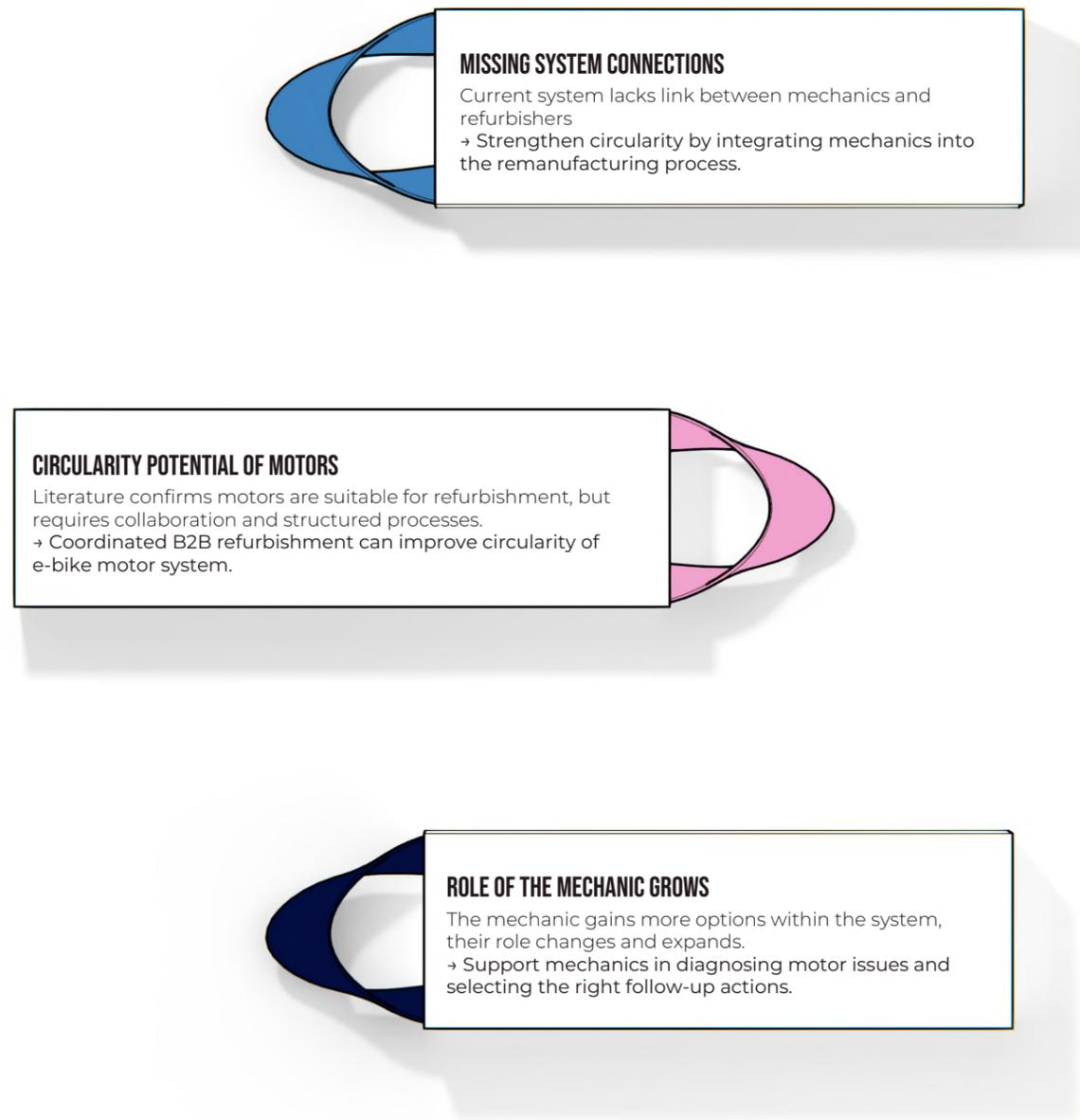
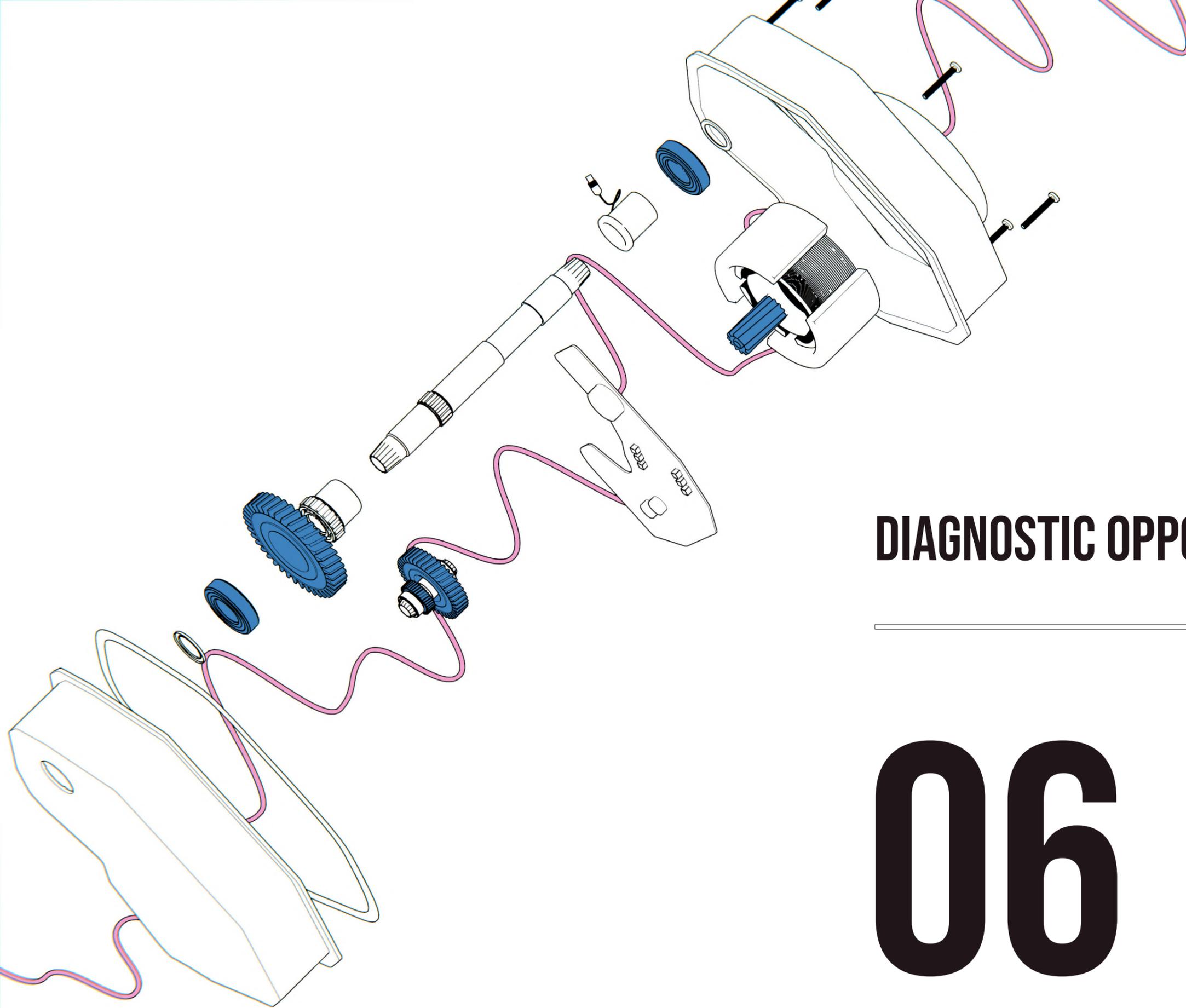


Figure 5.5: The main takeaways from this chapter



## DIAGNOSTIC OPPORTUNITIES.



# 06

This chapter analyses the technical construction of e-bike motors based on the teardown, disassembly mapping, and hotspot mapping methodologies described in sections 3.3 to 3.7. It identifies the main components and differences between brands and highlights which parts are most prone to wear or failure. Drawing on expert interviews (Section 3.2), the chapter also explores how motor problems are currently diagnosed by bike mechanics and revision companies, in order to identify opportunities for improvement.

6.1 Results

6.2 Conclusion

## 6.1 RESULTS

### 6.1.1 MOTOR ARCHITECTURE

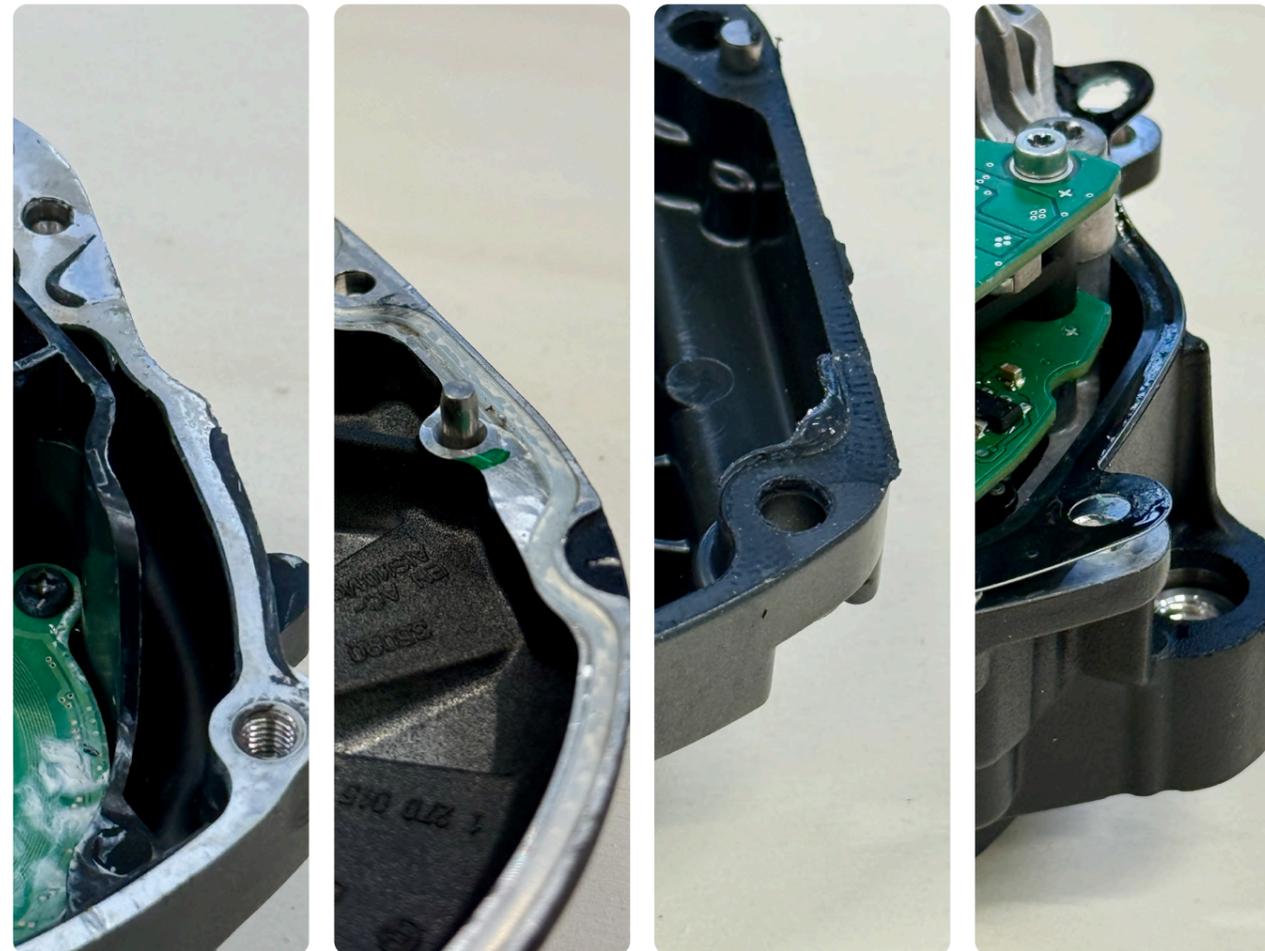
This section presents the results of the disassembly mapping and comparative analysis of nine mid-drive e-bike motors selected in section 3.3. The goal was to identify the main components that define their architecture, and to understand how these differ between brands in terms of layout, accessibility, and reparability. The complete disassembly maps, knolled images, comparison table and hotspot maps can be found in appendix D, E and F.

#### Casing and sealing

All motors featured two aluminium casing halves, typically fastened with Torx T25 screws, five or six per motor in most cases. In eight out of nine motors, the housings were connected with a friction fit, requiring a flat screwdriver to separate them after unscrewing. In more than half of the

cases (five out of nine), one or two circlips around the crankshaft had to be removed first, an easily overlooked but critical step to prevent damage during opening.

While every motor included a seal between the casing halves, the sealing method varied considerably (figure 6.1). Two brands, Shimano and Gobao, used a non-reusable adhesive seal (made from a rubber-like material such as silicone or polyurethane), preventing clean reassembly after opening. Shimano's sealing was applied unevenly, while Gobao used a thick, uniform adhesive layer that was difficult to separate. The remaining brands used removable gaskets (rubber rings or thin metallic gaskets) in various configurations.



Shimano DU-E5000

Bosch BDU 350

Gobao P101

Brose Specialized 3.1

Figure 6.1: The variety of seals and gaskets used to prevent water ingress

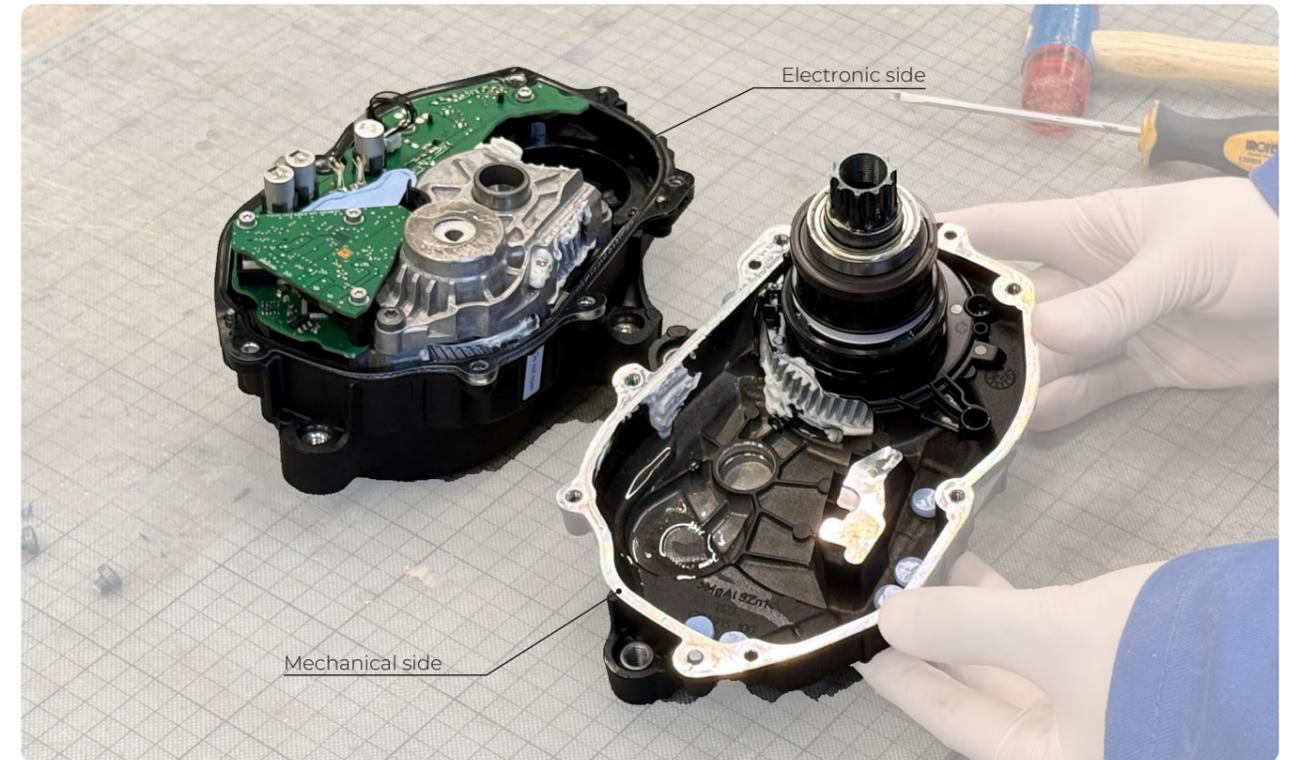


Figure 6.2: The mechanical and electronic sides of the Brose Specialized 3.1



Figure 6.3: Reversible connections between motor and motherboard in the Bosch BDU350

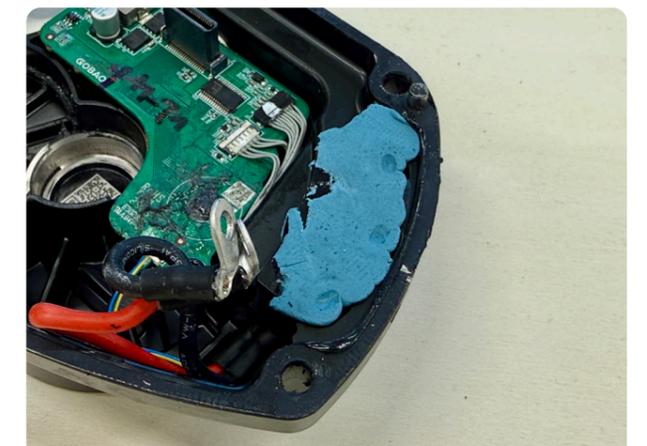


Figure 6.4: Thermal paste used for heat transfer in the Gobao P101

#### Internal layout

The two casing halves could broadly be described as a mechanical side and an electronic side (figure 6.2):

- The mechanical side contained relatively few components, typically a bearing seat and a shaft seal to ensure water tightness at the crank interface.
- The electronic side contained the motor, the main PCB, connectors, and additional sensors

In seven of nine motors, the battery and display connectors were positioned on this electronic

side, likely due to proximity to the motherboard. Only three motors, Brose, Bosch (3rd gen), and Bafang, featured a removable motherboard that was not irreversibly connected to the motor housing. In these cases, the electronics were cleverly designed to slide into connector pins (as shown in figure 6.3), enabling disassembly without permanent damage.

Interestingly, these same three motors (and the Gobao P101) were also the only ones to include thermal paste for heat transfer between the electronics and the casing (figure 6.4).

### Crankshaft assembly

All examined motors contained a crankshaft with two bearings, positioned at the outer ends near the seals, and a primary gear with a freewheel mechanism (figure 6.5).

Gear material was either metal or nylon; three of the nine motors (Bosch Gen 2, Bosch Gen 3,

and Bafang M210) used a nylon gear to reduce friction (figure 6.6). In seven of the nine motors, the crankshaft assembly was removable. Exceptions were the Bafang M210, where the torque sensor was permanently integrated into the casing, and the Shimano DU-E6110, where the fixed motherboard obstructed removal.

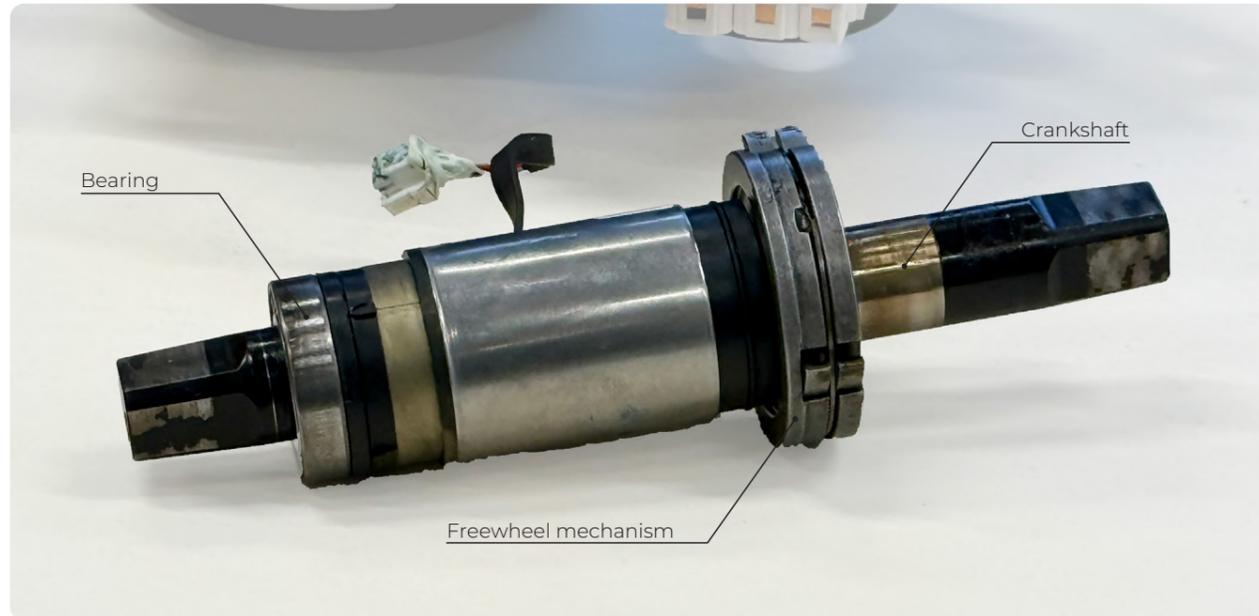


Figure 6.5: The crankshaft assembly of the Ananda M81

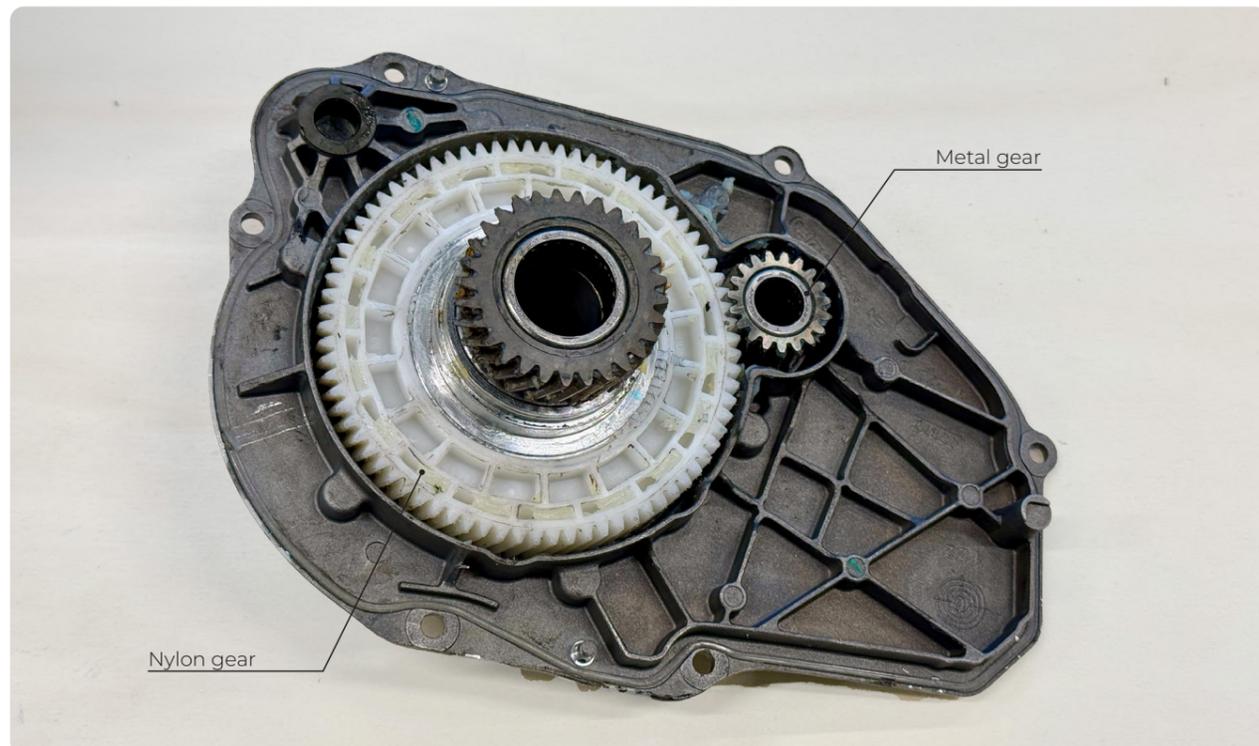


Figure 6.6: Both metal and nylon gears from the Bosch BDU 250

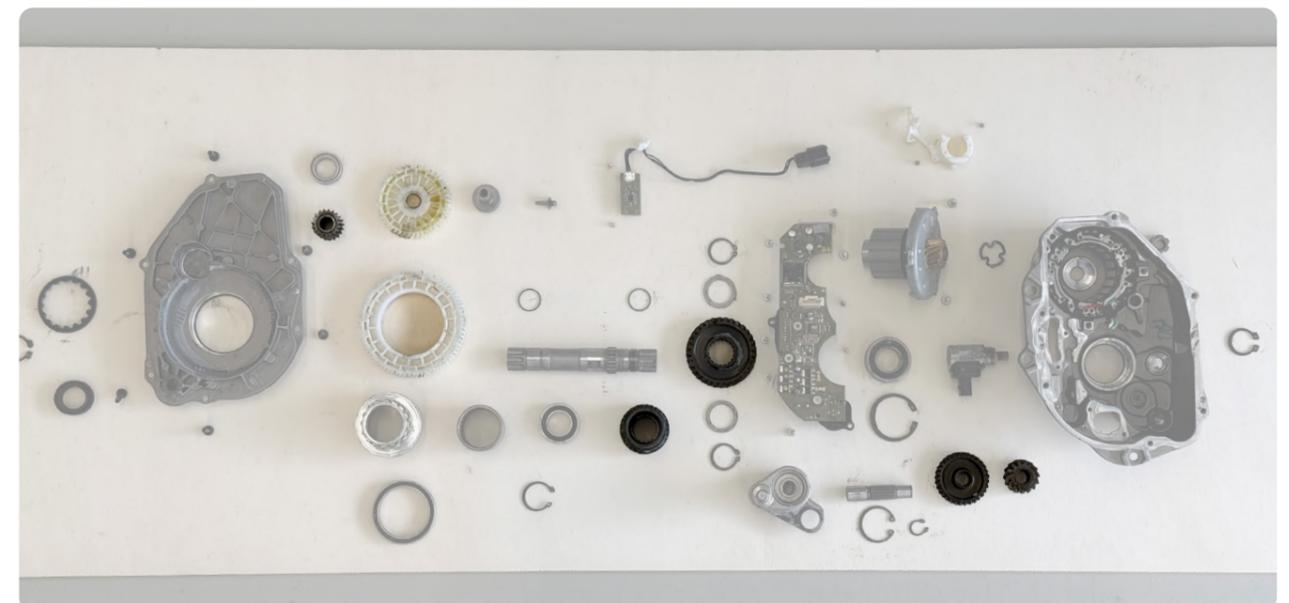


Figure 6.7: Transmission gears of the Brose Specialized 3.1 (top, one gear assembly) compared to Bosch BDU 250 (bottom, several separate gear stations).

### Transmission

Seven out of nine motors had a set of gears to transmit motion from the motor to the crankshaft. The remaining two (Bosch Gen 3 and Bafang M210) only had a single large nylon gear running directly on the motor shaft.

Among the seven geared motors, most used

one or two independent gear stations that could be removed separately. The Brose Drive C stood out by incorporating all gears into a single, removable gearbox subassembly, simplifying both assembly and repair. In nearly all cases (six of seven), the transmission gears were made of metal. Figure 6.7 show a comparison of the Bosch BDU 250 and Brose Specialized 3.1.

### Takeaway

Main differences between brands and models are in type of gasket, gear material, and (ir)reversible connections between motor and motherboard.

→ Brand/model has a major impact on maintenance and repairability potential.

### Summary of common architecture

Despite significant variation in layout and materials, all mid-drive motors follow a broadly similar architecture consisting of two casing halves, a central crankshaft assembly, a

transmission section, a set of electronics (motor, motherboard, sensors), and several seals and bearings to ensure watertightness. The overall structure and component hierarchy are shown in figure 6.8.

#### Takeaway

Mid-drive e-bike motors share a similar basic structure: two aluminium casing halves, central crankshaft, transmission, and integrated electronics.  
→ Each motor contains roughly the same parts and assemblies.

### 6.1.2 CRITICAL PARTS AND DIAGNOSTIC METHODS

To understand which components in e-bike motors are most prone to failure and how these problems can be detected, findings from the teardown analysis were combined with insights from expert interviews and literature. As discussed in Chapter 4 (based on interviews with revision experts R1–R4) most failures occur in bearings (50%), followed by software-related issues (25%) and other mechanical problems (25%). This section explains the common problems within these categories and the typical signals that indicate them. Although even specialised repair companies often struggle to

solve electronic or software-related issues, this section also considers how these problems can be recognised, as they also require follow-up action by the bike mechanic.

The interview with the specialised revision company (R2) provided insight into their diagnostic steps for e-bike motors, in this case focused on Bosch systems. Most problems start with an error code beginning with “500”. Using the manufacturer’s diagnostic software, the mechanic can read the full code to identify the issue. The software, for example, detects when

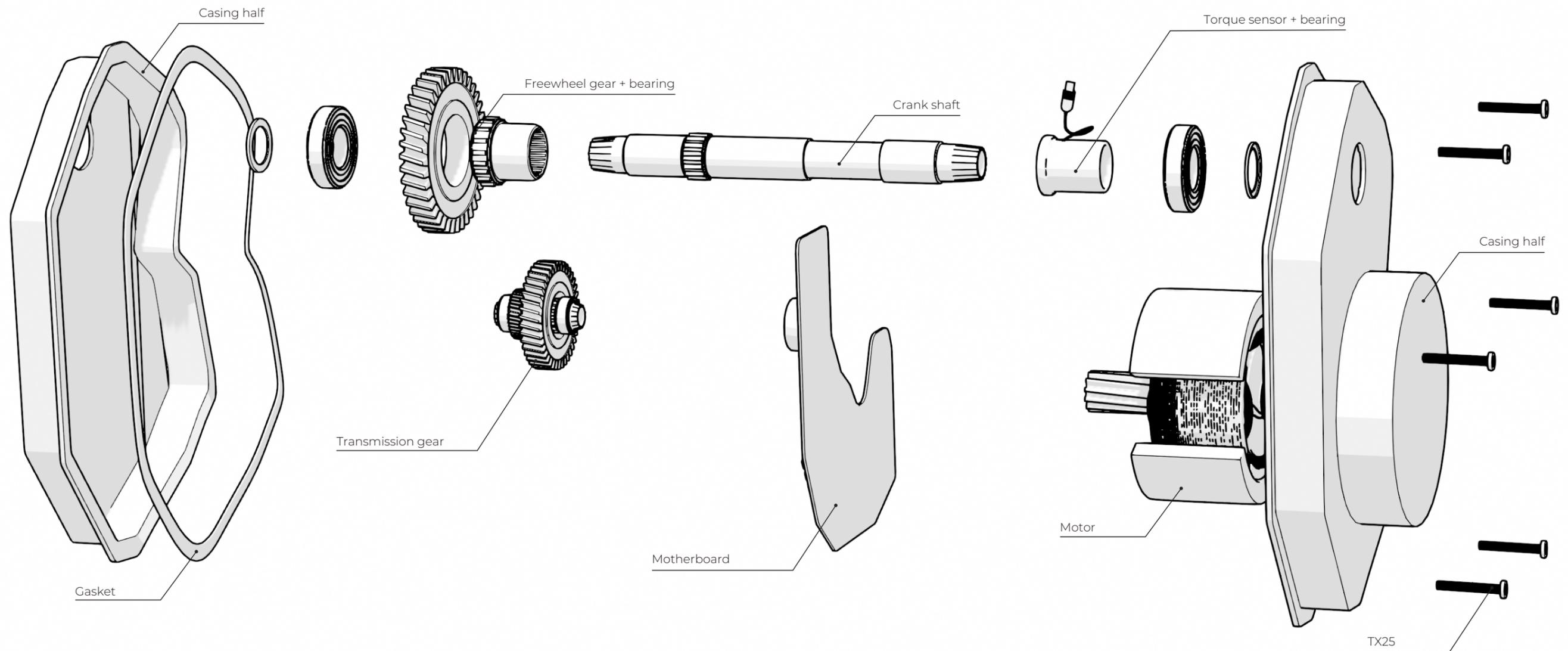


Figure 6.8: An overview of the structure and components of a typical e-bike motor. Note: this is not an existing brand or model, but a generalized design derived from the component analysis.

the motor runs less smoothly or struggles to reach certain speeds, which often points to mechanical problems such as worn or damaged bearings. Reading the motor with this software is therefore the first step in the diagnostic process. Bike mechanics working with Bosch motors already have access to this tool.

The interview and observation with a local bike mechanic (M1) showed that each brand has its own diagnostic software. This software runs on a computer that is connected to the bike via a USB-C cable. According to the mechanic, Bosch provides the most detailed software, offering the most insights. It shows an overview of the system's main parts – the motor, display, and battery – and provides information about warranty, updates, and errors. Despite this, the mechanic receives only limited information from the software and can mainly use it to decide whether the motor should be sent back to the manufacturer.

However, there is another way to gather useful information. The second step in the revision company's diagnostic process is to mount the motor on a test bike and ride it while observing its behaviour. During this test, they pay attention to factors such as noise and vibrations or shocks. Together with the error codes, these observations provide valuable information about the motor's condition and often allow experts to identify which parts are causing problems. For example, a bearing issue usually produces a dragging, rough noise, while a damaged gear may cause occasional shocks depending on which gear is affected. If the shock occurs every pedal rotation, it indicates a problem in the bottom bracket gear; if it happens less frequently, the issue is likely in another gear. Table 6.1 provides an overview of the critical parts, their common problems, and diagnostic signals. Figure 6.9 presents an overview of the diagnostic procedure as described by R2 during the interview.

As mentioned earlier, bearings are the cause of failure in about 50% of cases. They are relatively easy to replace, but not all bearings are the same. The interviews mentioned in section 3.2 revealed that every motor has a "weakest" bearing that tends to fail first. Unfortunately, identifying which bearing this will be in advance is difficult. This type of information is highly valuable, yet it is rarely

shared by manufacturers, and little research is available on the topic. According to the revision expert, it is also difficult to determine which bearings are worn or damaged without opening the motor. Therefore, bearings are grouped in one row in the table without distinguishing between types or positions.

**Takeaway**

Revision companies use both software and physical indicators such as sound and vibration to diagnose problems.  
→ Focus on enabling bike mechanics to identify physical signals

Table 6.1: Overview of e-bike motor components suitable for repair/replacement, their common failure modes and diagnostic signals focussed on Bosch motors

Component	Typical failure mode	Diagnostic signal
Bearings (50%)		
Bearings	Wear, dislocation (e.g., due to mechanical (over)loading, water damage, and/or impact)	Diagnostic software might show error codes (e.g., 500-503, motor mechanical fault), motor feels stiff, dragging noise, vibration, play on crankshaft
Software and electronics (25%)		
Software	System not working, error codes	Diagnostic software shows error codes (e.g., 550, "unprogrammed")
Electronics	System not working, error codes	Diagnostic software shows error codes (e.g., 530-540, communication or sensor faults)
Connectors	System not working, error codes	Visual damage on plugs and cables, diagnostic software shows error codes, component does not show up in software
Other mechanical failures (25%)		
Gears	Wear, breakage (e.g., due to impact)	Diagnostic software might show error code (e.g., 505-507 sensor misalignment). Sudden noise/shock/vibration during rotation. Frequency of shock indicates which gear (e.g., once per pedal rotation = Crankshaft), motor slipping when accelerating

## VISUAL INSPECTION AND READ SOFTWARE

1

Combining a visual check with reading the manufacturer's software. Serves as a first filter to detect obvious issues.

**Action:**

- Check the crank, pedal, casing, connectors and seals for cracks, dents, or deformation.
- Connect the bike to the computer and check the brand-specific software for updates, error codes, and warranty status.

**Result:**

An overview of the system status and potential failure sources. The mechanic can see if the issue is likely mechanical (e.g., resistance) or electronic (e.g., communication error).

## MECHANICAL INSPECTION

2

Look for signals and judge them correctly.

**Action:**

- Spin the crank by hand to feel for resistance.
- Make a short test ride to observe signals (table 6.1)

**Result:**

Detection of wear or mechanical issues

## EVALUATE FINDINGS

3

The goal of the protocol is not just to find out if the motor is broken, but to determine the correct follow-up action.

**Action:**

Combine results from software, inspection, and test ride to conclude whether the problem is mechanical or electronic, and whether repair is realistic.

**Result:**

Make the decision with confidence (repair/open or not)

Figure 6.9: Overview of the diagnostic procedure described by R2 during the interview

**Takeaway**

The main failure-prone components have been identified, along with their typical failure modes and warning signals.  
→ Focus on translating these findings into practical diagnostic tools or guidelines that help mechanics recognize early signs of failure without opening the motor.

## 6.2 CONCLUSION

The teardown and mapping analyses revealed that mid-drive e-bike motors share a broadly consistent architecture, consisting of two aluminium casing halves, a central crankshaft assembly, a transmission, and integrated electronics (motherboard, motor and torque sensor). While the general structure is similar across brands, significant variation exists in accessibility and sealing methods, which directly influence repairability.

This chapter has shown that diagnosing e-bike motor problems is a combination of digital and physical observation. The diagnostic software provides a useful first indication through error

codes, but offers only limited information about the underlying cause. Complementing this with sensory observation, such as listening for noise and feeling for vibration, allows experts to narrow down the source of the problem. Bearings account for the majority of failures and are relatively easy to replace, highlighting the value of accurate diagnosis in extending motor lifespan. However, current diagnostic tools provide little guidance on how to interpret signals or verify findings.

Figure 6.10 describes the main takeaways from this chapter.

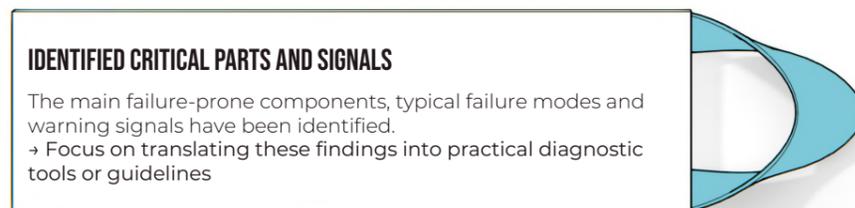
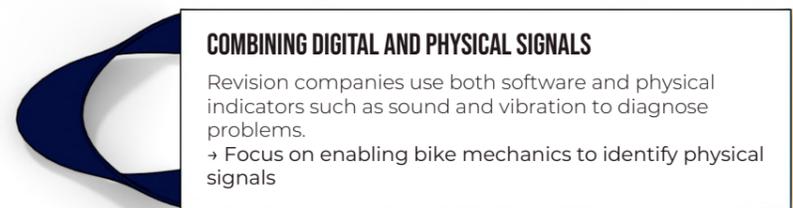
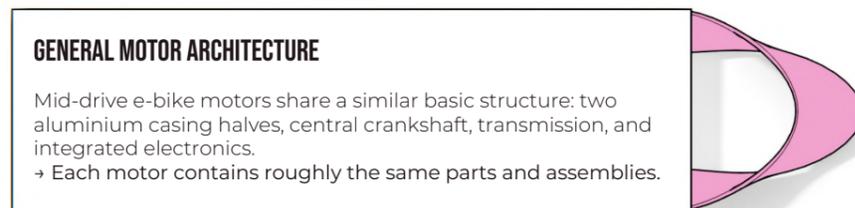


Figure 6.10: The main takeaways from this chapter



## 7.1 MAIN FINDINGS

The previous chapters revealed important insights about the current situation, including key barriers and challenges, insights into the system and its development towards a more circular

approach, and technical understanding of the structure of e-bike motors and their common problems, signals, and diagnostic methods. The main findings are summarized in Table 7.1.

Table 7.1: Main findings from chapters 04–06 and their implications for the design directions.

Chapter	Key findings	Design focus
04	Warranty limitations Barriers & challenges Failure patterns	Focus on post-warranty replacement of mechanically critical parts. Not feasible for regular bike mechanics to repair e-bike motors
05	Missing system connections Circularity potential of motors Role of the mechanic grows	Focus on strengthening circularity by integrating mechanics into the remanufacturing process and support them in diagnosing motor issues
06	Differences between brands General motor architecture Combining digital & physical signals Identified critical parts and signals	Focus on giving bike mechanics brand-independent, practical diagnostic support that helps them recognize failure signals early, without opening the motor, and guides them toward the correct follow-up action.

## 7.2 DESIGN VISION

“The design vision is to empower bike mechanics to detect and diagnose motor problems early, without opening the motor.”

Using non-invasive diagnostics, the solution should help mechanics recognize issues in critical components, with a strong focus on bearing and gear failures, before they become severe or unrecoverable. This enables mechanics to make informed decisions and direct motors toward the right next step.

This vision directly responds to the research findings. It targets the components most prone

to failure, avoids the time and cost barriers of opening the motor, and provides guidance where official repair information is limited. It fits both the current and future system: today, it increases awareness that remanufacturing options already exist; in the potential future system, it allows the mechanic to identify wear early, order a remanufactured motor, and send the old one for refurbishment.

Ultimately, this vision strengthens the mechanic’s role in creating a more circular e-bike motor system by extending motor lifetime and reducing e-waste.

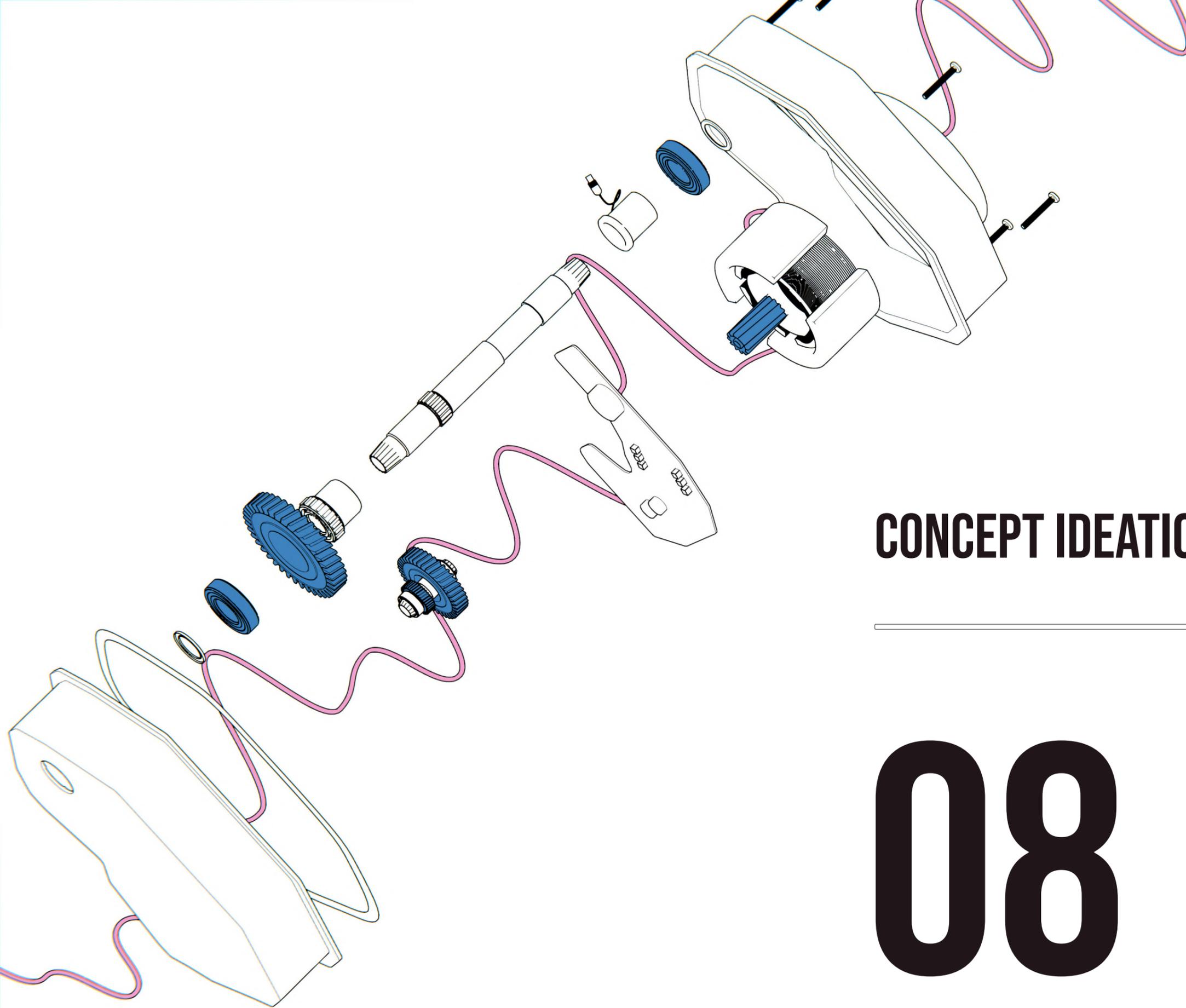
## 7.3 LIST OF REQUIREMENTS

Based on the main findings and the design vision, a set of requirements is defined to guide the development of a solution that supports

mechanics in detecting and diagnosing motor problems. The requirements can be found in table 7.2.

Table 7.2: List of requirements based on the main findings from chapters 04–06.

Requirements
The tool(kit) must diagnose mechanical failures without opening the motor.
The tool(kit) must identify early symptoms of bearing and gear wear.
The tool(kit) must operate independently of manufacturer software.
The tool(kit) must support mechanics in making better referral decisions.
The tool(kit) must be quick and simple to use in motor service routines.
The tool(kit) must make expert knowledge from motor-revision companies accessible to bike mechanics.
The tool(kit) must deliver consistent and repeatable results.



## CONCEPT IDEATION.



# 08

This chapter translates the design vision from Chapter 7 into a concrete concept. Previous chapters showed that bike mechanics are willing to help, but often lack the tools and experience to look beyond standard software error codes. As a result, mechanical problems inside the motor remain difficult to diagnose. The goal of this chapter is to develop a concept that helps mechanics identify these problems in a reliable way.

- 8.1 Scoping the toolkit functions
- 8.2 Translating signals into metrics
- 8.3 Vibration analysis
- 8.4 The concept: vibration analysis tool

## 8.1 SCOPING THE TOOLKIT FUNCTIONS

To define what the toolkit should contain and communicate, a mind map was created to explore its role within the e-bike system. It can be

seen in figure 8.1 and shows that the toolkit can create value in three areas.

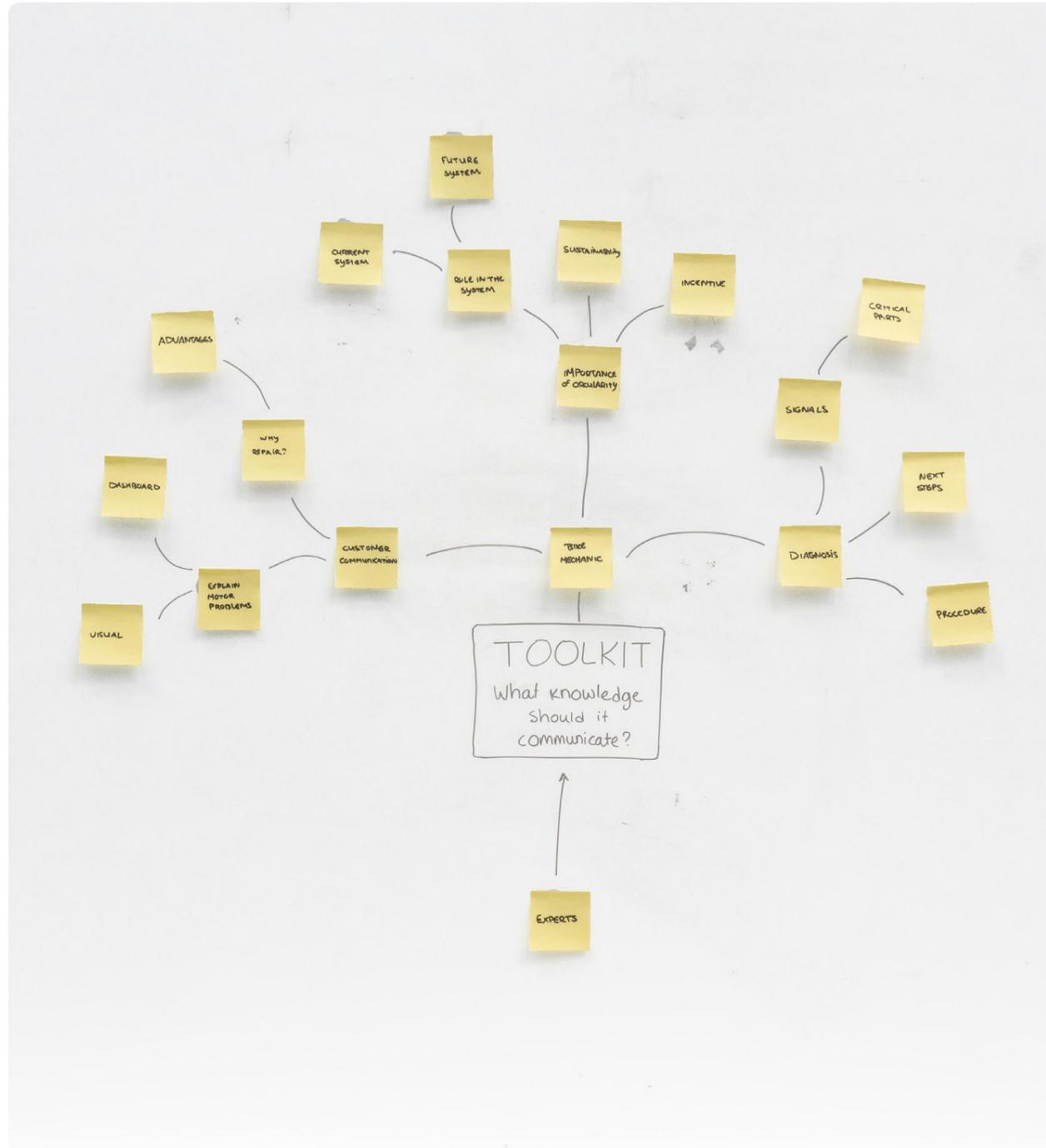


Figure 8.1: A mindmap showing the potential value of the toolkit

### Technical diagnosis (Right)

Supporting the diagnosis of problems with critical parts, such as worn bearings or damaged gears, and linking these findings to next steps. Previous chapters showed that identifying what is broken is crucial, as it strongly influences repair and refurbishment decisions.

### Customer communication (Left)

Helping mechanics explain the problem to customers and justify costs and follow-up actions. This includes explaining why repair or refurbishment is (or is not) a good option and what the function of the failed component

is. Clear communication is important, as the customer ultimately decides and pays.

### System integration (Top)

Clarifying the importance of circularity, the economic incentives behind it, and the role of the mechanic within both the current system and future systems (Chapter 5).

The map also highlights a crucial link at the bottom: the toolkit connects the expert (the revision company) with the mechanic. It must take the knowledge from the experts and make it usable for the mechanic.

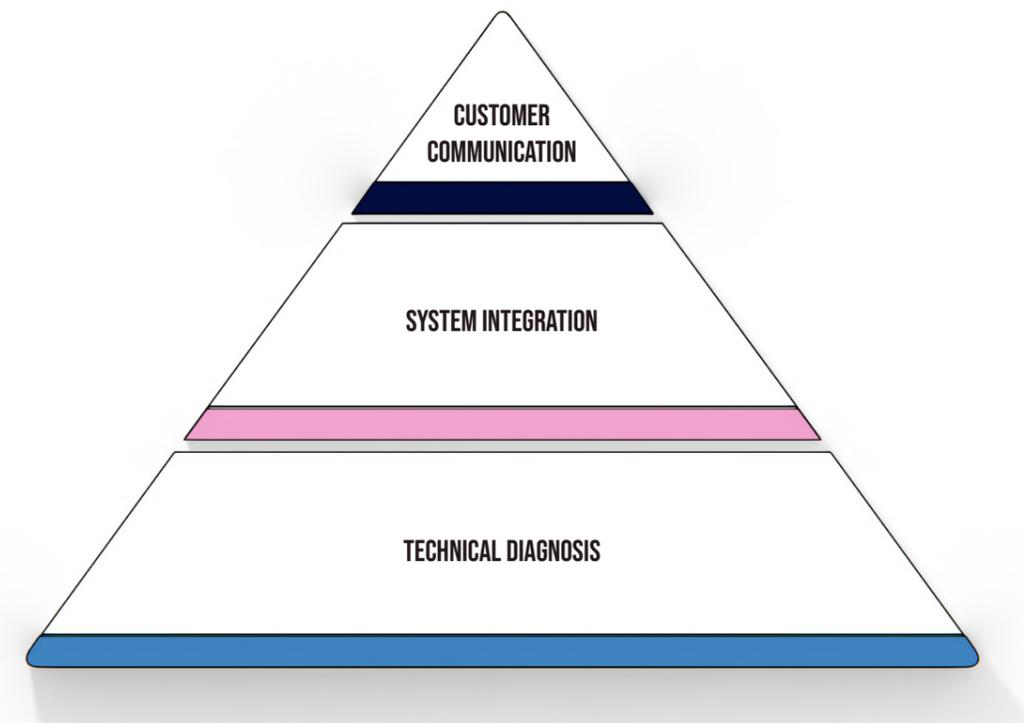


Figure 8.2: The main functions that the toolkit can fulfil and their interdependence

#### Important design decision

Although customer communication and system awareness are important, they depend on a correct diagnosis (as shown in figure 8.2). A mechanic cannot explain a problem without knowing what is wrong. Therefore, this concept focuses primarily on technical diagnosis. By addressing the diagnostic problem first, the toolkit provides bike mechanics the basis for better understanding of their role in the system and improved customer communication.

The diagnostic protocol described in section 6.1.2 offers a clear structure, but phase 2 remains the main bottleneck. In this phase, mechanics rely on subjective signals such as noise, vibration, and stiffness, often without expert knowledge. To make this protocol scalable and accessible to all mechanics, these subjective signals need to be translated into objective data.

## 8.2 TRANSLATING SIGNALS INTO METRICS

To make phase 2 of the diagnostic procedure reliable and accessible for all mechanics, subjective signals must be converted into measurable variables. The signals identified in Chapter 6 (table 6.1) are based on an interview with a refurbishment expert (R2) and are mostly

subjective terms like 'stiffness' or 'noise'. Where needed/possible, these signals were linked to measurable variables. Figure 8.3 shows a map made during this process. The terms used in this map will be explained on the next page.

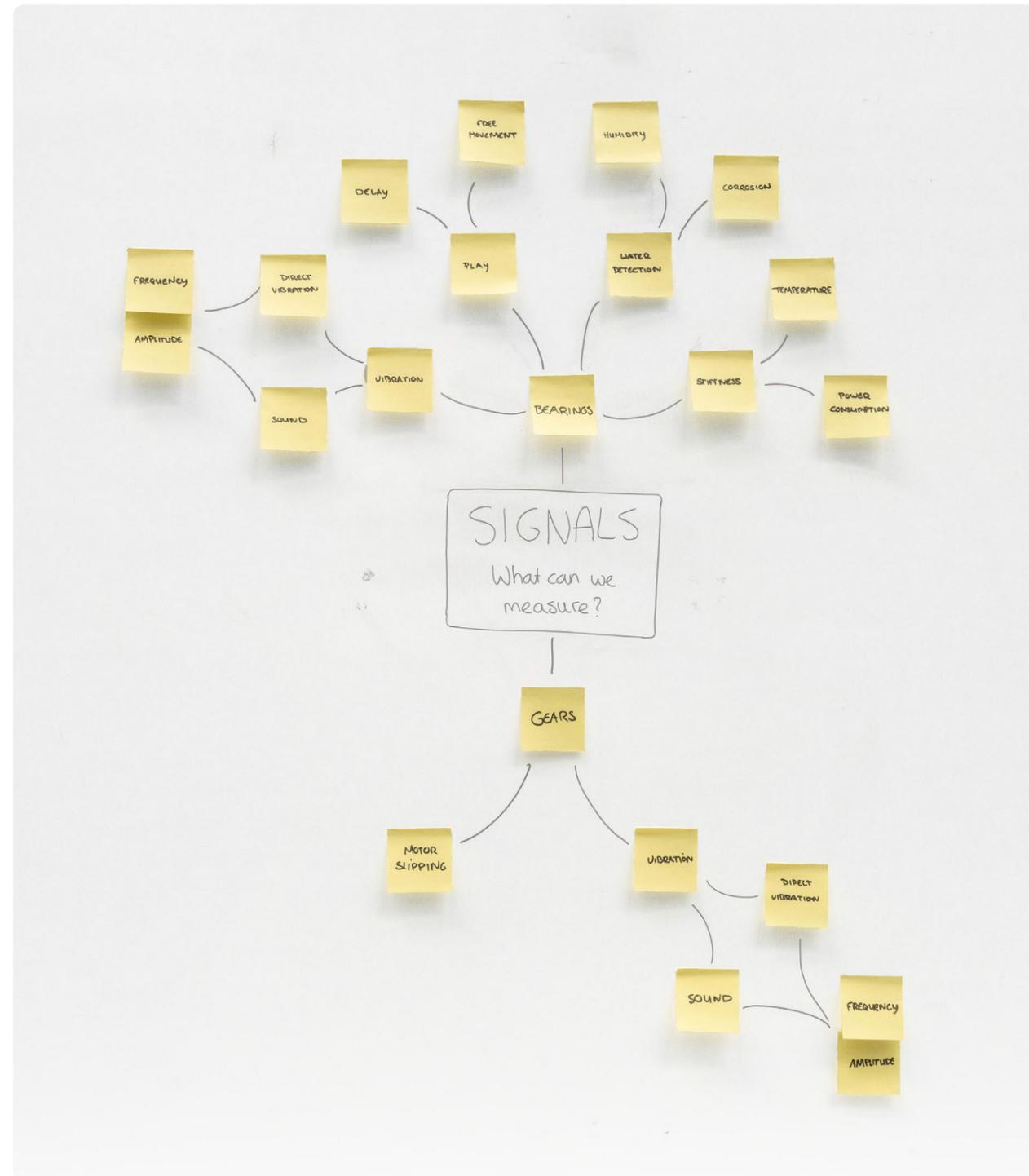


Figure 8.3: A mindmap showing the signals and variables that might indicate problems within a e-bike motor

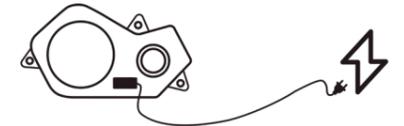
### Play

Refers to unwanted free movement between parts that should normally be fixed or tightly connected. In a healthy motor, play is minimal and barely noticeable. In a worn motor, play increases and can often be felt as a small knock or delay when the load direction changes. Play mainly indicates advanced wear in gears or bearings.



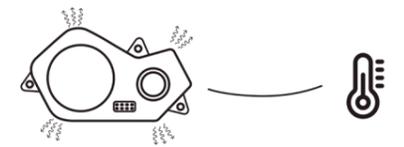
### Power

Refers to the electrical power or current the motor draws to achieve a certain mechanical output. In a healthy motor, the required current for a given load remains relatively stable. In a faulty motor, increased internal friction or misalignment causes the motor to draw more current to deliver the same output. This signal can indicate developing mechanical issues such as bearing wear or lubrication problems.



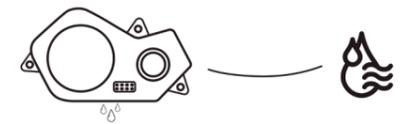
### Temperature

Using motor temperature as an indirect indicator of mechanical losses. A healthy motor operates within a normal temperature range. A faulty motor may heat up faster or reach higher temperatures due to increased friction. This method can indicate general inefficiency or friction but does not clearly point to specific components.



### Water detection

This signal concerns the presence of moisture or water inside the motor housing. Water ingress can be detected through humidity sensors or signs of corrosion. Water itself is not a failure, but it strongly increases the risk of corrosion, bearing damage, and electrical issues.



### Slipping

Slipping refers to a loss of torque transmission between components, often felt as a sudden loss of drive. In a healthy motor, power transfer is continuous. In a faulty motor, slipping may occur under load. This typically indicates severe wear of gears or one-way mechanisms.



### Vibration

This signal refers to mechanical vibrations generated by the rotating components inside the motor. A healthy motor produces low and stable vibration levels. A faulty motor shows increased vibration or distinct peaks at specific frequencies.



To select the most suitable diagnostic signal, a Harris Profile (Van Boeijen et al., 2020) was created for each option. This method allows a systematic

comparison by scoring each variable against several relevant criteria. The four evaluation criteria are described in table 8.1.

Table 8.1: The four evaluation criteria including an explanation

Criteria	Explanation
Early detection	Can the method detect problems before they cause serious damage?
Ease of use/time	Can it be applied quickly during a regular service check?
Feasibility	Is the technology available and usable without opening the motor?
Coverage	Does it detect failures in both critical mechanical components (bearings and gears)?

Using these criteria, the six potential diagnostic options were assessed. The scores represent relative performance, rather than absolute measures. For example, a low score may show

late detectability, dependence on manufacturer software or long measurement times. Table 8.2 presents the results, ranging from very poor (--) to excellent (++)

Table 8.2: A Harris profile for each signal to score (– to ++) them on the criteria described in table 8.1.

### PLAY

	--	-	+	++	Explanation
Early detection	■				Usually becomes noticeable only when wear is already advanced
Ease of use/time				■	Can be checked quickly without the motor running.
Feasibility			■		No special equipment is needed, but access to the relevant components is limited without opening the motor
Coverage			■		Mainly indicates wear in gears and bearings, but not all failure modes.

### POWER

	--	-	+	++	Explanation
Early detection			■		Increased current draw can indicate rising internal friction before functional failure occurs.
Ease of use/time			■		Electrical data can be read relatively quickly if access is available.
Feasibility			■		Current measurements depend on manufacturer software, firmware access, and controlled conditions.
Coverage			■		Increased power demand can result from both bearing- and gear-related losses.

### TEMPERATURE

	--	-	+	++	Explanation
Early detection		■			Changes occur relatively late and only after friction has increased significantly.
Ease of use/time		■			Needs time to build up, making it unsuitable for quick checks.
Feasibility			■		Can be measured externally using simple sensor.
Coverage			■		Elevated temperature can result from both bearing and gear-related problems.

### WATER DETECTION

	--	-	+	++	Explanation
Early detection				■	Can be detected early, before direct mechanical damage occurs.
Ease of use/time			■		Can potentially be checked relatively quickly using sensors or visual inspection.
Feasibility	■				Detecting water inside sealed motors is difficult without opening the housing.
Coverage		■			Presence does not indicate which mechanical component is affected.

### SLIPPING

	--	-	+	++	Explanation
Early detection	■				Typically appears only when components are already severely worn.
Ease of use/time	■				Is difficult to reproduce consistently and probably requires load-dependent testing.
Feasibility		■			Reliable detection is difficult without controlled conditions or disassembly.
Coverage		■			Mainly indicates problems in gears, but not in bearings.

### VIBRATION

	--	-	+	++	Explanation
Early detection				■	Small defects in bearings or gears generate measurable vibration long before failure.
Ease of use/time			■		Can be measured quickly using an externally mounted sensor, but motor has to run.
Feasibility				■	Used in industrial applications. Technologies allow reliable measurement through closed motor housings
Coverage				■	Patterns can indicate both continuous wear and periodic faults in multiple components.

Vibration analysis was selected as the most promising option for several reasons:

- **Early detection:** even small defects in bearings or gears generate characteristic vibration patterns long before complete failure occurs (McFadden and Smith, 1984).
- **Ease of use:** vibrations can potentially be measured quickly by attaching a sensor to the motor housing (Reliability Maintenance Solutions Ltd., 2015).

- **Feasibility:** technologies such as piezoelectric sensors to detect vibrations are well established and vibration analysis is widely used for condition monitoring of rotating machinery in industrial applications (Randall, 2010).
- **Coverage:** vibration patterns can indicate both continuous wear (bearings) and periodic shocks (gears) (McFadden and Smith, 1984).

#### Important design decision

The remainder of this thesis focuses on exploring whether vibrations in e-bike motors can be measured and used to detect and diagnose problems at an early stage.

## 8.3 VIBRATION ANALYSIS

This section briefly explains the principles of vibration analysis. In industries such as manufacturing and wind energy, vibration analysis is a standard method for monitoring

rotating machinery (ISO 13373). The following sections describe the key concepts relevant to this project.

### 8.3.1 THE BASICS OF VIBRATION

A vibration signal is defined by two main variables (Mobius Institute, 2018):

- **Frequency:** how often the vibration occurs per second, measured in Hertz (Hz). Different components rotate at different speeds. For example, the crank rotates slowly (on walk assist mode around 0,25-0,5 Hz), while internal motor components rotate much

faster. Frequency information can therefore help identify which component is affected.

- **Amplitude:** the magnitude of the vibration, or how strongly the system is vibrating. Higher amplitudes generally indicate more severe wear, imbalance, or looseness.

Figure 8.3 visually explains the difference between these two variables.

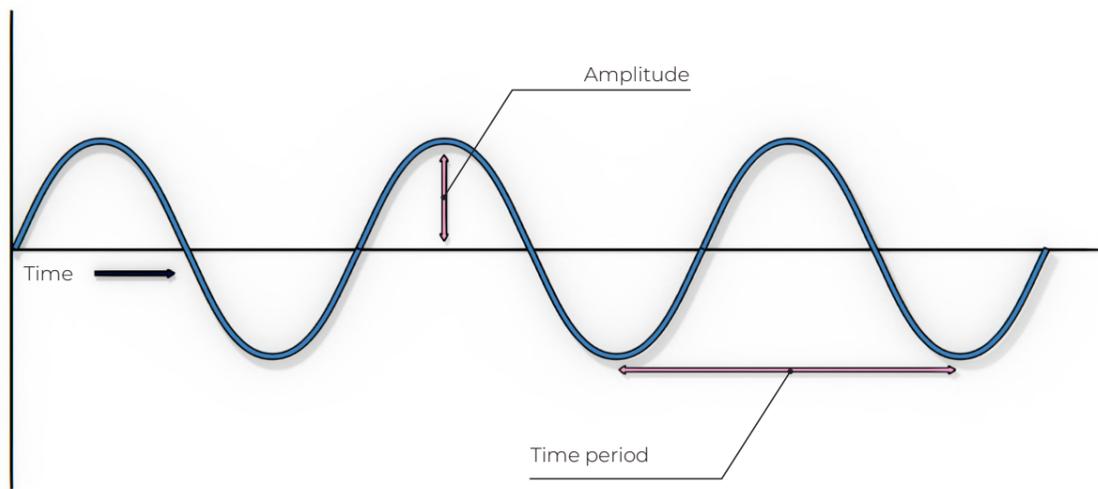


Figure 8.3: The basics of vibration: amplitude and frequency ( $= 1 / \text{time period}$ )

### 8.3.2 TIME VS FREQUENCY DOMAIN

A raw sensor signal is a waveform in the time domain. This often looks like a noisy line where vibrations from the motor, gears, and environment are mixed together. To make this data useful for diagnosis, it must be filtered and sorted.

explained by Randall (2010), FFT converts the raw signal from the time domain into the frequency domain (figure 8.4). This process separates the complex signal into distinct peaks. This makes it possible to identify specific fault-related frequencies, such as those caused by bearing defects, and distinguish them from background noise (Hamedynia & T, 2010).

To do this, a mathematical technique called Fast Fourier Transform (FFT) is often used. As

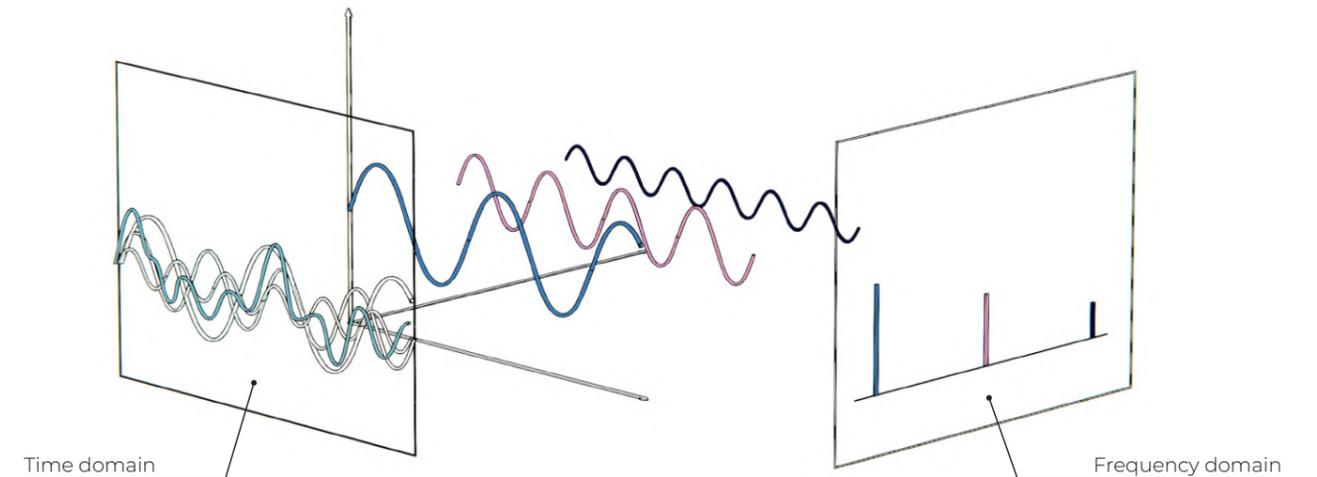


Figure 8.4: Time (left) vs frequency (right) domain, converted with a FFT. The light blue line represents the raw sensor signal, which is composed of multiple frequency components (blue, pink, and dark blue).

### 8.3.3 AMPLITUDE AND ENERGY COMPARISON

In vibration analysis, not only the presence of specific frequencies is important, but also the amount of vibration energy in the signal. While frequency information helps to indicate which component may be affected, amplitude-based metrics help to describe how severe the vibration is (Randall, 2010).

measurements to be compared in a quantitative and objective way (Vibromera, 2025).

A commonly used measure is the Root Mean Square (RMS) value of the vibration signal. The RMS represents the effective vibration energy over time (figure 8.5) and allows different

In addition to a single overall RMS value, vibration energy can also be analysed within specific frequency bands. Randall (2010) explains that faults such as bearing damage often cause an increase in vibration energy within specific frequency ranges. By calculating RMS values, it is possible to analyse abnormal energy distributions and compare motors based on these values.

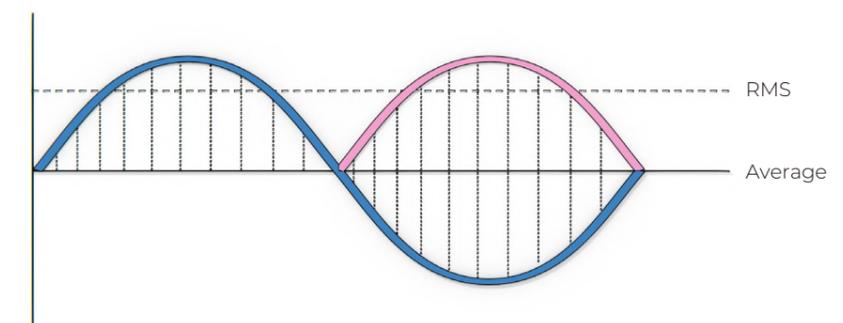


Figure 8.5: Explanation of RMS and its difference compared to the average value. RMS represents the overall vibration energy of a signal, while the average value can cancel out positive and negative variations.

### 8.3.4 VIBRATION IN PREDICTIVE MAINTENANCE

Vibration analysis is well suited for predictive maintenance because mechanical defects develop gradually. McFadden and Smith (1984) showed that a small defect in a bearing creates a repetitive impact each time a rolling element passes over it. These impacts generate vibration signals long before functional failure occurs. This process is often described using the P-F

curve (Potential failure to Functional failure, shown in figure 8.6). Vibration signals appear at point P, well before audible noise or motor seizure at point F. According to Vlachou et al. (2025), using these early signals allows maintenance to be planned proactively, creating a larger window for repair or refurbishment and prevent further damage.

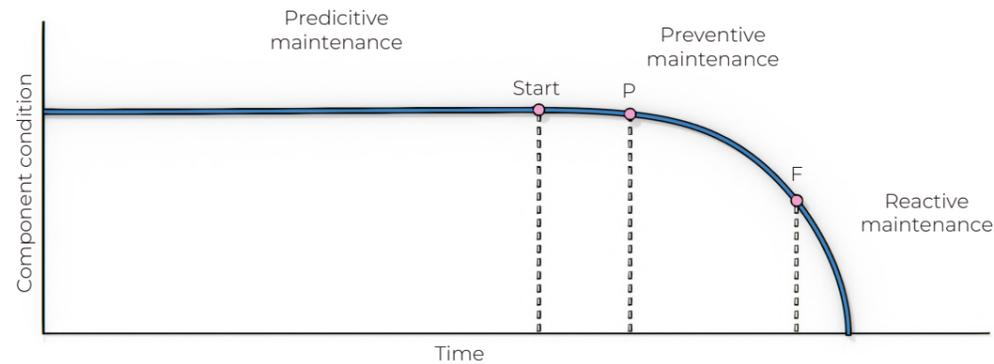


Figure 8.6: The P-F curve (P: potential failure, issues can be detected; F: functional failure, issues cause motor to seize)

## 8.4 THE CONCEPT: VIBRATION ANALYSIS TOOL

Based on this analysis, the proposed concept is a non-invasive vibration analysis tool. It is designed to make the “test ride” and “physical check” objective and translate the signals into measurable variables.

The concept has three parts:

1. **Sensor:** a (contact) microphone that picks up vibrations from the motor
2. **Processor:** software that processes the signal and analyses present amplitudes and frequencies.

3. **Baseline database:** every motor type vibrates differently. The tool compares the measured signal against a “healthy baseline” from the database.

The tool checks for deviations. If the total energy or the vibration at a specific frequency (band) is much higher than the baseline, the tool detects a defect. It mimics the motor expert (“this sounds wrong”) but uses data to prove it. This process is described in figure 8.7.

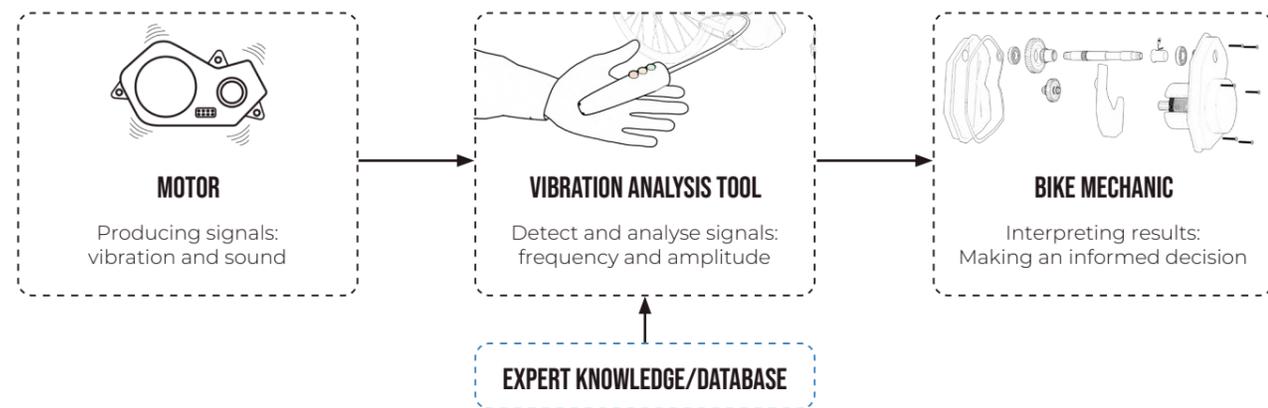


Figure 8.7: Overview of the concept function. Vibration signals are detected, analysed, and translated into understandable information for bike mechanics.

### 8.4.1 USE CONTEXT

The tool is intended to be used during a regular service check (figure 8.8). The mechanic briefly measures the motor and checks whether the vibration signal falls within an expected range. If the values exceed this range, the tool indicates that there is a potential problem. This gives

the mechanic an early warning that further inspection, repair, or refurbishment may be needed. The tool presents the data in a simple and accessible way, enabling the mechanic to confidently choose the most appropriate next step and advice to the customer correctly.

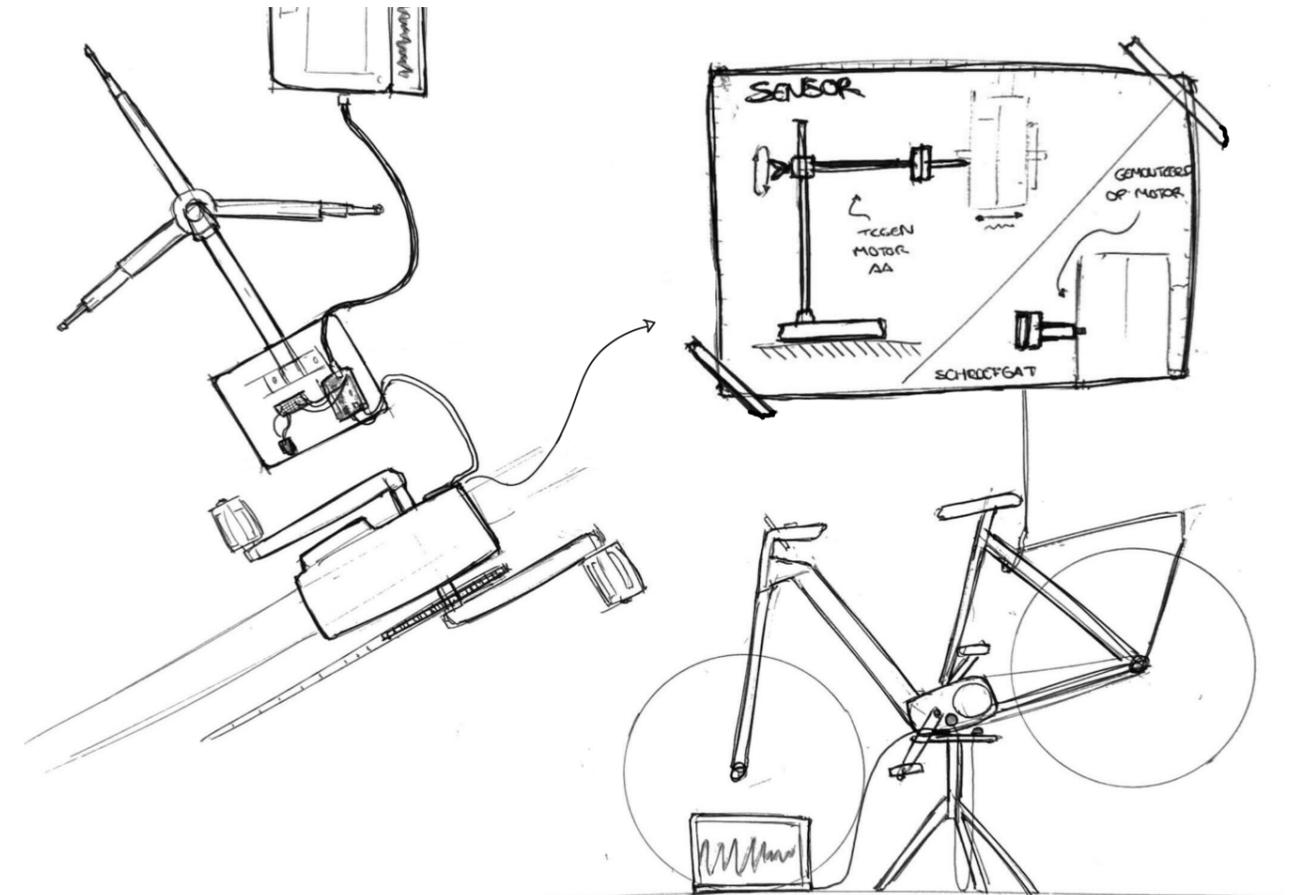


Figure 8.8: A sketch from the first phase of concept development, showing the setup, required components, and two potential ways to mount the sensor.

### 8.4.2 SCOPE AND LIMITATIONS

The concept has a clear focus on technical diagnosis and also has several limitations.

- The measurement can be influenced by noise from other parts of the bike, such as the drivetrain or moving components. This requires further research, for example by isolating the motor during measurements and testing different measurement setups to compare results.
- Sensor placement probably affects the measurement outcome. Consistent measurement is therefore essential. The mounting method of the sensor needs to be defined, tested, and validated to ensure

reliable and repeatable results.

- Different motor types likely require different baseline data, which means that collecting and maintaining reference datasets is necessary.
- The tool does not directly address customer communication or the broader role of the mechanic in the system. These aspects were considered outside the scope of this concept. However, the diagnostic result provides a clear basis for both: it supports communication with the customer and signals when follow-up actions are required.



## 9.1 GOAL AND HYPOTHESIS

The goal of this prototyping and testing phase was to create a proof of principle for vibration-based condition monitoring of e-bike motors. The objective was not to develop a final product or a mechanic-ready tool, but to investigate whether vibration signals can be used to distinguish between healthy motors and motors with internal defects, such as worn bearings or damaged gears, without opening the motor.

By measuring and comparing vibration signals from well-functioning motors and motors with known defects, this study explores whether differences can be observed in both vibration frequency and amplitude. The underlying hypothesis of this experiment is therefore:

“Mechanical vibrations measured at the motor housing can be used to detect early bearing or gear damage in e-bike motors.”

## 9.2 TEST SETUP

The experimental setup was designed as a low-cost, exploratory prototype to investigate whether mechanical defects in e-bike motors can be detected through vibration-based

measurements. The focus of the setup was on relative comparison between different motor conditions rather than absolute calibrated measurements.

### 9.2.1 HARDWARE

To position the sensors that detect the vibration close to the motor without physically attaching them to the bicycle, a camera tripod was used. A small platform was mounted onto the tripod using two 3D-printed parts and a wooden rod. This platform served as a mounting surface for the electronics, particularly the microphone sensor (figure 9.1, number 1).

In addition to this tripod, a second, more stable stand was used to press the piezo sensor against the motor housing. This stand was part of professional measurement equipment and provided a stable and heavy base. Its rigidity was important to ensure consistent contact pressure between the piezo sensor and the motor during measurements (figure 9.1, number 2).

### 9.2.2 ELECTRONICS

The electronic setup consisted a microcontroller (figure 9.1, number 3) to which two vibration sensors were connected. The microcontroller sampled the analog sensor signals and

transmitted the data to a laptop for storage and analysis. Two different microcontrollers were used during the development and testing phase (table 9.1)

Table 9.1: The two microcontrollers used during development and testing of the prototype

Microcontroller	Explanation	Picture
Seeeduino Lotus	Was used for the initial prototype to explore sensor behaviour, signal quality, and achievable sample rates. With this microcontroller, a sampling rate of approximately 2400 samples per second was achieved. According to the Nyquist frequency, this allows frequency analysis up to approximately 1200 Hz. This platform was mainly used for early experimentation.	
Seeeduino XIAO	Was used for the actual tests. This board is more compact and offers higher performance, allowing a higher sampling rate. During testing, a sampling rate of approximately 4000 samples per second was achieved, enabling frequency analysis up to 2000 Hz.	

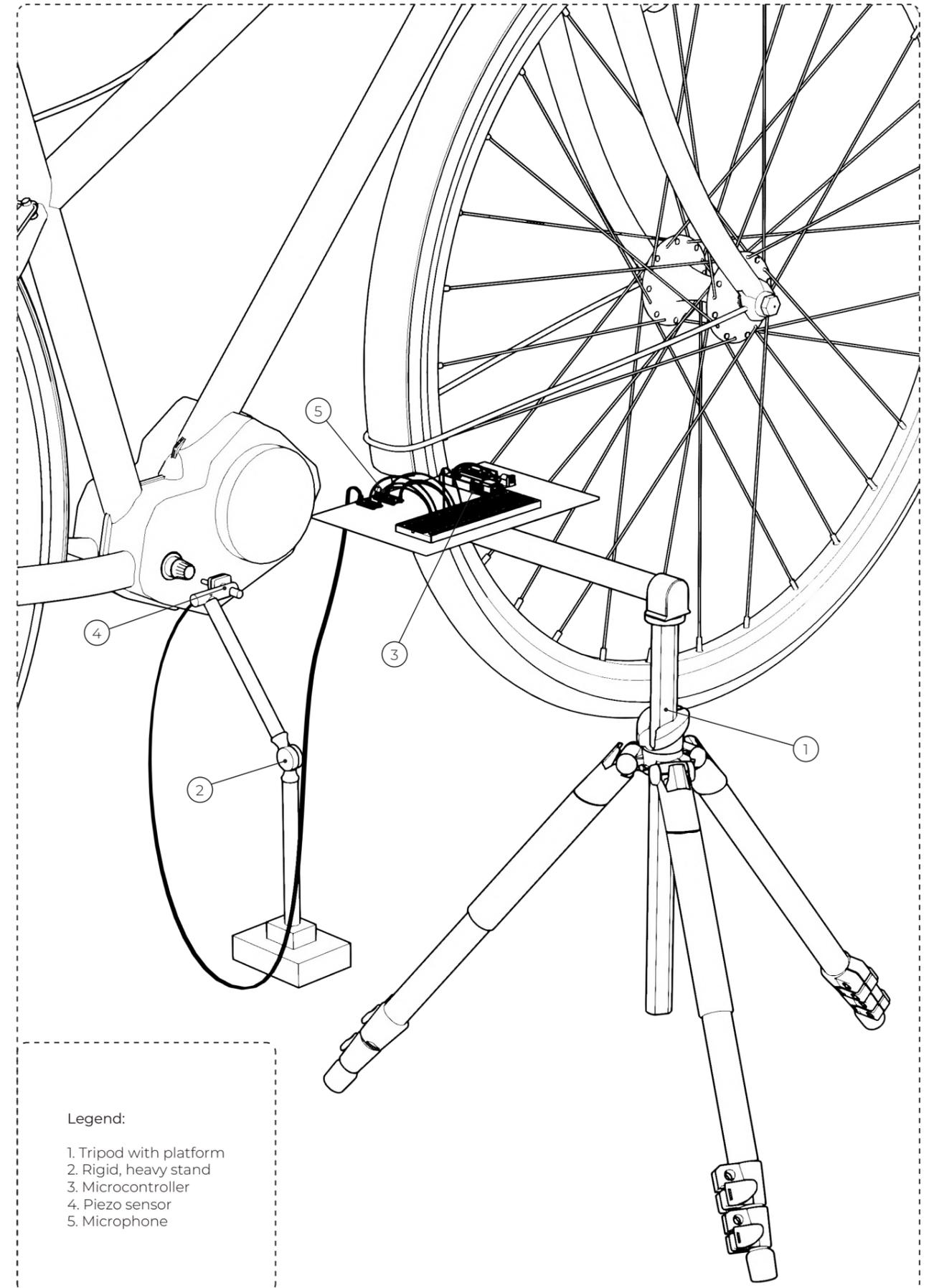


Figure 9.1: Overview of the test setup used during the first test round (Bosch BDU 3 motors)

As mentioned before, two different sensor types were used to capture vibrations during the experiments. The purpose of using multiple sensors was to compare their measured signals

and determine which sensor type was more suitable for detecting motor-related vibrations. Both sensors are described in table 9.2.

Table 9.2: The two sensors used during development and testing of the prototype

Sensor	Explanation	Picture
Piezo element	Detects mechanical vibrations by converting deformation of the piezoelectric element into an analog voltage signal.	
Microphone	Captures airborne sound emitted by the motor.	

The piezo sensor was placed in direct contact with the motor housing. Finding a suitable mounting method required some experimentation, because a piezo sensor only works when there is a "difference" in pressure (stable stand vs vibrating motor). Several test setups and mounting configurations were explored before a stable and reliable option was found. Figure 9.2 explains the result of this process. See appendix G for more information about the test setup.

sensor was pressed against the motor housing using a 3d printed 'finger'. This configuration provided a stable pressure difference.

The microphone was mounted on the platform attached to the camera tripod and positioned close to the motor, facing the housing (figure 9.1, number 5). However, preliminary measurements showed that the microphone was highly sensitive to environmental noise. This limited its usefulness for consistent defect detection. As a result, microphone data was excluded from further analysis and the focus shifted to the piezo-based vibration measurements.

In the final prototype, the piezo sensor was mounted on a rigid arm attached to a heavy stand positioned on the floor (figure 9.1, number 4). The

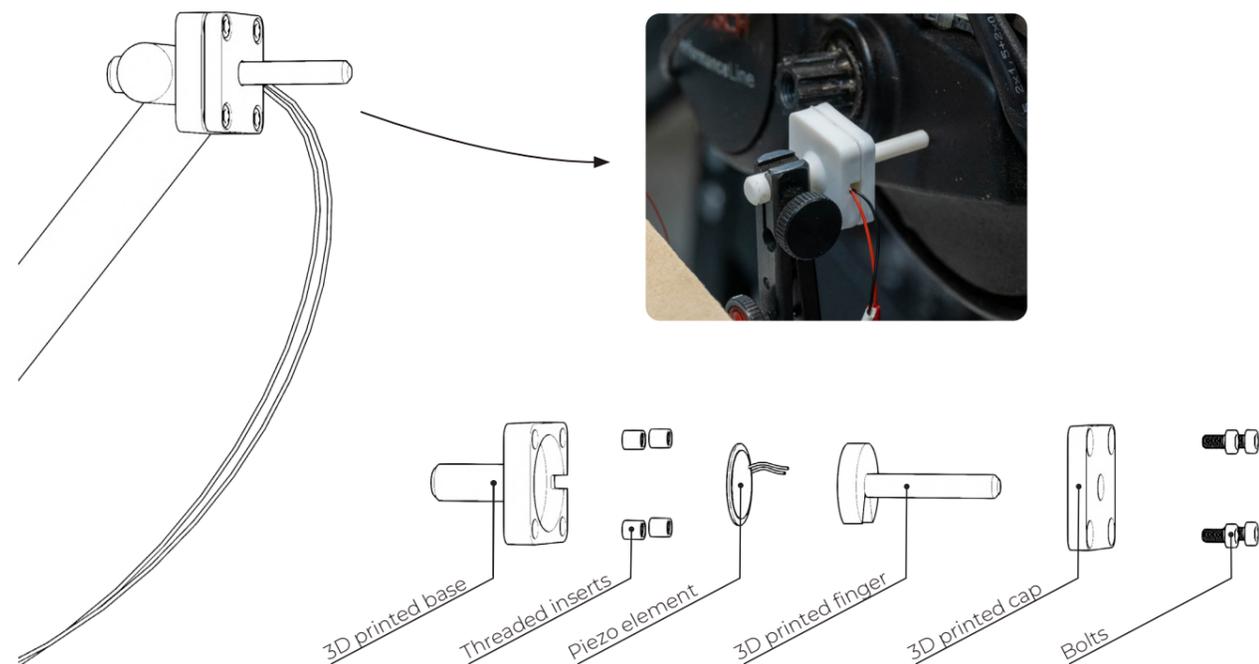


Figure 9.2: Mounting of the piezo sensor. The setup uses 3D-printed parts connected with screws and inserts, with a small 'finger' pressing the sensor against the motor housing.

### 9.2.3 TEST SUBJECTS

Tests were conducted on two different e-bike motor models. The selection of test subjects was primarily based on availability, as access to both healthy motors and motors with mechanical defects depended on collaboration with external partners. The following motor types were tested:

- Bosch BDU 350 (in collaboration with R2)
- Shimano DU-E5000 (in collaboration with R3)

For the Bosch motors, defects were tested in a controlled and isolated manner. With support

from R2, specific defective components were intentionally installed, allowing the exact nature of the defect to be known. For the Shimano motors, the exact internal defects were unknown prior to testing. Table 9.2 shows the motor configurations tested.

Including different motor brands allowed exploration of whether defect-related vibration patterns could be observed across different motor types.

Table 9.2: Overview of the motors used during testing; Shimano and Bosch motors in different conditions.

Motor	Mileage (km)	Scenario	Condition
Bosch motor 1	1500	B1	Good
Bosch motor 2	10000	B2	Good
		B3	All bearings damaged
		B4	Damaged left crankshaft bearing
		B5	Damaged right crankshaft bearing
		B6	Damaged rotor bearing
		B7	Damaged gear
Shimano motor 1	N/A	SH1	Good
Shimano motor 2	N/A	SH2	Motor with mechanical damage (exact problem is unknown)
Shimano motor 3	N/A	SH3	Motor with mechanical damage (exact problem is unknown)
Shimano motor 4	N/A	SH4	Motor with mechanical damage (exact problem is unknown)



Figure 9.3: Left: removing and installing defective components during the Bosch motor tests. Right: the Shimano motors lined up before testing (one of them had a software error and could not be used for the test).

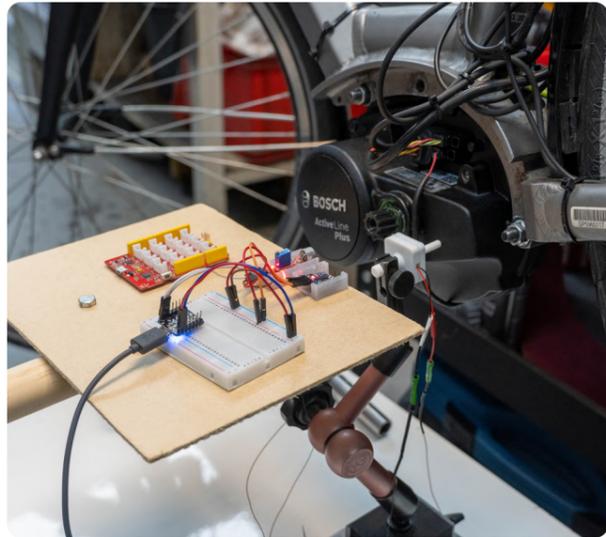


Figure 9.4: Photos taken during the first test session with the Bosch motors. Top left: sensor setup. Top right: clamp used to engage walk assist. Bottom: bicycle suspended in the air, with motor pressed against the piezo sensor.

### 9.2.4 ENVIRONMENT

During the test with the Bosch motors, the bicycle was suspended in the air so that the motor housing could be pressed directly against the piezo sensor without interference from the ground. With the Shimano motors, tests were conducted with the bicycle both placed on the ground and suspended in the air to explore whether this influenced the measurement results.

The chain was removed and all external motor components, such as covers and sprockets, were detached. This ensured that the motor was

mechanically isolated and that vibrations from the drivetrain were excluded.

The motor was activated using the walk assist function, which was continuously engaged using a clamp. This allowed the motor to rotate at a constant speed without human interaction. Testing was performed under no-load conditions to isolate internal motor vibrations. Although this does not fully represent real-world riding conditions, it enabled comparison between different motor types and configurations.

## 9.3 TEST PROCEDURE

Using the setup described before, vibration data was collected from the piezo sensor and microphone while the motor was running in walk assist mode. For each measurement, data was recorded for a duration of 10 seconds. This duration was chosen as a balance between sufficient frequency resolution for vibration analysis and practical measurement time during testing. Data collection was initiated from the laptop using a button implemented in the Python script.

During each test session, this Python script was used to visualise the incoming sensor signal in real time and to store the raw data as a CSV file. Each measurement was labelled and stored to allow structured post-processing. As mentioned before, data was collected for multiple defect scenarios, with each scenario measured twice to improve reliability. All measurements were performed using the same sensor placement, sampling settings, and measurement duration to ensure comparability between tests.

## 9.4 DATA PROCESSING

Custom code was developed to collect, store, and analyse the vibration data (as described in figure 9.5). The complete scripts can be found in appendix H. The data processing software consisted of three main components:

### Arduino code

The microcontroller ran a simple program that continuously sampled the analog signals from the piezo sensor and microphone. These values were streamed to the laptop.

### Python script for data collection and visualisation

A Python script was used to receive the serial

data from the microcontroller, visualise the signal in real time in an oscilloscope-like interface (which allowed inspection of the signal quality and comparison of vibration amplitudes during testing), and store selected time windows as CSV files.

### Python script for data analysis

A separate Python script was used to analyse the recorded CSV files. This script performed frequency-domain analysis using FFT and calculated amplitude- and energy-based metrics. The results of this analysis were saved in Excel to enable comparison between motor conditions.

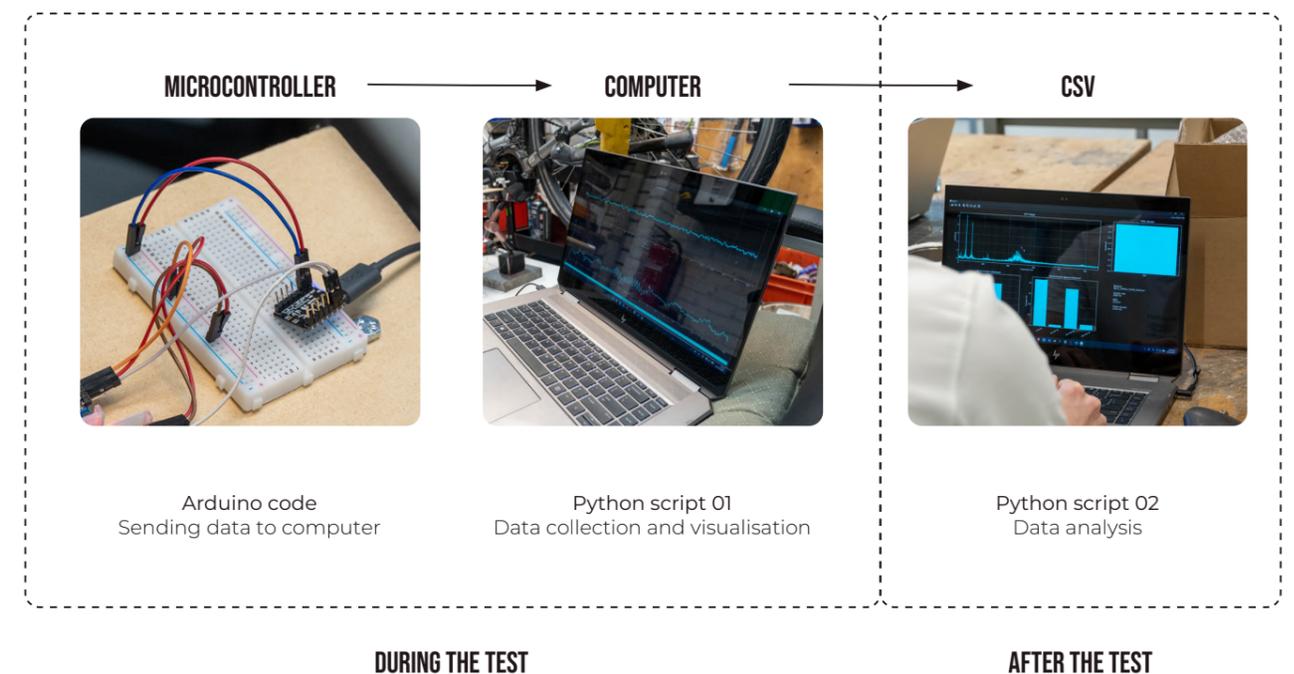


Figure 9.5: Overview of the data processing workflow: sensor signals are collected by the microcontroller, transmitted to the computer, and stored as CSV files for analysis.

The analysis script requires additional explanation, as it implements several vibration analysis methods discussed in section 8.3. These methods were applied to the measured vibration data to enable comparison between different motor conditions.

### Root Mean Square (RMS)

The overall vibration level is quantified using the RMS value. This provides a single value that describes how strongly the motor is vibrating. The RMS value is calculated as:

$$RMS = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} x_{dc}^2[n]}$$

Where:

$N$  is the total number of samples in the measurement

$x_{dc}[n]$  is the DC corrected vibration signal (offsets removed, signal centered around zero) at sample  $n$ .

This results in a single scalar value that allows comparison of vibration intensity between measurements.

### Frequency analysis using FFT

To analyse the frequency content of the vibration signal, a Fast Fourier Transform (FFT) is applied. The FFT converts the signal from the time domain to the frequency domain, making it possible to identify which vibration frequencies are present and how strong they are. The Fast Fourier Transform formula is defined as:

$$X[k] = \sum_{n=0}^{N-1} x_{dc}[n] e^{-\frac{2j2\pi kn}{N}}$$

Where:

$X[k]$  is the frequency-domain representation at frequency index  $k$

$x_{dc}[n]$  is the vibration signal in the time domain

$N$  is the total number of samples

The FFT output  $X[k]$  is complex and contains both amplitude and phase information. For the purpose of condition monitoring, only the magnitude of the vibration at each frequency is relevant. Therefore, the amplitude spectrum was calculated as:

$$A[k] = |X[k]|$$

This amplitude spectrum shows how strongly the motor vibrates at each frequency. During the test, defects such as damaged bearings or gears are expected to result in increased vibration amplitudes at specific frequencies or frequency ranges.

### Energy per frequency band

In addition to analysing individual frequencies, the energy content of the signal was analysed over broader frequency bands. This approach is commonly used in vibration-based fault detection, as mechanical defects often increase vibration energy across a range of frequencies rather than at a single discrete frequency (Randall, 2010).

The frequency spectrum was divided into the following bands (based on the frequencies present during initial tests):

- 0-80 Hz
- 80-160 Hz
- 160-300 Hz
- 300-550 Hz
- 550-2000 Hz

These bands were defined after the initial tests showed that most of the vibration energy was concentrated below 500 Hz. For each frequency band, the band energy was calculated as the sum of the squared amplitudes within that band:

$$E_b = \sum_{k \in b} A[k]^2$$

Where:

$A[k]$  is the amplitude at frequency index  $k$

$b$  is the selected frequency band

To allow comparison between measurements with different absolute vibration levels, the band energies were normalised by the total energy:

$$E_{b, norm} = \frac{E_b}{\sum A[k]^2}$$

This normalisation results in a relative energy distribution across frequency bands, expressed as a percentage of the total vibration energy.

The formulas described above explain the basic mathematical principles used in this analysis (Randall, 2010). Vibration analysis can be performed in more detail using advanced signal processing techniques, but this level of analysis is sufficient for the purpose of this test.

The Python script applies these principles using functions based on the presented formulas. It reads the data from CSV files and performs the RMS, FFT, and band-energy calculations. The results are shown in a dashboard for each measurement. The calculated values are also saved in Excel files, allowing comparison between measurements.

## 9.5 RESULTS

This section presents the results of the vibration measurements. The aim is to check whether differences between healthy motors and motors with defects can be observed using vibration data.

For each measurement, as mentioned in section 9.4, a dashboard was created showing the RMS value, frequency spectrum, and (relative) energy distribution over frequency bands. These dashboards are included in appendix I. To make comparison between motor conditions easier, the main results were collected in table 9.3. This

table contains the RMS values and the normalised energy per frequency band for each test.

The results are discussed in three steps. First, the RMS values are compared to look at differences in overall vibration level. Second, the distribution of vibration energy across frequency bands is analysed to see whether defects affect specific frequency ranges. Finally, additional observations from the test are described. These observations might not be visible in the table or dashboard, but they provide extra insight into certain defect types.

Table 9.3: Test results, showing the average RMS value, the percentage deviation relative to the average RMS of healthy motors measured in the same orientation (RMS (%) = deviation from baseline), and the average energy per frequency band.

Motor	Scenario	Condition	Bicycle orientation	RMS (mean)	RMS (%)	Average energy per frequency band			
						0-80 Hz (%)	80-160 Hz (%)	160-300 Hz (%)	300-550 Hz (%)
Bosch motor 1	B1	Good	Hanging	21.13	-	40	3	41	5
	B2	Good	Hanging	33.65	-	12.5	5	80	1.5
Bosch motor 2	B3	All bearings damaged	Hanging	108.44	296	9	28.5	57.5	4
	B4	Damaged left crankshaft bearing	Hanging	46.25	69	21	21.5	55.5	1
	B5	Damaged right crankshaft bearing	Hanging	51.56	88	20.5	17.5	59.5	1.5
	B6	Damaged rotor bearing	Hanging	19.79	-28	36.5	10.5	35	9
	B7	Damaged gear	Hanging	64.98	137	6.5	19	69.5	4
Shimano motor 1	SH1	Good	Standing	3.85	-	22.5	4	6	10
			Hanging	4.25	-	34.25	3.5	4.25	7.75
Shimano motor 2	SH2	Motor with mechanical damage (exact problem is unknown)	Standing	6.91	79	16	3	15.25	4.5
			Hanging	6.95	63	18.5	2	33	7.75
Shimano motor 3	SH3	Motor with mechanical damage (exact problem is unknown)	Standing	11.69	204	20	4	49.5	5
			Hanging	6.62	56	29.5	3	36	6
Shimano motor 4	SH4	Motor with mechanical damage (exact problem is unknown)	Standing	5.25	36	26.5	5	6.5	6
			Hanging	4.74	11	23.5	3	15	8.5

### 9.5.1 RMS COMPARISON

As described in Section 8.3.3, the RMS value represents the overall vibration level of the motor. A higher RMS value means that more vibration energy is present over time. In this section, the RMS values of healthy and defective motors are compared (figure 9.6) to see whether defects lead to an increase in vibration level.

#### Bosch motors

For the Bosch motors, a clear difference can be observed between healthy motors and motors with defects. The healthy motors show relatively low RMS values compared to most defective configurations. Motors with damaged bearings or gears generally show higher RMS values than the healthy reference motors. In addition, a clear trend can be seen: the motor with multiple defective components has higher RMS values than motors with only a single damaged part. One exception is the motor with a damaged rotor bearing. This motor shows a lower RMS

value than the other defective configurations and even lower than both healthy motors. The exact reason for this behaviour is currently unknown and should be investigated in future research.

#### Shimano motors

For the Shimano motors, the RMS values of all defective motors are higher than the RMS value of the healthy motor. Overall, the RMS values measured for the Shimano motors are much lower than those measured for the Bosch motors. This applies to both healthy and defective motor conditions.

For the Shimano motors, measurements were performed with the bicycle standing on the ground and suspended in the air. The RMS values differ between these two setups. However, the difference between healthy and defective motors remains visible in both cases.

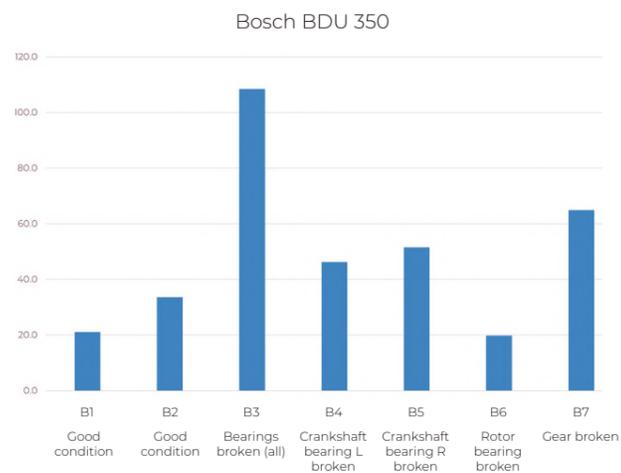


Figure 9.6: Average RMS values calculated from two measurements per test scenario. The left graph shows the results for the Bosch motors. The right graph shows the results for the Shimano motors, measured with the bicycle both standing on the ground and suspended in the air.

### 9.5.2 FREQUENCY BAND DISTRIBUTION

To analyse how vibration energy is distributed across different frequency ranges, the frequency spectrum was divided into four bands: 0–80 Hz, 80–160 Hz, 160–300 Hz, 300–550 Hz, and 550–2000 Hz. The energy in each band was normalised, allowing relative comparison between different motor conditions (figure 9.7).

#### Bosch motors

For the healthy Bosch motors, a clear difference in energy distribution is visible between the two tested motors. In one motor (B2), most of the energy is concentrated in the 160–300 Hz band (80%). In the other motor (B1), most of the

energy is evenly divided between the 0–80 Hz and 160–300 Hz bands (40%; 41%). Note that in both healthy motors, only a small percentage of energy is present in the 80–160 Hz and 300–550 Hz bands. For the defective Bosch motors, the energy distribution differs between defect types. One thing that stands out is the increase in relative energy in the 80–160 Hz frequency band for all defective motors compared to the healthy motors. Each defect type also shows a slightly different distribution across the frequency bands. However, the motors with damaged crankshaft bearings (left and right side) show very similar energy distributions.

#### Shimano motors

For the Shimano motors, not all vibration energy is captured within the first four frequency bands. Compared to the Bosch motors, the total vibration energy is much lower, which means that energy outside the first four bands (containing little energy) represents a relatively larger portion of the signal. The healthy Shimano motor shows most of its energy in the lowest frequency band (0–80 Hz). For the defective Shimano motors,

an increase in energy in the 160–300 Hz band is visible in two out of the three cases.

When comparing the standing and hanging measurement setups, small differences in energy distribution are visible. The overall patterns remain similar. The largest difference between the two setups appears in the 160–300 Hz frequency band.



Figure 9.7: Frequency band distribution for the different test scenarios. The left graph shows the Bosch motors. The right graph shows the four Shimano motors measured in two different bicycle orientations. Note that for the Shimano motors, a larger percentage of the vibration energy lies outside the defined frequency bands.

### 9.5.3 ADDITIONAL FINDINGS

In addition to the RMS values and frequency band distributions, some patterns were observed directly in the time-domain signals (figure 9.8). For the Bosch motor with a gear defect, sudden large peaks were visible in the vibration amplitude over time. These peaks appeared at regular intervals and were related to the rotation

of the crankshaft. This behaviour was only visible in the time-domain signal plotted directly from the CSV data. These peaks are not clearly visible in the RMS and frequency-domain dashboard or in the summary table. This means that this behaviour would not have been identified using RMS values or frequency band energy alone.

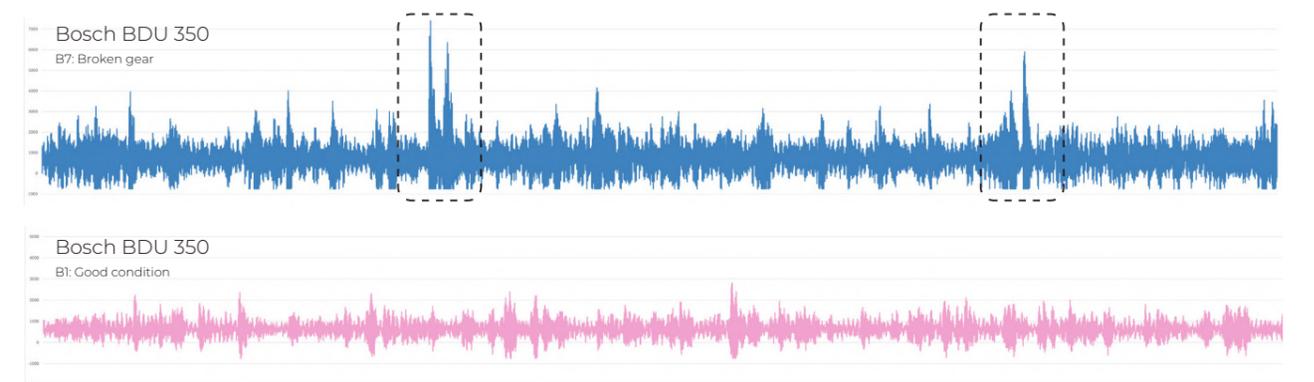


Figure 9.8: Comparison of time-domain vibration signals of a motor with a damaged gear (B7) and a healthy motor (B2), shown on the same amplitude scale. Periodic peaks (every 4 seconds, corresponding with crankshaft RPM; 1 rotation every 4 seconds) are visible in the defective motor, which are not captured by RMS or frequency band analysis.

## 9.6 CONCLUSION

This chapter evaluated whether vibration measurements at the motor housing can distinguish between healthy e-bike motors and

### 9.6.1 INTERPRETATION OF THE RESULTS

The results show that vibration measurements can reveal differences between healthy and defective e-bike motors within this test setup. In most cases, defective motors produce higher RMS values, indicating that RMS is a useful first indicator of motor condition.

Frequency band analysis can provide more detail about the nature of the failure. For the Bosch motors, defects often caused a shift of vibration energy to higher frequency bands, particularly 80–160 Hz. Different defects show distinct energy distributions, suggesting frequency-based features can help distinguish motor conditions. For Shimano motors, differences are smaller, and exact defect types are unknown, so interpretation is limited.

Overall, these tests demonstrate that measurable differences exist and that vibration analysis can be used to detect defects (proof of principle). However, the results do not yet show which

### 9.6.2 LIMITATIONS

Several limitations should be considered when interpreting these results:

- Only two motor models were tested.
- Defects in Shimano motors were not precisely known, limiting conclusions.
- Each condition was measured only twice, and Bosch and Shimano tests were performed at different times, with slightly different setups, possibly introducing variability.
- Only a single measurement point on the motor was used, missing local variations.
- Environmental factors, such as temperature

motors with internal defects. The analysis focused on relative differences between motor conditions rather than absolute diagnostic thresholds.

exact patterns can be used to reliably distinguish between specific defect types or to identify which internal components are failing. Further research is required to achieve this level of diagnostic certainty.

Time-domain analysis revealed defect-specific patterns, such as periodic peaks from the Bosch gear defect, that were not captured in RMS or frequency-band summaries. This shows that analysing the raw time-amplitude signal is an important addition to RMS and frequency-domain analysis.

The measurement setup (bicycle standing on the ground versus suspended in the air) affects absolute RMS and band values. However, relative differences between healthy and defective motors remain visible, showing that consistent measurement conditions are important. Both setups can be used, but standardization is necessary

- and background vibrations, were not controlled.
- Sensors and electronics have noise and sensitivity/sample limits, affecting absolute RMS and frequency values (max. 2000 Hz).
  - The applied vibration analysis methods were basic and exploratory and could be expanded and improved in future studies.

Despite these limitations, the tests provide valuable insights and support further development of the concept.

### 9.6.3 IMPLICATIONS FOR THE DESIGN

The results demonstrate that the concept is technically feasible: vibration measurements can distinguish healthy from defective e-bike motors.

For future development, several aspects should be addressed:

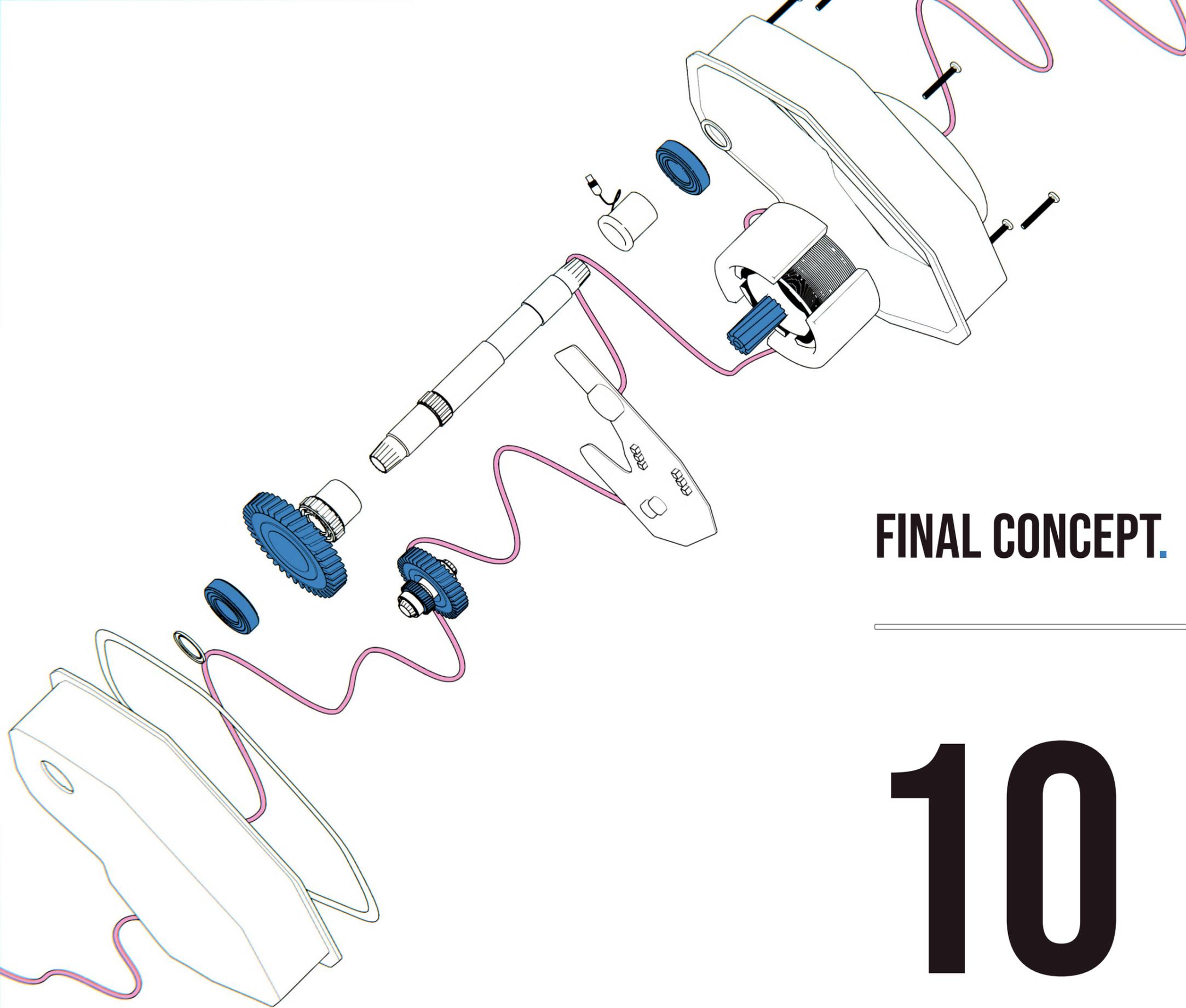
- Further research is required to identify characteristic vibration patterns that allow specific defects to be identified reliably.
- The vibration analysis methods should be expanded beyond the basic exploratory approach used in this study.
- Unexplained results, such as the lower RMS value observed for the motor with a damaged rotor bearing, should be investigated in more detail.
- Multiple measurement points and repeated measurements would increase confidence in the results.

Conversations with R2 during the tests suggested potential applications beyond supporting bike mechanics. At refurbishment companies, vibration analysis could be used as an additional diagnostic step to objectively assess whether a motor is repairable before disassembly. In addition, vibration measurements could serve as a quality control tool, allowing refurbished motors to be checked before being returned to customers.

Overall, this phase provided a proof-of-principle that vibration-based condition monitoring of e-bike motors is technically feasible. At the same time, the results and limitations highlight that development and validation are still needed before the method can be applied as a diagnostic tool.



Figure 9.9: A photo taken during the test with Bosch motors in collaboration with R2



## FINAL CONCEPT.



# 10

This chapter presents the final concept developed in this project. First, the concept is explained in detail, including its purpose, technical setup, and intended use. Next, the concept is validated on feasibility, viability, and desirability. Finally, the chapter discusses the outcomes of this validation, reflects on limitations, and outlines directions for further development of the concept.

- 10.1 Concept overview
- 10.2 Validation
- 10.3 Concept discussion

## 10.1 CONCEPT OVERVIEW

This section presents the proposed concept for a non-invasive diagnostic tool for e-bike motors. The concept is explained through its problem-solution fit, user and context, technical setup,

measurement procedure, output and decision making, and finally a possible business model. Figure 10.1 shows an overview of the proposed concept in context.

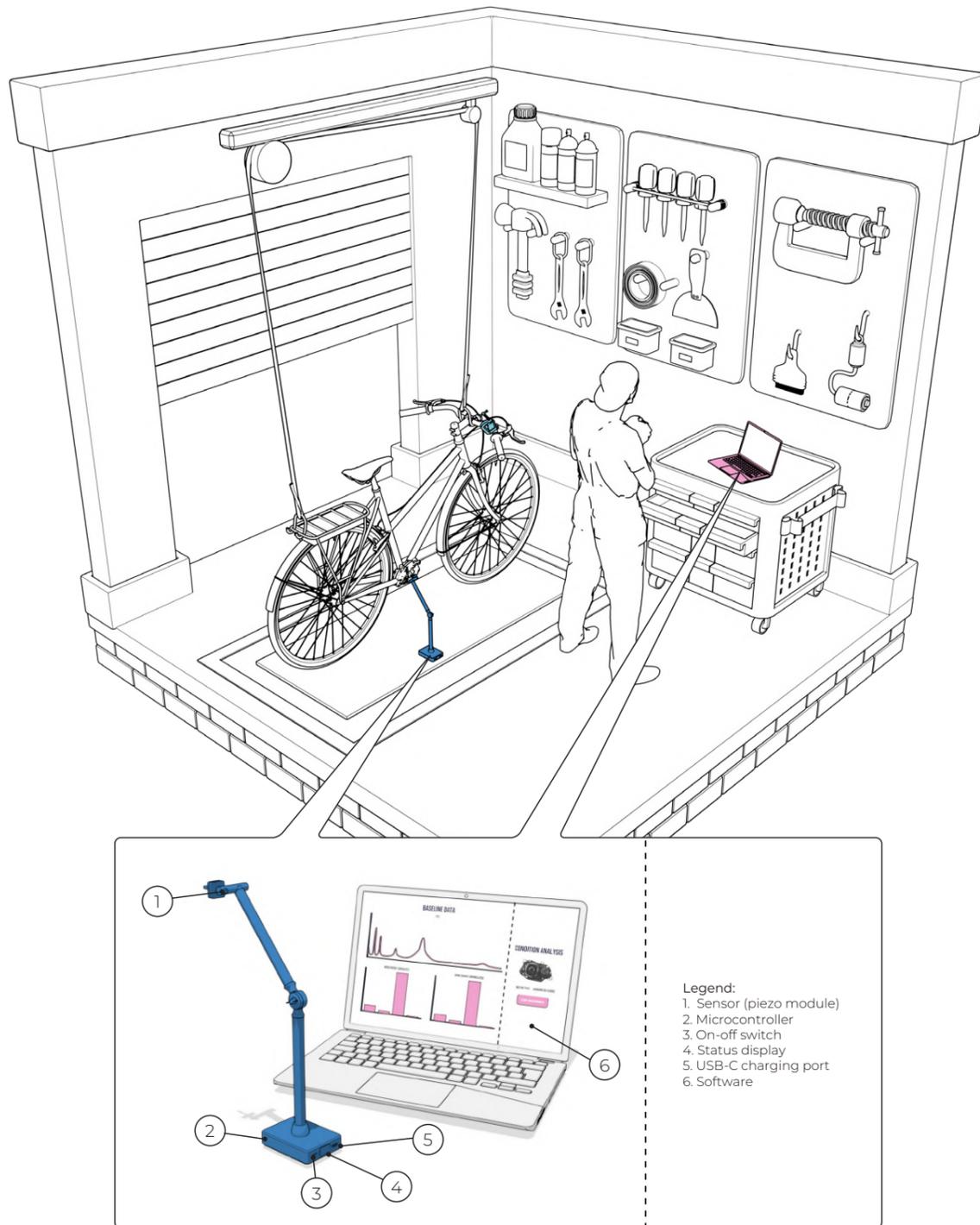


Figure 10.1: Overview of the proposed concept in context. The sensor is wirelessly connected to the computer, from which the bike mechanic can start measurements and perform analyses.

### 10.1.1 PROBLEM AND SOLUTION

Mechanical wear in e-bike motors is difficult to identify without opening the motor. In practice, bike mechanics often lack the specialist knowledge and experience that revision companies have when it comes to recognizing internal mechanical defects. Current diagnosis at bike shops is mainly based on manufacturer software, while mechanical diagnosis at revision companies is largely subjective and based on sound, feel, and experience.

At the same time, the bike mechanic is usually the first point of contact for customers experiencing

### 10.1.2 USER AND CONTEXT

The user of the tool is the bike mechanic. The tool is used during a regular service appointment, with the motor still mounted in the bicycle. Parts such as the chain, sprockets, and covers are removed, while the motor remains in the frame. The bicycle is suspended in the air, as is common during normal workshop service.

The bike mechanic plays an important role as the first contact point for the user when motor problems occur. Research in Chapter 5 shows

### 10.1.3 TECHNICAL SETUP

The concept consists of a vibration-based measurement system that is used to assess the mechanical condition of an e-bike motor. The system is composed of three main elements: a sensor, a microcontroller, and computer software supported by a database.

#### Sensor

The vibration sensor is based on a piezoelectric element and is mounted on a solid mechanical arm with a heavy base. During the measurement, the hanging bicycle is positioned so that the motor housing rests against the sensor setup. The sensor has a 'finger' that makes direct contact with the motor housing. The exact contact location is motor-specific and is defined in the measurement procedure provided by the software. Consistent sensor placement is essential to ensure that measurements can be compared reliably between motors of the same type.

When the motor is running (using the walk-assist function), vibrations from the motor housing are transferred through the finger onto the piezoelectric element. The combination of the stable base and the vibrating motor creates a varying pressure on the piezo element. This

motor problems. As a result, motors are often discarded unnecessarily or sent for revision too late, when damage has already progressed.

The proposed concept offers an objective diagnosis method based on vibration analysis. The tool translates vibration signals into a clear analysis and recommendation for next steps. This allows bike mechanics to provide well-founded advice to customers and make better-informed decisions about maintenance, revision, or replacement.

that this role is becoming more important, especially when it comes to diagnosing motor problems and deciding on follow-up actions. For this reason, correct diagnosis is essential.

The value of this concept lies in making mechanical diagnosis more objective and repeatable. It brings knowledge from revision companies into the workshop and helps bike mechanics decide what the next step should be when motor-related problems are found.

pressure change is converted by the piezoelectric material into a voltage signal, which represents the vibration behaviour of the motor.

#### Microcontroller

The microcontroller reads the analog signal from the sensor. When the user starts a measurement via the computer software, the microcontroller records vibration data for a predefined duration (10-20 seconds). The data is stored locally on the device and, after the measurement is completed, transmitted as a complete CSV file to the computer via Bluetooth. This approach supports stable data transfer and allows higher sampling rates during the measurement in comparison to the test.

#### Software and database

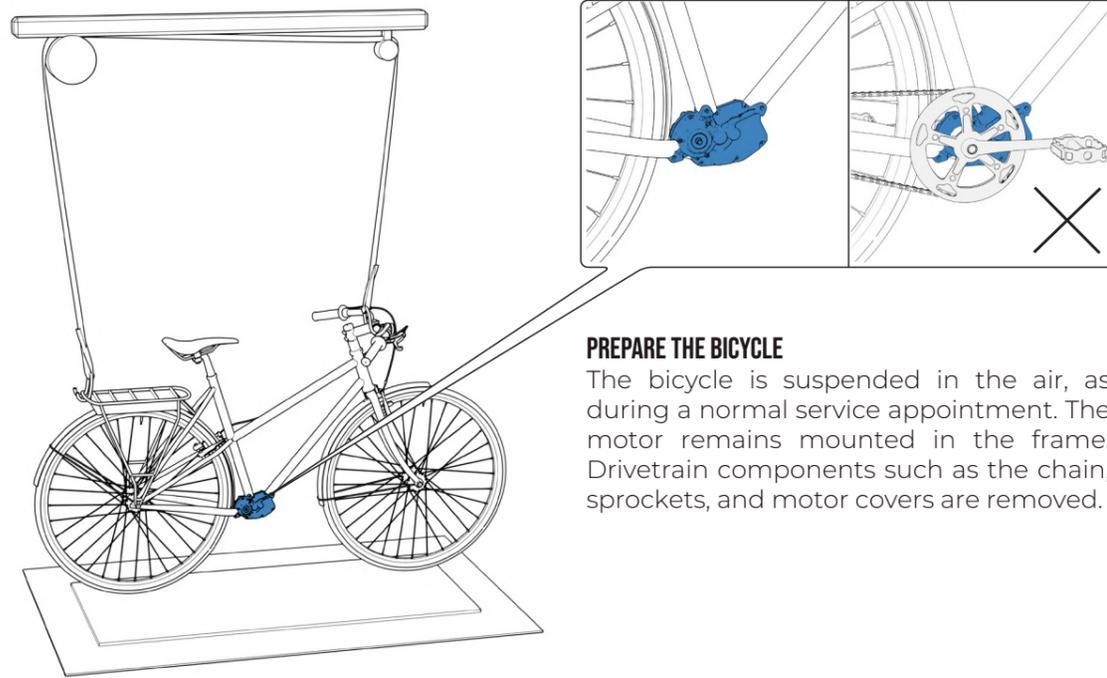
The computer software receives and stores the measurement data and performs the vibration analysis. This includes time-amplitude analysis, RMS calculation, frequency analysis using FFT, and energy calculation per frequency band. The results are compared with baseline measurements from healthy motors. Based on this comparison, the software generates a report and provides a recommendation for possible follow-up actions.

### 10.1.4 MEASUREMENT PROCEDURE

To ensure reliable and comparable results, measurements must always be performed in a consistent way. For this reason, the computer software includes a predefined measurement procedure for each motor type. Each procedure

is supported by clear visual instructions, such as drawings or diagrams, showing the correct setup and sensor placement. Although the exact details differ per motor type, the general procedure follows the steps below:

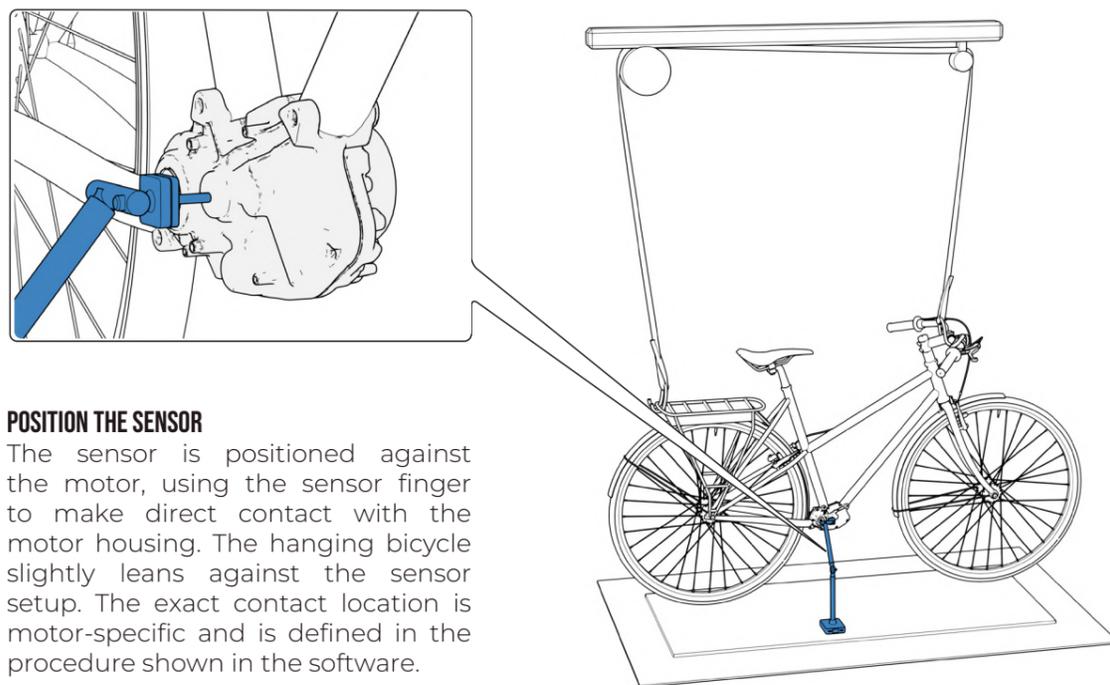
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#### PREPARE THE BICYCLE

The bicycle is suspended in the air, as during a normal service appointment. The motor remains mounted in the frame. Drivetrain components such as the chain, sprockets, and motor covers are removed.

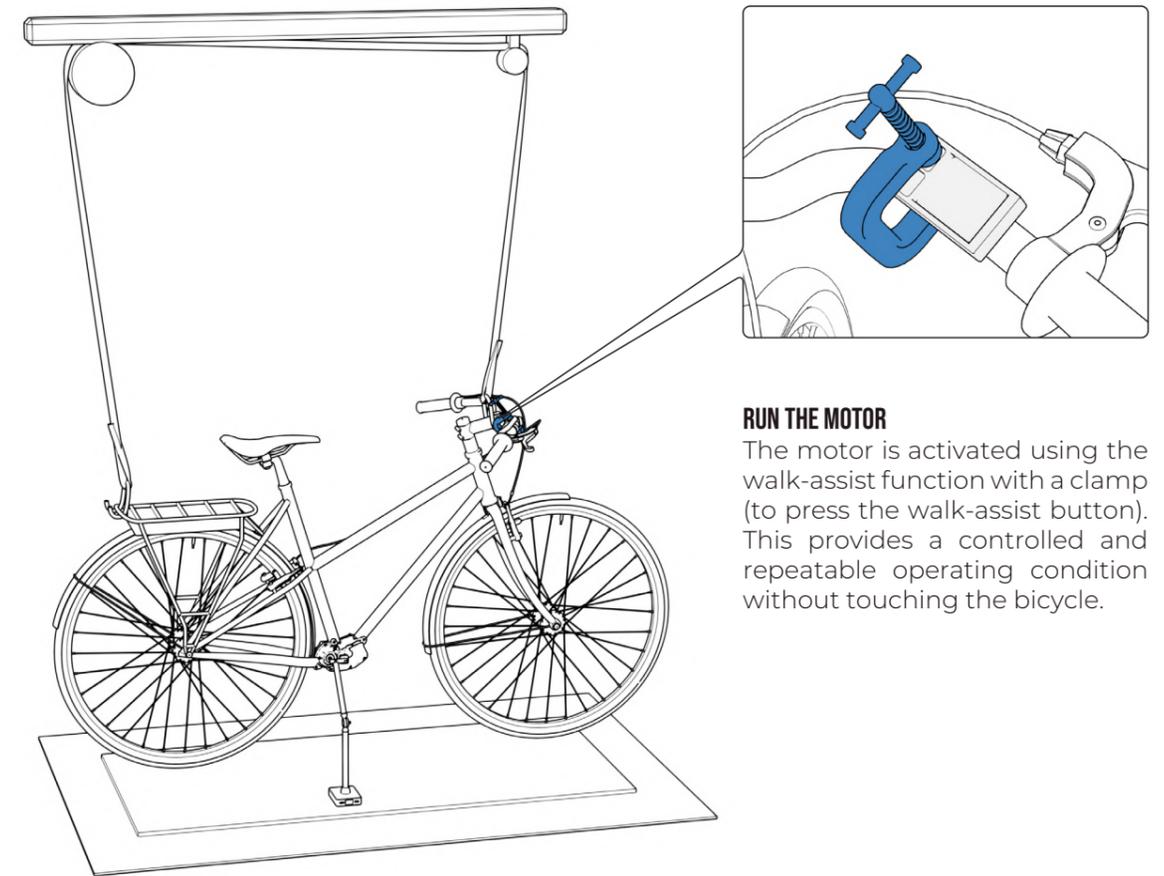
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#### POSITION THE SENSOR

The sensor is positioned against the motor, using the sensor finger to make direct contact with the motor housing. The hanging bicycle slightly leans against the sensor setup. The exact contact location is motor-specific and is defined in the procedure shown in the software.

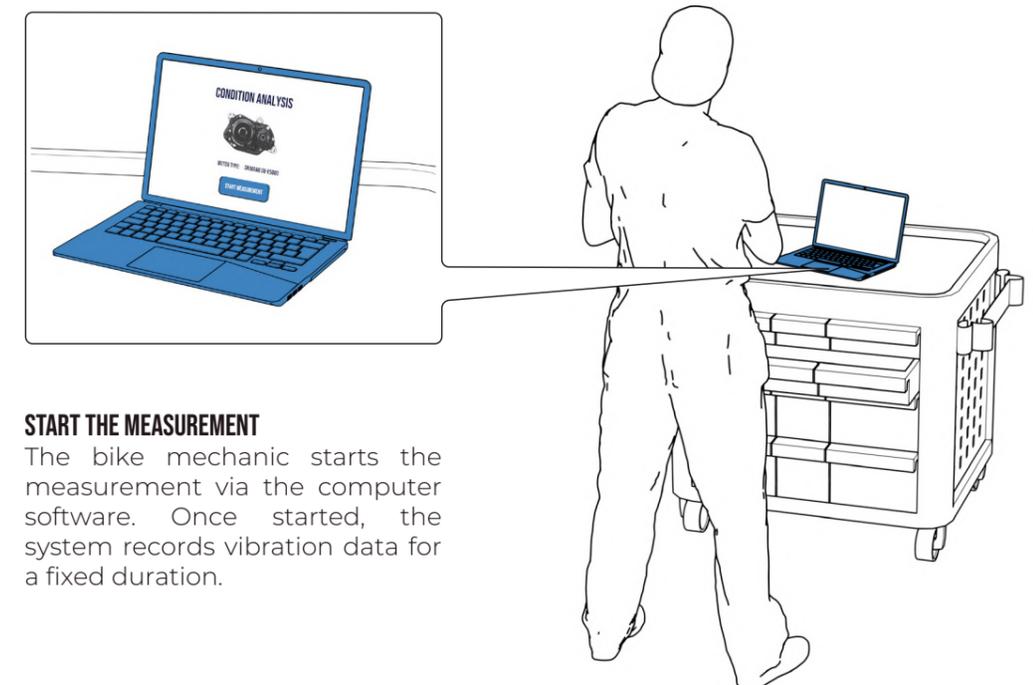
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#### RUN THE MOTOR

The motor is activated using the walk-assist function with a clamp (to press the walk-assist button). This provides a controlled and repeatable operating condition without touching the bicycle.

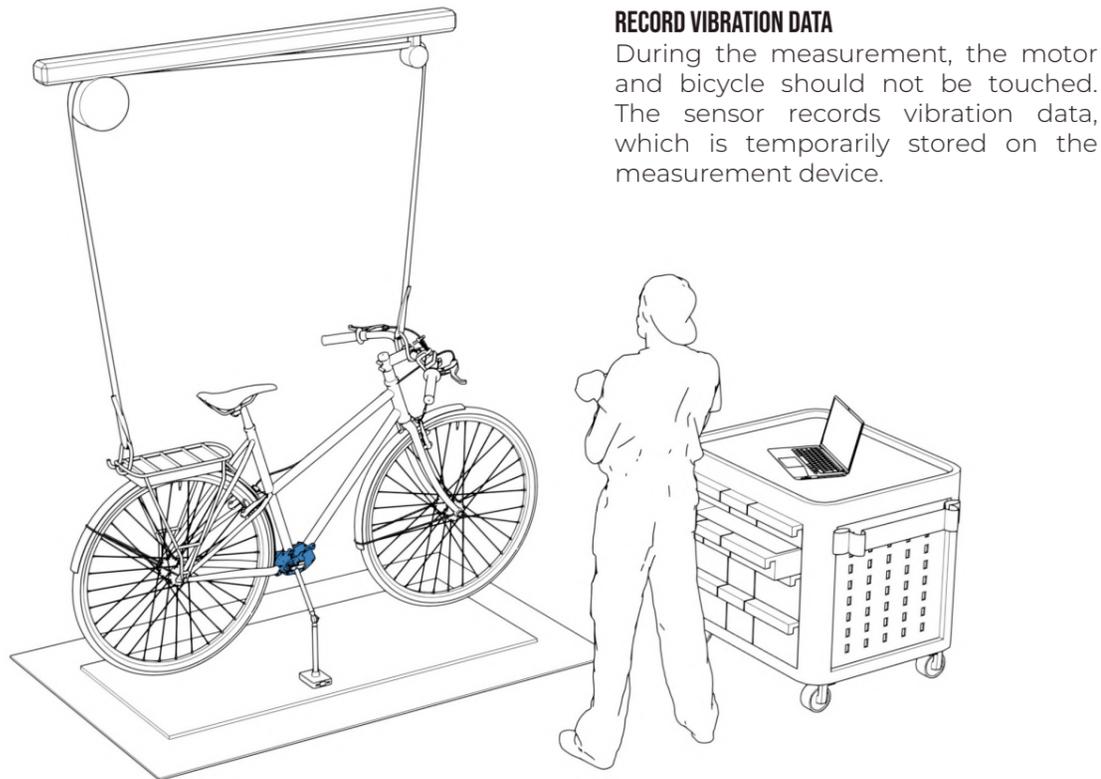
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#### START THE MEASUREMENT

The bike mechanic starts the measurement via the computer software. Once started, the system records vibration data for a fixed duration.

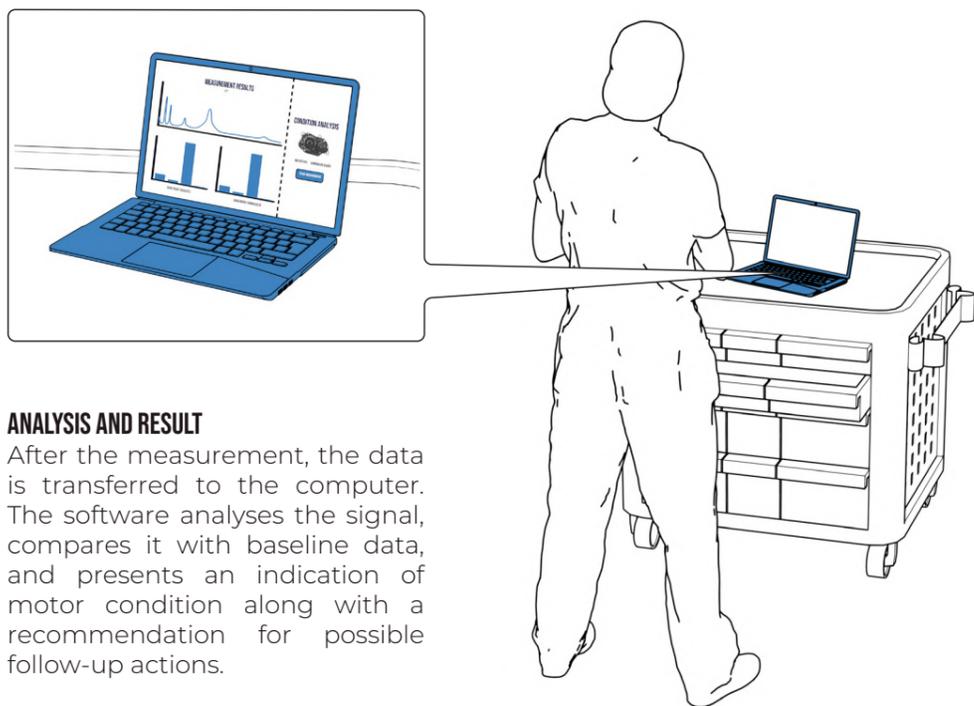
5



**RECORD VIBRATION DATA**

During the measurement, the motor and bicycle should not be touched. The sensor records vibration data, which is temporarily stored on the measurement device.

6



**ANALYSIS AND RESULT**

After the measurement, the data is transferred to the computer. The software analyses the signal, compares it with baseline data, and presents an indication of motor condition along with a recommendation for possible follow-up actions.

The goal is to keep the procedure as short and simple as possible, so it fits easily into the bike mechanic's regular service workflow. A quick and clear process increases the chance that

mechanics will actually use the tool. At this stage, the procedure is estimated to take about fifteen minutes. Further testing is needed to confirm the exact duration in practice.

**10.1.5 OUTPUT AND DECISION MAKING**

The output of the system consists of measured values, deviations from baseline data, and an interpretation of potential mechanical wear. The tool provides an advisory outcome rather than a

definitive decision. The bike mechanic remains fully responsible for communication with the customer and for deciding on the appropriate follow-up action.

**10.1.6 BUSINESS MODEL**

The diagnostic tool is intended to support bike mechanics in identifying problems in e-bike motors. However, since bike mechanics do not directly generate revenue from the diagnosis itself, it is important to carefully consider how the product is sold and maintained. Although this project primarily focuses on the technical feasibility of the concept, a possible business model is outlined below.

**Razor and blade**

The concept consists of a combination of hardware (the sensor) and software (the analysis and database). To make this viable, a 'Razor and Blade' revenue model is proposed:

- The Razor (hardware): The physical tool is sold for a one-time fee. This covers production and distribution costs.
- The Blade (software and baseline data): The true value lies in the database of 'healthy baselines'. To keep this database relevant, new motor types must be tested and added continuously. To fund this ongoing maintenance, the customer pays a recurring subscription fee to access the software.

user, the primary value is captured by the revision expert (either a revision company or a revision hub, see Chapter 5). They benefit from receiving a higher number of repairable motors and from receiving them earlier in the wear process.

Therefore, the proposed business strategy is that the revision expert acts as the paying customer. The expert purchases the tools and subscriptions and lends them to their partner mechanics (figure 10.2).

- For the mechanic: the barrier to entry is removed. They get a high-tech diagnostic tool for free (or a low deposit), enabling them to advise customers professionally and objectively.
- For the revision expert: the tool acts as a "service enabler." It ensures that mechanics send motors specifically to their hub. It increases the volume of incoming motors and improves the probability of the motor being actually repairable (early detection).

In this model, the tool is not just a measuring device, but the physical link in the partnership between the local mechanic and the revision expert.

**The hub as the customer**

As mentioned before, while the mechanic is the

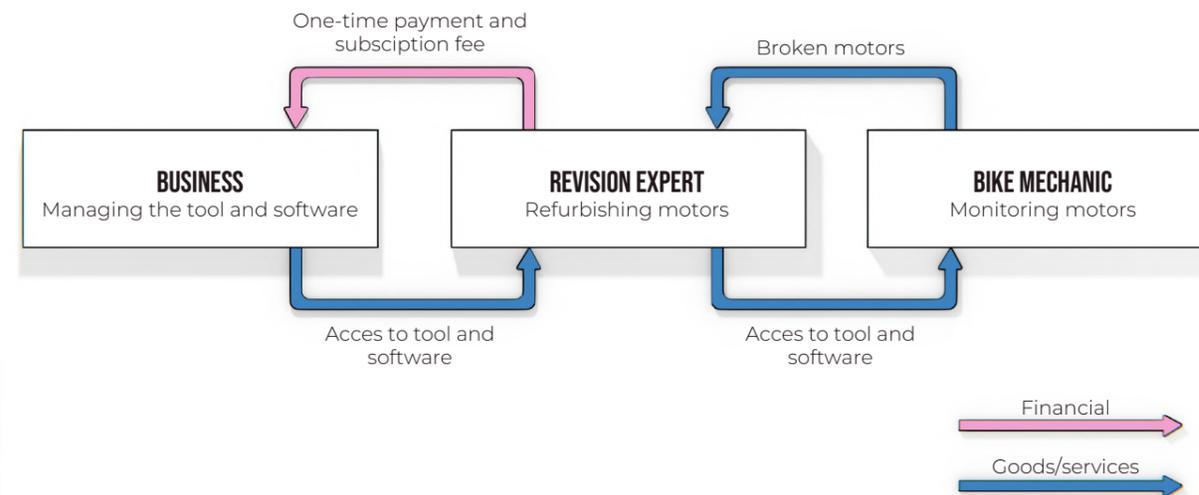


Figure 10.2: Value exchange map of the proposed business model. The revision expert pays for the diagnostic tool and software, enabling bike mechanics to use the system and supply a higher number of repairable motors to the revision expert.

## 10.2 VALIDATION

This section evaluates the proposed concept through validation. The concept is assessed from three perspectives: feasibility, viability, and desirability. Feasibility focuses on the technical

### 10.2.1 FEASIBILITY

To evaluate the technical feasibility of the proposed concept, a functional prototype was developed and tested. Using this prototype, vibration measurements were performed on both healthy and mechanically defective e-bike motors (figure 10.3). The goal of this feasibility study was to determine whether vibration analysis can be used as a non-invasive method to distinguish healthy motors from defective ones.

#### What did it prove?

The tests show that non-invasive vibration measurements are technically possible. Measurable differences between healthy and defective motors were observed using this approach. Even with a limited dataset and a simple measurement setup, relative comparison between motor conditions proved feasible.



viability of the concept, viability reflects on its economic potential, and desirability considers whether the concept provides sufficient value for its intended users and stakeholders.

#### What did it not prove?

At this stage, the system cannot reliably identify specific defect types or failure patterns and the dataset is too small to define absolute thresholds. In addition, the sensor choice and mechanical setup are not yet optimised for consistent and repeatable measurements. These aspects require further development and more extensive testing.

#### Conclusion

The feasibility of the concept has been demonstrated through a proof of principle. Vibration analysis shows potential as a non-invasive method to assess the mechanical condition of e-bike motors. However, further development is required to improve accuracy, standardisation, and reliability before the concept can be applied in practice.



Figure 10.3: Photos taken during measurements on Shimano motors with the bicycle in a suspended position (left: overview of the measurement setup, right: close-up of the sensor placed against the motor housing).

### 10.2.2 VIABILITY

This subsection briefly evaluates the economic viability of the proposed concept. Rather than presenting a full business case, it assesses whether the concept could realistically be developed into a product or service.

#### Economic logic of the business model

The proposed business model combines low-cost hardware with software and a database of baseline measurements, where most of the value is created. Because the software and database

require ongoing maintenance and updates, a subscription-based model is logical. Without access to the software and baseline data, the hardware has little value, which supports a “razor and blade” model (Dhebar, 2016).

A key challenge is that the main user of the tool, the bike mechanic, is not the party that gains the most (economic) value from it. Using the tool takes additional time during a service appointment and does not directly generate

revenue for the mechanic. The main benefit for the mechanic lies in improved diagnosis and better customer advice, which is valuable but difficult to translate into direct financial gain. The main value is created for revision companies or centralized revision hubs, which benefit from receiving more motors and earlier in the wear process. This mismatch between user and value beneficiary complicates adoption and reduces the viability of this specific business case.

#### Implementation and scalability

The hardware investment costs are relatively low; the prototype was built using standard components with an estimated electronics cost of around €15. This suggests that, especially at larger production scales, the hardware could be produced at relatively low cost. The main barrier lies in the development and maintenance of the software and the baseline database, which require significant upfront investment and time. The concept would therefore need to be introduced gradually, starting with the most

### 10.2.3 DESIRABILITY

This subsection evaluates the desirability of the proposed concept by presenting it to two experts: a revision specialist (R2) and a bike mechanic (M1). The goal of this evaluation was to understand how users and stakeholders perceive the concept, and to identify perceived strengths, weaknesses, and opportunities for improvement.

The concept was presented using a poster (see figure 10.4 and Appendix J). During the sessions, the poster was explained in detail, with a specific focus on the working principle of the concept and the measurement procedure for the bike mechanic. For both participants, a set of predefined questions was used to structure the conversation and gather feedback on usability, relevance, and perceived value.

#### Revision company (R2)

The revision expert responded positively to the concept. R2 indicated that they were impressed by the clarity of the explanation and the quality of the visuals. The use of clear diagrams and line drawings was specifically mentioned as a strong aspect. This suggests that the visual style could also be suitable for future applications, such as manuals or training materials.

However, R2 also identified several practical concerns. The use of a clamp to activate the walk-assist function was considered too improvised and not suitable for professional use. According to R2, this method introduces risks, such as potential damage to the display or control panel, and could lead to inconsistent operation. As an

common motor types and/or those most prone to mechanical issues.

#### Conclusion

At a conceptual level, the proposed business model shows potential economic viability. The combination of low-cost hardware, subscription-based software, and a clear value proposition for revision experts provides a realistic starting point. However, a key challenge remains that the primary user of the tool is not the party that benefits most from it. This makes implementation and adoption more difficult.

At this stage, the business case is therefore not strong enough to conclude that the concept would be profitable in practice. This project mainly focused on technical feasibility, while economic viability has only been explored at a high level. Further development of the business model, cost structure, and stakeholder incentives is required to better assess real-world viability.

alternative, R2 suggested that manufacturers could implement a software mode that allows the motor to run for a fixed period of time for testing purposes. This would simplify the procedure, but it would require cooperation from manufacturers.

In addition, R2 questioned whether bike mechanics would be willing to remove gears, covers, and chains as part of the measurement procedure. From their perspective, this level of disassembly could form a barrier to adoption and should be minimized in future development.

Beyond the current concept, R2 also reflected on broader opportunities. They suggested that manufacturers could integrate vibration sensors directly into the motor. These sensors could continuously monitor the condition of the motor and provide diagnostic information through manufacturer software. Such data would not only support bike mechanics, but would also be highly valuable for manufacturers, as it could provide insight into real-world usage patterns, failure modes, and critical components. This perspective is further discussed in Chapter 11.3.

#### Bike mechanic (M1)

The bike mechanic described the concept as an interesting and promising approach. They particularly valued the fact that the concept offers an objective diagnostic method that is not dependent on manufacturers or closed software systems. According to M1, this is a clear advantage compared to current practice, where

mechanics often have limited insight into the internal condition of e-bike motors.

At the same time, M1 was critical about the current measurement procedure. According to the mechanic, the procedure is too time-consuming to fit into a regular service appointment. In its current form, M1 indicated that they would only use the tool when a motor already makes noise or runs poorly. This means that clear symptoms must already be present, which undermines the goal of early detection. To be suitable for use during a regular service appointment, the measurement process would need to become significantly faster and simpler.

M1 estimated that the current procedure, which requires removing the chain guard, chain, cranks, gear, and motor covers, would take around thirty minutes. This is considered too long for a standard service workflow. To increase the chance of adoption, both the number of disassembly steps and the total measurement time should be reduced as much as possible.

In addition, M1 expressed concerns about the reproducibility of the measurement setup. Suspending the bike in the air could allow additional movement, which may influence the measurements. M1 reasoned that a consistent and standardized measurement setup is essential to ensure that results are reliable

and comparable between different bikes and workshops. According to the mechanic, the current setup could lead to variation in results, and the measurement method should therefore be more robust and foolproof.

Despite these concerns, M1 remained enthusiastic about the tool and the underlying principle of using vibration measurements. The mechanic indicated that paying for tools that are used infrequently, as well as software subscriptions, is common practice and not a major barrier. Overall, the mechanic saw clear potential in the concept and expressed interest in using such a tool in practice, provided that the procedure and setup are further optimized.

#### Conclusion

The desirability of the concept was evaluated by discussing it with a revision expert (R2) and a bike mechanic (M1). Although these conversations provided valuable insights, the number of participants was limited and does not allow for strong conclusions. Both stakeholders responded positively to the concept and recognized its potential value, particularly the objective diagnosis of mechanical motor problems. At the same time, they highlighted important concerns regarding practicality, measurement time and reproducibility. The feedback from both stakeholders has been used as input for the concept discussion in the following section.

## 10.3 CONCEPT DISCUSSION

This section provides a critical discussion of the proposed concept. It describes the current limitations of the concept and on opportunities for further development. The goal is to reflect

on what has been demonstrated within this project, what still does not work sufficiently, and what would be required to develop the concept further into a usable product.

### 10.3.1 LIMITATIONS

A key limitation of the concept is that it only creates value when motor revision options are sufficiently accessible. The tool can indicate whether an e-bike motor is mechanically defective and, potentially in the future, which component is failing. However, this information is only useful if there are clear and accessible follow-up options (fast, affordable, and reliable revision services). At this moment, these options are still limited. The concept therefore depends on the assumption that motor revision will become more widely available for bike mechanics in the future, as discussed in Chapter 5.

concept is based on comparing measured vibration signals with reference data from healthy motors. If this database is small, incomplete, or not well validated, the tool cannot provide reliable results. This limits the usefulness of the concept, especially in the early stages, when only a limited number of motor types and conditions are included.

Together, these two limitations show that the concept cannot stand on its own, but depends on developments in the e-bike motor revision system. The next section therefore discusses possible directions for further development and improvement of the concept.

Another important limitation is the strong dependence on reliable baseline data. The

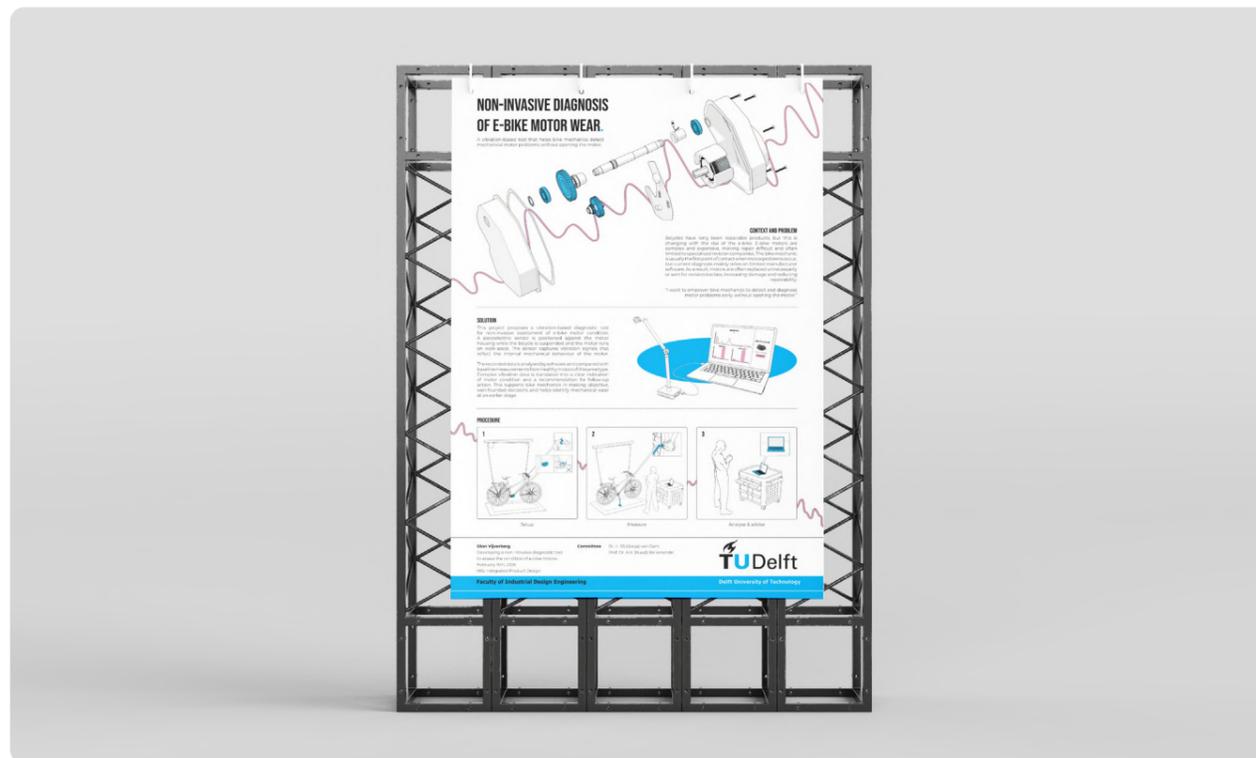


Figure 10.4: The poster used to gather feedback on the concept from R2 and M1.



Figure 10.5: The sensor setup as used during the feasibility test.

### 10.3.2 RECOMMENDATIONS

The most important recommendation for future work is further validation of the concept in practice. Additional research is needed in the areas of viability and desirability. This includes more extensive discussions with bike mechanics, revision companies, and potential revision hubs. These conversations are necessary to better understand who would use the tool, who would pay for it, and who would be responsible for hosting, managing, and maintaining the system. The business model should be further developed and supported by basic cost estimates, market insights, and willingness-to-pay research before real-world implementation can be considered.

From a technical perspective, future development should investigate the use of accelerometers instead of piezo-electric sensors. In this project, a piezo sensor was selected because it is easy to use and well suited for comparing different situations. However, an accelerometer may ultimately be a more suitable option. Accelerometers measure absolute acceleration values and provide data in multiple directions, which allows better comparison between measurements and between motor types. This could improve the reproducibility and reliability of the measurements. In addition, accelerometers contain an internal reference, removing the need for the external "solid base" required by piezo sensors. This could allow the sensor to be mounted directly onto the motor casing, simplifying the measurement setup. However, this also introduces more complex data processing, as multiple directions must be combined in the analysis. Further research is needed to determine how this data can best be processed within a complete vibration analysis.

The vibration analysis used in this project was intentionally basic and exploratory. Future work should focus on more advanced signal processing techniques, including improved filtering and the extraction of more (complex) data in both the time and frequency domains. Automated pattern recognition and machine

learning techniques could further improve early fault detection and help distinguish between different types of defects.

The baseline database should be expanded gradually. Development should start with the most common motor types and/or those known to suffer most often from mechanical problems. Building a reliable and representative database requires collaboration with parties that have access to motors, test data, and technical expertise, such as revision companies or manufacturers.

To increase adoption by bike mechanics, the measurement procedure should be simplified as much as possible. Future research should investigate whether measurements can be performed without removing chains, gears, or motor covers. The total measurement time should be tested and optimized to minimize disruption of the regular service workflow. In addition, the measurement setup itself should also be further developed and validated (for example, bike suspended in the air or standing on the ground). This is necessary to ensure that measurements are reproducible and consistent across different workshops and users.

Finally, the concept should be further developed into a product-oriented design. This includes improvements in hardware, such as casing design, robustness, and clear user feedback through buttons or indicator lights. In addition, the software interface should be designed and tested. The user interface should be clear, intuitive, and focused on supporting the mechanic in making quick and confident decisions, rather than presenting complex raw data. Visual feedback, clear status indications, and simple diagnostic outcomes are important for practical use in a workshop environment. Different system configurations could be explored, ranging from a wireless sensor connected to computer software to a fully standalone device with an integrated display.

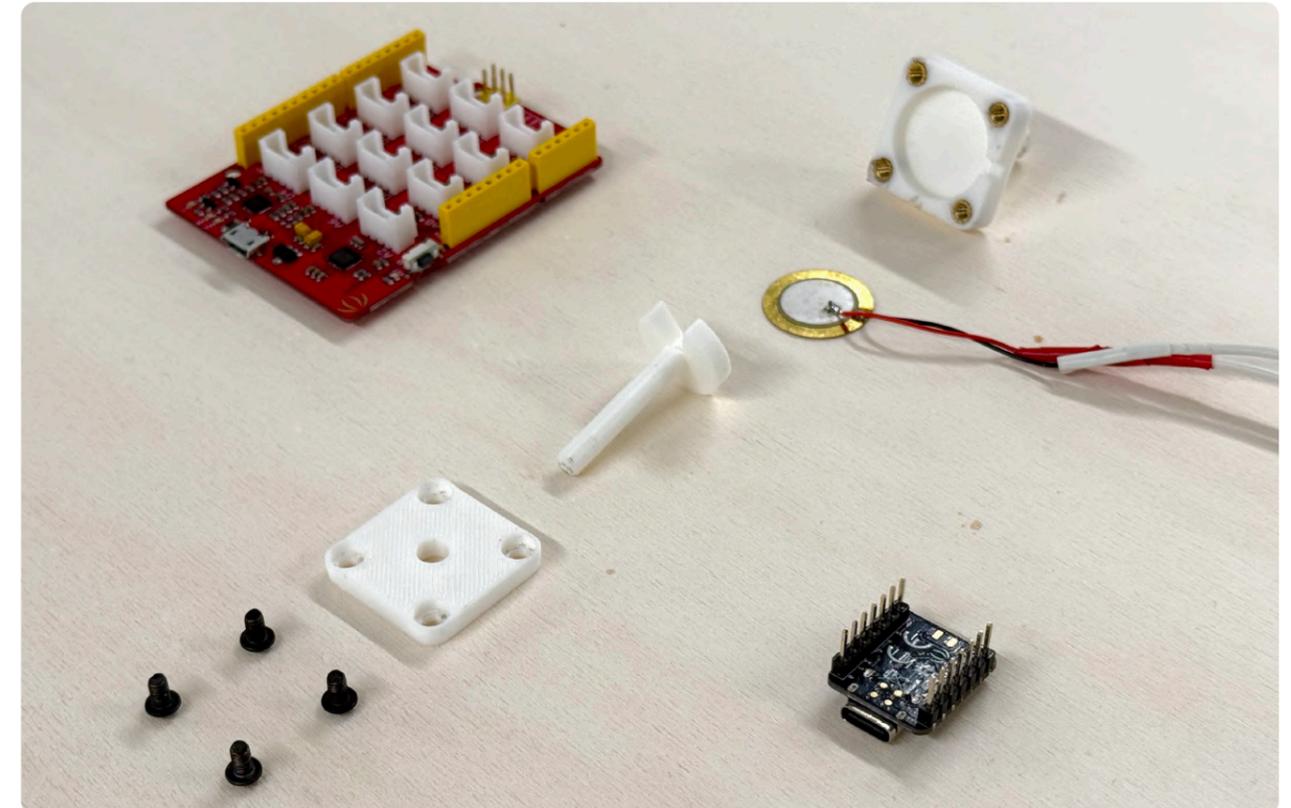
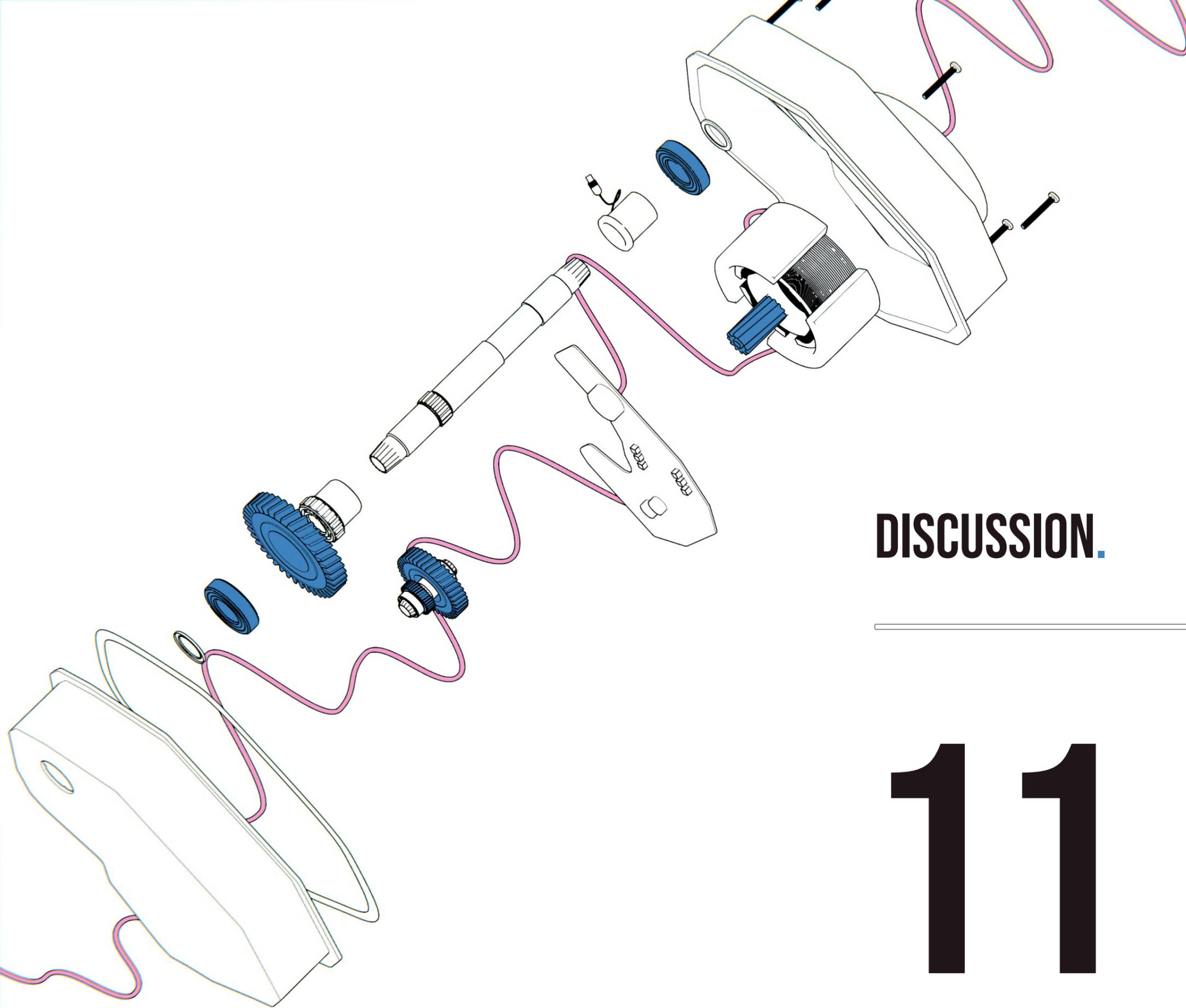


Figure 10.6: The electronics used during the test: a microcontroller and a piezo sensor housed in a 3D-printed casing. Future research should investigate whether an accelerometer is a better option.



Figure 10.7: Dashboard created using a Python script, showing measurement data from a Shimano motor. Future work should further investigate vibration analysis to enable more complete and reliable conclusions from the measurements.



## DISCUSSION.



# 11

This chapter reflects on the broader context of the research. It discusses the uncertainty regarding market data, the limitations of the project scope in relation to the total e-bike system, and the dependency on market developments. Finally, it outlines topics that future research should focus on to build on the results of this project.

- 11.1 Discussion
- 11.2 Limitations
- 11.3 Recommendations

## 11.1 DISCUSSION

Throughout this project, a recurring challenge was determining the actual scale of the problem: how often do e-bike motors really fail? While there are many anecdotal stories about prematurely failing and non-repairable motors, hard quantitative data is scarce. Manufacturers do not publish failure rates, and revision companies mainly see broken motors, which gives a biased view on the actual size of the problem. Interviews showed strongly differing perspectives. Some experts indicated that motor reliability has improved and that failure rates are relatively low, while others described a steady stream of early failures. The lack of quantitative data makes it difficult to determine the exact economic and environmental impact of the problem. However, the qualitative insight remains strong. Even if the overall failure rate is relatively low, the impact of a single motor failure is high and largely unnecessary. It is a shame to discard an entire motor unit (or even worse: an entire e-bike), often worth several hundred euros, because of a single worn bearing worth only a few euros.

The project deliberately focused on mechanical failures, such as bearings and gears, which experts estimated to account for roughly 75% of motor failures. As a result, electronic and software-related failures were excluded from the scope.

## 11.2 LIMITATIONS

This project was carried out within a limited timeframe, which strongly influenced its scope and depth. Because of these time constraints, the focus was placed on exploring the problem space and developing a proof of principle, rather than delivering a fully validated or optimized solution. While this approach made it possible to demonstrate that vibration analysis could be used as a diagnostic tool, it also meant that absolute values, clear thresholds, and long-term reliability could not be established.

Several research methods were also limited by practical constraints and the availability of resources. The expert interviews provided valuable insights, but the number of interviews was relatively small. Ideally, more stakeholders should have been interviewed to collect additional data and to better validate the assumptions made throughout the project. However, due to time limitations, this was not feasible within the scope of this project.

These failures remain a black box for both bike mechanics and revision experts, as diagnosis and repair are typically locked behind manufacturer-specific software and error codes. Even with the proposed diagnostic tool, mechanics remain dependent on the manufacturer for electronic issues. This means the concept does not solve all repair barriers. Instead, it offers a partial solution that improves mechanical diagnosis and chances for repair, while leaving software and electronics largely untouched.

Finally, the concept should be understood as an enabling tool rather than a standalone solution. As discussed earlier, it only creates value when accessible and reliable revision options exist. The tool helps mechanics make better decisions by identifying mechanical defects and indicating when revision is a viable option, but it does not perform the repair itself. Without well-organized revision services, including efficient logistics, reasonable costs, and acceptable turnaround times, the diagnosis loses much of its value. Knowing that a motor can be repaired is of little use if there is no viable partner to carry out that repair. The value of the concept is therefore strongly dependent on the further scaling and professionalization of the e-bike motor refurbishment market.

The disassembly research was constrained by access to materials. The analysis was based on a limited set of nine motors, which were made available through collaborations with companies. Other motor types and brands were therefore not included. It should also be noted that the motors that were analysed were not the newest models on the market. It was assumed that these motors are broadly representative in terms of internal structure and working principles, but this assumption could not be fully verified. In addition, the disassembly process itself was influenced by the tools that were available. Certain components proved difficult to remove without specialized tools, which affected the perceived repairability in the disassembly maps. With the correct professional tools, some of these steps would likely be easier in practice.

Hotspot mapping was performed, but not for every individual motor. This decision was made because the method relies on the researcher

defining both the likelihood of failure and the impact of that failure on the overall system. Based on this method, priority parts are identified. Since all analyzed motors contained similar components, the resulting priority parts were the same for each motor: bearings and gears. This outcome was further supported by the expert interviews, which indicated that the critical components are largely identical across different motor types. For this reason, and to save time, hotspot maps were not created for every individual motor.

Finally, the proposed concept is based on findings from the research phase and a limited number

## 11.3 RECOMMENDATIONS

Future research should first focus on understanding the size of the problem. This is important to determine whether developments in this area are truly valuable. For example, for the parties described in this report that aim to set up a revision hub, it is crucial to know whether a viable business case exists. This requires quantitative data on how often e-bike motors fail, how many of these failures are mechanical, and how many motors could realistically be revised instead of replaced. Without this data, it remains unclear whether there is sufficient volume to support a sustainable system of bike mechanics, logistics, and revision options. Establishing the actual size of the problem is therefore a key step in assessing the value and relevance of diagnostic tools such as the one proposed in this project.

In addition, further research should explore vibration analysis more broadly, especially independent of the specific concept developed in this project. This research demonstrated that vibration analysis can be used as a method to detect mechanical issues in e-bike motors. Future work could investigate other applications of this technology. One example, suggested by R2 during the validation phase, is that manufacturers could integrate vibration sensors directly into motors to monitor their condition over time. The collected data could then be used by diagnostic software to detect early mechanical wear and identify specific failing components. Such an approach could be valuable not only for bike mechanics, but also for manufacturers, as it would provide insight into real-world usage, failure patterns, and critical components. This highlights the broader potential of vibration analysis beyond the specific concept presented in this project.

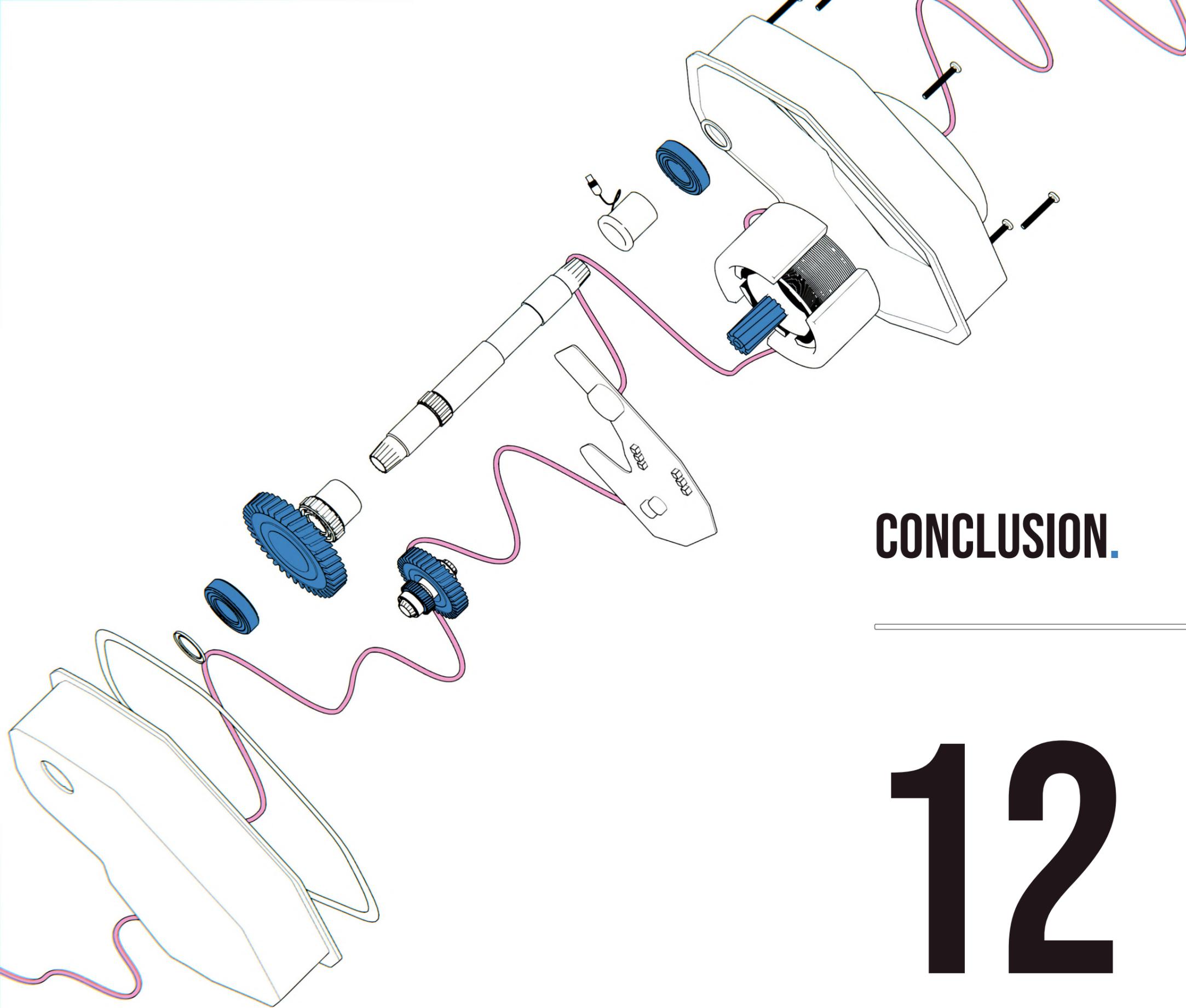
of tests. Further research is needed to determine whether vibration analysis is equally effective for different motor types, different failure modes, and different usage conditions. The prototype and test setup were built using available materials and limited technical expertise in vibration analysis, electronics, and software development.

Although the setup was far from professional, it proved sufficient to collect meaningful data and draw initial conclusions. The results should therefore be interpreted as exploratory rather than definitive, and further development and validation are required before real-world application can be considered.

Another important direction for future research is improving collaboration within the repair ecosystem. This project primarily explored a technical solution. However, many of the challenges related to e-bike motor repairability are systemic rather than purely technical. Future research should examine why different stakeholders are currently poorly aligned and how this alignment could be improved. This includes bike mechanics, revision experts, manufacturers, and consumers. Each of these actors has different incentives and interests, which are not always aligned with the circular economy principles. Manufacturers were largely outside the scope of this project due to their closed systems, but changing regulations may alter their role in the short term. Consumers were also not directly involved in this research, even though they ultimately decide whether a motor is revised or replaced. A deeper understanding of these stakeholder relationships is essential to enable meaningful system-level change.

Finally, future research should closely examine the impact of changing legislation related to repairability and right-to-repair. There is ongoing regulatory development at the European level that could significantly influence access to spare parts, repair information, and software. Software-related problems remain one of the most difficult aspects of e-bike motor repair and can currently only be addressed by manufacturers. It is therefore important to study whether upcoming regulations will shift responsibilities and/or enable new forms of third-party repair.

Understanding these aspects is crucial for designing solutions that improve the circularity of the e-bike motor system.



## CONCLUSION.



# 12

This final chapter presents the overall conclusion of the project. It also includes a personal reflection in which I look back on the project and describe my main learning experiences and lessons learned.

- 12.1 Final conclusion
- 12.2 Personal reflection

## 12.1 FINAL CONCLUSION

The growth of the number of e-bikes has led to an increasing number of electric motors entering the market. These motors play an important role in the performance and value of the bicycle, but they are often poorly repairable. In current practice, bike mechanics rarely open motors, and only a small number of specialized revision companies in the Netherlands have the knowledge and tools to refurbish them. As a result, when an e-bike motor fails, it is common for the entire motor, or even the complete e-bike, to be replaced instead of repaired. This happens despite the fact that many failures are caused by relatively simple and repairable mechanical components. Exact numbers on motor failure rates and replacement are difficult to obtain, which makes it hard to quantify the true scale of the problem. Nevertheless, the impact of a single motor failure is high in terms of cost, material use, and waste.

With this background, the design assignment of this project was to explore and support the potential role of bike mechanics in the transition towards a more circular e-bike motor system. Based on the research carried out during this project, it can be concluded that this goal has been achieved. The changing role of the bike mechanic has been explored and defined, and a first concrete step has been taken towards developing a tool that supports this role in practice.

To reach this conclusion, the project first focused on understanding the current situation. Through expert interviews, several key insights were identified. Barriers and challenges for both bike mechanics and revision companies were mapped, showing that it is currently not feasible for mechanics to open and repair motors themselves. At the same time, experts indicated clear failure patterns: mechanical components such as bearings and gears fail most frequently, and these parts are often repairable.

In addition, the project examined broader system-level developments related to circularity. Using interviews and literature research, the current e-bike repair system was mapped, highlighting the missing link between bike mechanics and revision companies. Upcoming developments related to circular economy and repairability were explored, as well as how these may affect the role of the bike mechanic. This role is expanding: from mainly reading out manufacturer software to actively diagnosing problems and deciding on next steps, such as replacement or refurbishment.

A technical analysis of e-bike motors formed the foundation for the design phase. Through teardowns, disassembly mapping, hotspot mapping, and expert interviews, insights were gained into the construction of different motor types and models, their general structure, and the diagnosis procedures used by both bike mechanics and revision experts. The research showed that bike mechanics currently rely mainly on manufacturer software for diagnosis and make little use of physical signals. Because mechanics are not motor experts and only occasionally encounter a failed motor, it is difficult for them to interpret these signals reliably. This highlighted diagnosis as a key leverage point for improving repairability.

Based on these insights, a concept was developed: a non-invasive, vibration-based diagnostic tool that supports bike mechanics in detecting and interpreting mechanical signals. The tool measures vibrations from the outside of the motor, analyses these signals, and compares them to baseline data from healthy motors. In doing so, it supports the mechanic in making a more informed diagnosis and enables targeted referral to revision experts. The concept was tested through prototyping and experiments, demonstrating a proof of principle that vibration data can be used to distinguish between healthy and defective motors.

At the same time, the project revealed important limitations and challenges. The concept only functions if a suitable revision infrastructure exists and if reliable baseline data is available and maintained. In addition, a key challenge lies in the business case: the primary user of the tool (the bike mechanic) is not the party that captures most of the economic value (the revision expert). This complicates implementation and adoption.

When zooming out, this project provides valuable insights into the structural problems surrounding e-bike motor repairability and the critical role of diagnosis in creating a more circular system. It demonstrates the potential of vibration analysis as a diagnostic method and presents one possible way of applying it in practice. At the same time, it highlights that improving repairability requires system-level change and collaboration between stakeholders.

This project does not deliver a final solution. Instead, it provides a well-founded direction, a proof of principle, and a clear basis for further research and development towards a more circular e-bike motor system.



Figure 12.1: Overview of the test setup using Shimano motors, including the e-bike, motors, sensor, and software/analysis.



Figure 12.2: Removal of a bearing during the disassembly of a Shimano motor.



## 12.2 PERSONAL REFLECTION

Looking back on this graduation project, I feel proud of the result. It was a challenging journey, largely because there was very little existing research or data available on e-bike motor repairability. While this was difficult at times, it gave me the opportunity to go out and investigate the real world myself. It forced me to adopt a hands-on approach: I had to talk to people, tear down motors, and build prototypes to understand the system.

This way of working suits me well. Together with Pablo, I spent hours in the workshop (PMB), taking motors apart to figure out exactly how they worked. I discovered that I enjoy it when a project is physical and tangible, rather than abstract and vague. This approach also connected me with bike mechanics. I noticed their frustration and enthusiasm when I brought up the topic of my research; they genuinely wanted to repair these motors, but there were too many barriers making it unfeasible. Simply stepping into a shop to have a conversation revealed these barriers, and this way of researching gave me a lot of energy.

In the past, I sometimes thought I preferred working alone to have complete control over the project and the outcome. However, this project taught me that design is fundamentally a social act. The first few weeks, where I collaborated with Pablo, were incredibly productive. We gathered insights and found angles that I likely would not have found on my own. It made me realize that collaboration is not just about speed or efficiency, but also about raising the quality of the work.

This also applied to the rest of the project. Even though I worked independently during the later phases, I received a lot of help from experts

and companies. Since I did this project without a direct assignment from a company, getting access to motors and data was difficult at first. Yet, I learned that once you find the right person within an organization, a lot is possible. This approach allowed me to get the motors for the disassembly research, gather knowledge on failure patterns, and even perform on-site testing of the prototype with the help of a revision expert. I learned that resources are rarely the problem; finding the right entry point is. I am very grateful to the partners who helped me during this project.

Perhaps the most important lesson regarding my identity as an Industrial Design Engineer (IDE) came during the testing and prototyping phase. As designers, we are often a “jack of all trades.” We can learn about anything, but we are rarely the specialist. A clear example of this was the vibration analysis. Through framing the problem, I identified this technology as a potential solution. I dove into the physics of amplitude, frequency, and energy, learning just enough to build a working prototype. However, I also realized that I am not a vibration expert. To take this product to the next level, I would need a specialist.

This made me realize that an IDE graduate is a specialist in something else. I learned that our strength lies in managing the design process: dissecting problems, creating creative angles, generating concepts, and knowing when to involve the experts. We are the ones who connect the dots, manage the stakeholders, and filter the right signals from a complicated problem. That ability to oversee the whole system, rather than just one part, is what I will take with me into my future career.

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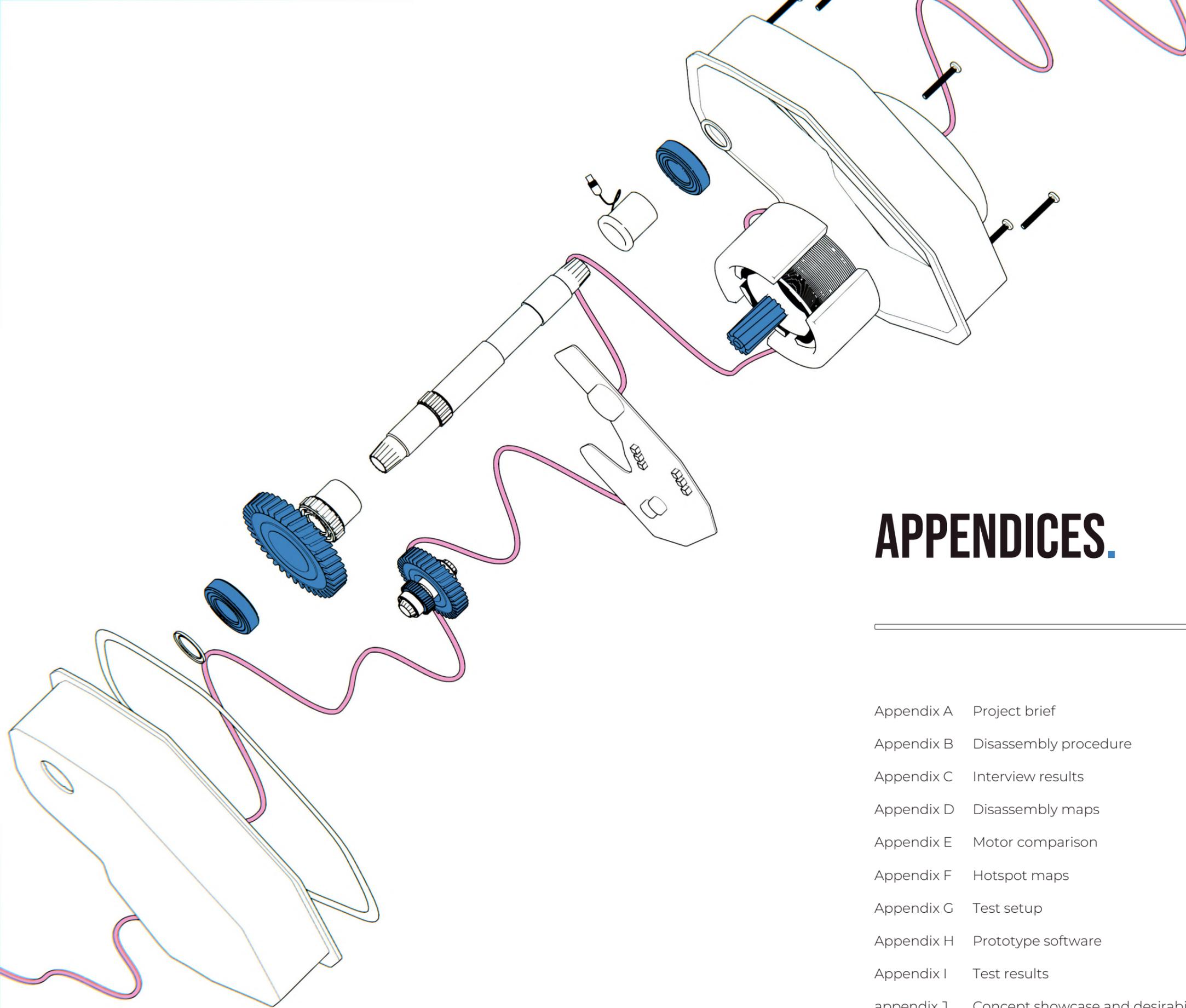
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# APPENDICES.



- Appendix A Project brief
- Appendix B Disassembly procedure
- Appendix C Interview results
- Appendix D Disassembly maps
- Appendix E Motor comparison
- Appendix F Hotspot maps
- Appendix G Test setup
- Appendix H Prototype software
- Appendix I Test results
- appendix J Concept showcase and desirability validation




**Personal Project Brief – IDE Master Graduation Project**

Name student Dion Vijverberg Student number 5,271,614

**PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT**  
Complete all fields, keep information clear, specific and concise

**Project title** Exploring e-bike motor remanufacturing, repair, and other lifetime extension strategies.

*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)*

E-bikes are presented as sustainable alternatives to cars, especially for commutes of 10 – 20 km, with lower material impact and health benefits compared to cars. For people working full-time, this can mean cycling 5,000 – 10,000 km per year. While the lifetime of batteries is relatively well documented at around 800 – 1000 charging cycles (Contò et al., 2023), much less is known about the lifespan of e-bike motors. According to a 2024 survey in Germany (Wertgarantie, 2023), 40.9% of e-bike technical failures involve the battery, 28.6% the display, and 24.2% the motor. Additionally, 21.8% of respondents cycle over 4,000 km per year, with 2.4% exceeding 10,000 km. Findings from user forums and industry discussions suggest that motors often fail around 15,000 km—sometimes much earlier—due to water ingress (Brignall, 2025) and wear. Few motors exceed 30,000 km, which may mean that frequent riders need replacements every 1.5 – 4 years. This short lifespan contrasts with the 10-year warranty on bike frames and the generally long-lived nature of electric motors in other industries. Given the high cost of replacements and limited repair infrastructure, there is a growing risk of premature disposal of otherwise functional e-bikes (Erdmann et al., 2023). The main stakeholders in this challenge are consumers, bicycle mechanics, and manufacturers. Consumers want reliable e-bikes that are affordable to maintain. Mechanics need products that can be opened, repaired, and reassembled without always returning them to the factory. Manufacturers want to sell products while balancing reliability and lifetime. During the project, these interests will be explored in more detail.

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**Personal Project Brief – IDE Master Graduation Project**

**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)*

There is a knowledge gap about how e-bike motors fail and when these failures occur. Current information is fragmented and limited, which makes it difficult to design targeted improvements. As described in the introduction, many motors fail much earlier than expected, leading to high costs for users and unnecessary waste. A key design challenge is the balance between conflicting requirements. Motors need to be compact, robust, and long-lasting, but these qualities often come at the expense of reparability and remanufacturability. On top of that, manufacturers discourage opening the motor and do not provide spare parts or service information, which creates additional barriers for repair and replacement. As a result, e-bikes that could potentially be repaired are often discarded, even when most parts are still functional. This is a problem because it shortens the lifetime of e-bikes and reduces their overall sustainability. Premature motor failures create extra waste, higher costs for users, and risk undermining trust in e-bikes as a reliable form of transport. For mechanics, it means they cannot properly service motors and remain dependent on manufacturers. For manufacturers, it creates tension between selling durable products and meeting growing demands for repair and circularity. These different perspectives and challenges will be further explored during the project.

**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 toolkit to enable bike mechanics to confidently perform preventive maintenance on e-bike motors, prolonging their lifespan without relying on OEM cooperation.

*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)*

To achieve this, the project will use a mixed research and design approach. First, failures will be analysed through literature, user experiences, and interviews with both consumers and mechanics. The disassembly process of e-bike motors will be documented using a disassembly map (De Fazio et al., 2021). This will make it possible to identify barriers and opportunities for repair. Based on these insights, strategies for improvement will be developed through ideation techniques (Van Boeijen et al., 2020) while using for example design for repair strategy's. Promising ideas will be refined and tested through iterative prototyping. The final prototype will demonstrate how bike mechanics can perform preventive maintenance on e-bike motors, resulting in a longer lifespan and improved sustainability. De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product reparability. *Journal Of Cleaner Production*, 320, 128552. <https://doi.org/10.1016/j.jclepro.2021.128552> Van Boeijen, A., Daalhuizen, J., & Zijlstra, J. (2020). *Delft Design Guide?: Perspectives - Models - Approaches - Methods*. <https://research.tudelft.nl/en/publications/delft-design-guide-perspectives-models-approaches-methods>

### 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	27 Oct 2025
Green light meeting	6 Jan 2026
Graduation ceremony	10 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)

This project gives me the opportunity to explore the field of repair and remanufacturing, a subject that is becoming increasingly important in the transition to a circular economy. I am motivated to study how consumer products, such as e-bikes, can be designed in a smarter way to reduce waste and extend their use.

The e-bike is a perfect example of a sustainable product that still faces big challenges in practice. By focusing on the motor, I can combine research and hands-on design to create practical improvements.

I am especially motivated by the hands-on character of this project. It will allow me to work with real users and real products, to test ideas in practice and not only in theory. By combining technical research with direct engagement with consumers, mechanics and maybe even manufacturers, I will gain insights that are both useful for the industry and relevant for my own professional growth.

## APPENDIX B - DISASSEMBLY PROCEDURE

### DISASSEMBLY STEPS

#### Disassembly / Repairability

Which components, tools, connections, etc. are used. A disassembly map is of course perfect for this. Important during the process:

- Write down dimensions/type of bearings
- For the bearings, also record which press tool/puller/adaptor was used

#### Durability

Identify weak spots through interviews later, but also check when the motor is open:

- Seal and housing design
- Water management inside the casing
- Vulnerability of electronics
- Removable PCB
- Materials of gears, bearings, etc.

#### Step-by-step plan for the disassemblies

1. Start the video
2. Open the motor → two casing parts
3. Analyze without removing parts. Pay attention to the seal, electronics, materials of the gears, and "water management." (Take notes on paper using the format)
4. Start the disassembly process. Pay attention to the required tools (e.g., for bearing removal), bearing dimensions, etc. (Again, take notes on paper using the format)
5. Stop the video
6. Lay out the parts neatly
7. Take photos
8. Reassemble
9. Create the disassembly map with the video

### DISASSEMBLY NOTES TEMPLATE

Motor: .....

#### Durability

Aspect	Score	Note
Seal and shape casing		
Watermanagement		
Durability electronics		
Removable PCB		
Materials, sprockets, bearings, etc.		
Grease		

## Disassembly

### Bearings and gears

Component	Size	Tools needed

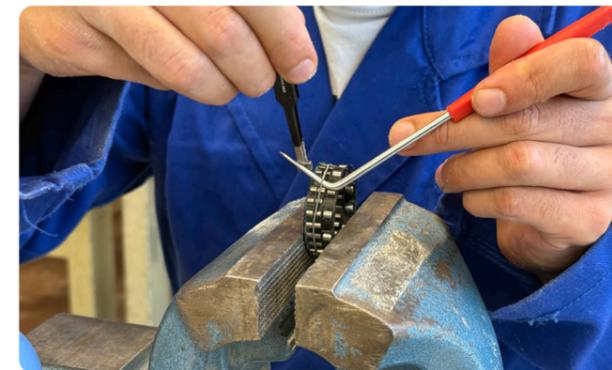
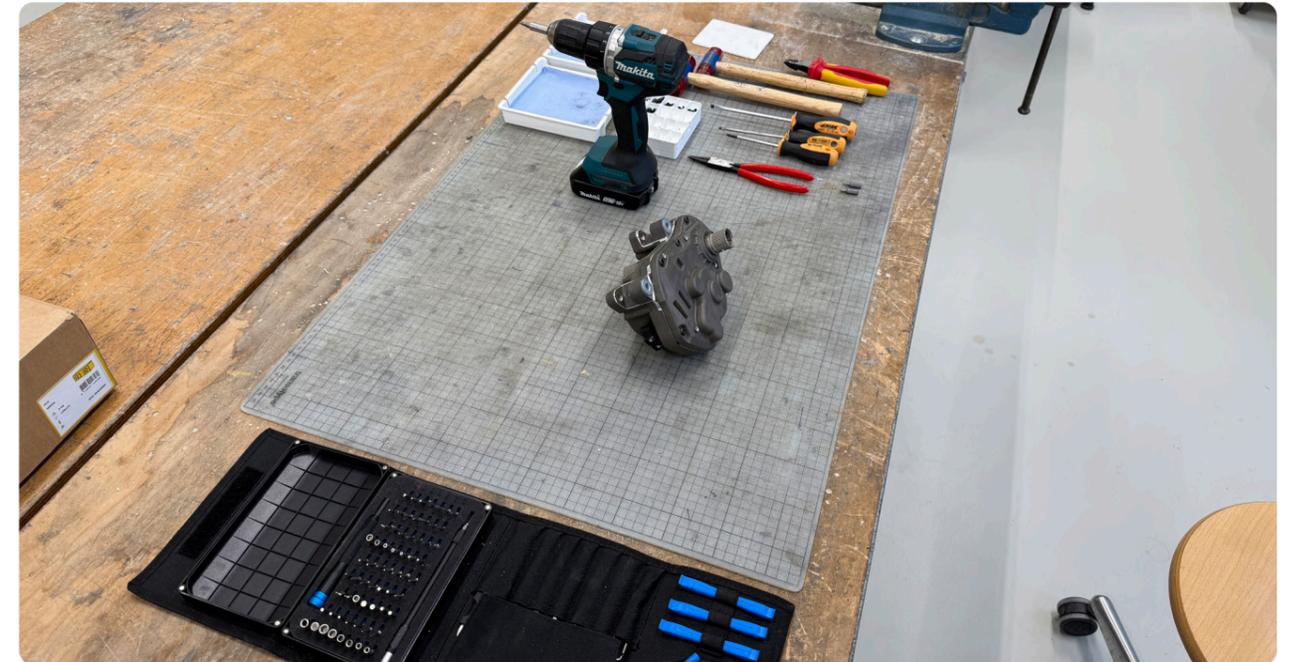
### General remarks

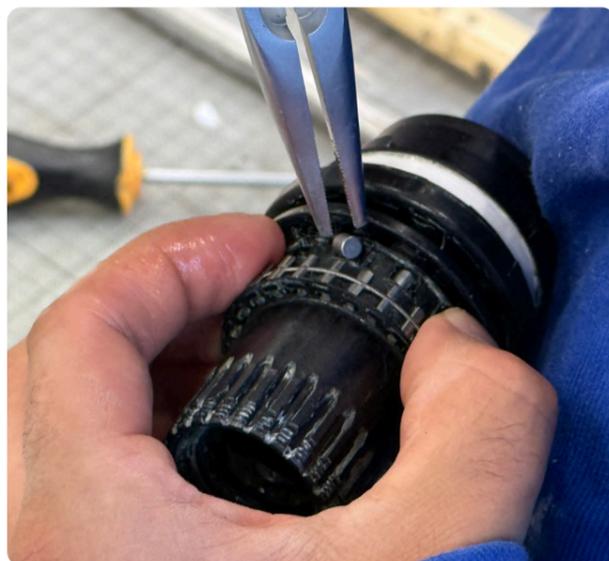
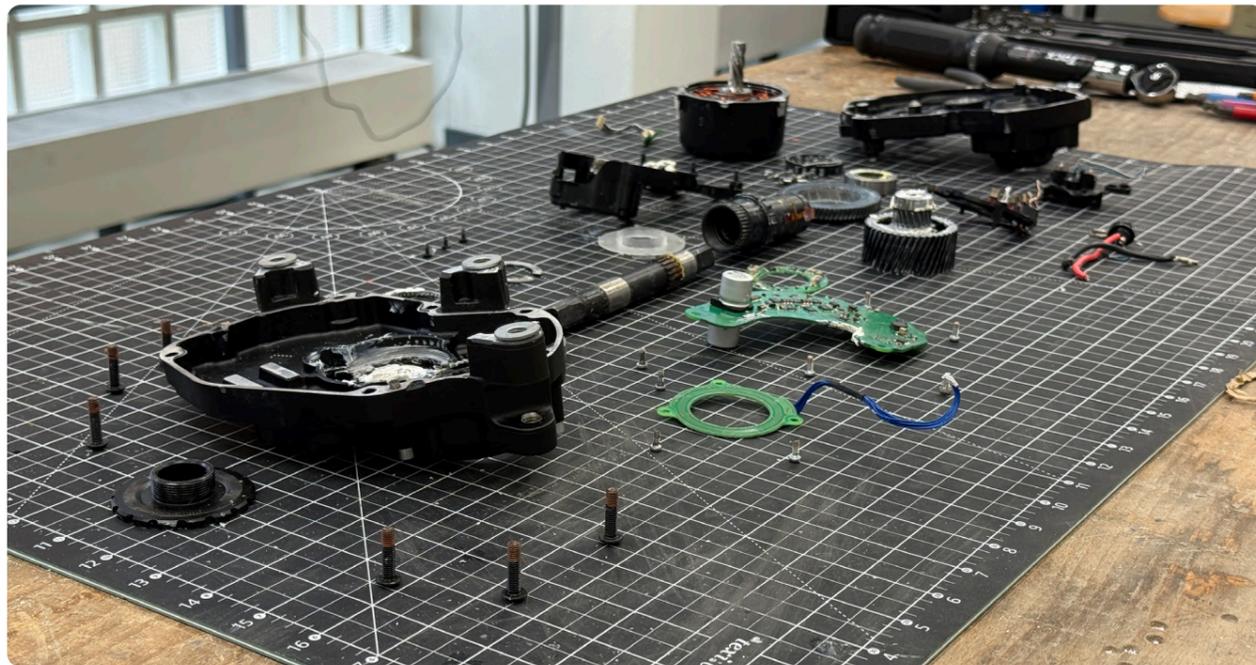
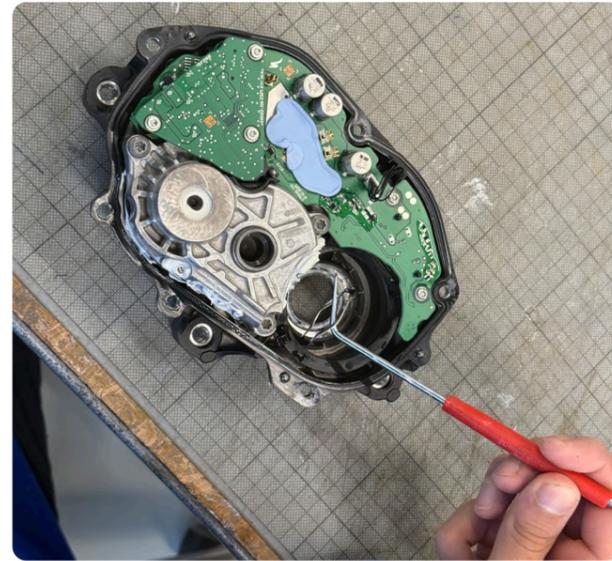
Which parts look replaceable in theory (standard bearings, gears)?

Which parts are clearly problematic (custom sizes, potted electronics)?

Could a mechanic realistically reassemble without damage?

## EXTRA DISASSEMBLY PHOTOS





## APPENDIX C - INTERVIEW RESULTS

### CURRENT PRACTICES

#### Preparation

#### Introduction

- Brief introduction to the project
- 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 bike 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?

#### Results (summary from notes, generated by AI)

##### M1

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.

##### M2

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.

##### M3

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.

M4

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.

M5

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.

M6

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."

M7

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

R1

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.

R2

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 non-standard 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.

R3

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.

#### R4

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 reparability 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 reparability 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.

## CIRCULAR SYSTEM DEVELOPMENT

### Preparation

#### General overview

- Can you briefly outline how the central refurbishment/service hub system is set up?
- What is the purpose of the system and what problems does it aim to solve?
- What types of e-bike motors would be reconditioned? All of them?

#### Stakeholders

- Who are the main stakeholders in this system? What does the system look like?
- What role does each stakeholder play (bicycle repairers, reconditioning hub, manufacturers, customers, transport/logistics, insurance, etc.)?
- How does communication between these parties work?

#### Value exchange

- What value is delivered and received by each stakeholder?
- What information, products or services are exchanged between bicycle repair shops and the hub?

#### Business model

- What does the business model look like? (subscription, per refurbishment, service fee?)
- What are the incentives for bicycle repair shops to send engines to the hub?

### Logistics

- How does the logistics process of collecting, overhauling and returning engines work?
- How long does an overhaul take on average?

### Diagnosis

- What information does the hub expect from the bicycle repair shop before sending an engine?
- How is this information collected and shared? (forms, apps, photos, data logs, etc.)
- Are there standards or formats used for diagnostic information?
- How is feedback given back to the bicycle repair shop?
- Are there plans for digital dashboards or tools to support the process?

## Results (summary from notes, generated by AI)

### S1

The interviewed organisation focuses on developing new companies around circular solutions. Its activities target product categories and waste streams that are difficult to recycle or repair, with the aim of reintroducing these products into the market through viable business models. Examples include e-bike motors, fibre-reinforced composite products, and electric tools. The organisation typically initiates ventures from an early stage, validates their commercial potential, and subsequently transfers operational control to specialised teams. The interviewee has a background in venture capital.

At the time of the interview, the organisation was in an exploration and validation phase regarding e-bike motor refurbishment. The core question was whether the scale of the problem is sufficiently large to support a sustainable business model. This includes assessing the volume of discarded motors, the origin of these waste streams, and which motor models should be prioritised. Initial focus is placed on motor types for which refurbishment activities already exist, while maintaining a broader exploratory scope.

Motors are sourced through multiple channels, including bicycle retailers, waste processors, and consumers. The origin of the motors is considered less important than their suitability for refurbishment. The organisation deliberately focuses on refurbishment rather than individual repairs, as refurbished motors can be processed in a standardised, factory-like manner and can be supplied with warranties. Distribution is primarily envisioned as business-to-business, with bicycle retailers as the main channel.

The organisation maintains contact with original manufacturers but currently operates independently due to initial resistance from manufacturers. The interviewee expects that successful demonstration of the model may eventually lead to collaboration. According to the interviewee, the main value proposition of refurbishment lies in sustainability, cost reduction for customers, and faster turnaround times compared to traditional repair processes. A key uncertainty remains whether a sufficient and stable supply of defective motors exists to sustain the business model.

### R3

The interviewee is involved in large-scale refurbishment of e-bike motors and discussed the potential role of vibration-based diagnostics as part of a business-to-business solution. In the current repair ecosystem, bicycle retailers typically encounter customers with defective motors but have limited tools to assess internal motor condition.

The interviewee questioned whether detailed knowledge of the exact internal defect is always necessary at the retailer level, as in-depth diagnosis can be performed by specialised refurbishment facilities. However, early detection of developing faults was considered valuable, as it may prevent secondary damage and allow motors to be sent for refurbishment at an earlier stage. Making the expertise of refurbishment specialists more accessible to bicycle retailers was identified as a key opportunity.

The interviewee emphasised the potential of combining software-based diagnostics with physical signals, such as vibration data, to improve early fault detection. Relying solely on software error codes was seen as insufficient, as these often appear only after significant damage has already occurred.

A centralised refurbishment system was described as a preferred model. In this system, refurbished

motor units are kept in stock and supplied to retailers when needed. Retailers can choose between replacing a motor with a new unit or installing a refurbished one, while returning the defective motor in exchange for a financial compensation that depends on its reparability. This approach enables faster service and more predictable costs.

The interviewee estimated that a substantial number of motor units fail annually, of which a significant portion is technically repairable. From a practical perspective, bearing diagnostics are often performed using auditory and tactile inspection rather than high-speed measurement equipment. Key questions for further development include which motor models fail most frequently, typical replacement costs, and the price point retailers are willing to accept for refurbished motors.

## DIAGNOSTIC VALIDATION

### Preparation

#### Current status

- Can you briefly explain how you deal with motor problems in e-bikes?
- What motor problems do your customers encounter most frequently?
- What usually happens to a motor that is no longer under warranty?
- Do you ever send motors in for reconditioning, and if so, when?
- Objective: To understand their current practices and the choices they are making.

#### Current diagnosis

- How do you usually notice that a motor has a problem? (noise, resistance, software errors, customer experience, etc.)
- What steps do you take to determine what is wrong without opening the motor?
- How long does this usually take?
- Are there certain tools or methods you currently use to support a diagnosis?
- What information would be useful to have in order to make the right decision?
- Objective: To find out what signals and tools they currently use and where the bottlenecks are.

#### Information

- Suppose you were to receive help in making a diagnosis: what do you think would be most practical to use? (Note: ask an open question, use 'what would be useful/practical' instead of 'would an app/tool be useful').
- What form of information do you prefer? (e.g. written steps, visual diagram, checklist, training videos, examples of previous cases)
- What works best in your daily work: short instructions or detailed manuals?

### Results (summary from notes, generated by AI)

#### R2

The interview focused on failure mechanisms in e-bike motors, diagnostic practices, and the potential role of vibration-based condition monitoring. According to the interviewee, motor reliability has improved significantly over successive product generations. Newer generations show design optimisations, although new vulnerabilities also emerge. For example, in later-generation motors, water ingress may occur via the bottom bracket area, where water can reach bearings with steel cages. While external bearings are often equipped with labyrinth seals, alternative ingress paths through the crankshaft remain possible.

Mechanical failures are frequently linked to high-impact loads on the crankshaft, such as heavy impacts during riding or transport. Circlip failures were mentioned as an example, often caused by such impacts rather than material fatigue. Water-related damage was identified as a dominant failure mode, often preceding wear-related damage. Condensation inside the motor housing was suggested as a likely contributor to moisture-related failures.

Current diagnostic practice typically combines multiple steps. These include visual inspection of the crank, housing, seals, and connectors; reading fault codes via manufacturer-specific software (where available); physical inspection by manually rotating the crank to detect resistance, roughness, or periodic irregularities; and a short test ride to assess noise, vibration, and power delivery. Software-based diagnostics are available for some motor brands but are limited or unavailable for others. As a result, auditory and tactile assessment remains an important diagnostic tool, particularly for detecting bearing and gear defects.

Bearing defects are often characterised by a rough, continuous noise, whereas gear-related defects tend to produce periodic sensations or sounds that repeat every few rotations. In practice, motors are often mounted on a test bicycle before being sent for refurbishment to verify their condition.

The interviewee expressed interest in making vibration- and sound-based diagnostics more objective and repeatable. Suggestions included using a dedicated measurement device with a fixed sensor position and orientation, performing measurements under controlled conditions (e.g. walk-assist mode, no load), and establishing baseline measurements for healthy motors. Deviations from this baseline could then be used to trigger refurbishment decisions. Consistent sensor placement and standardised measurement procedures were emphasised as critical requirements.

Access to motors in different conditions (healthy, worn, refurbished) was identified as essential for building reference datasets. The interviewee indicated willingness to support data collection and prototype development, including access to motors from multiple generations and with known defects.

#### M1

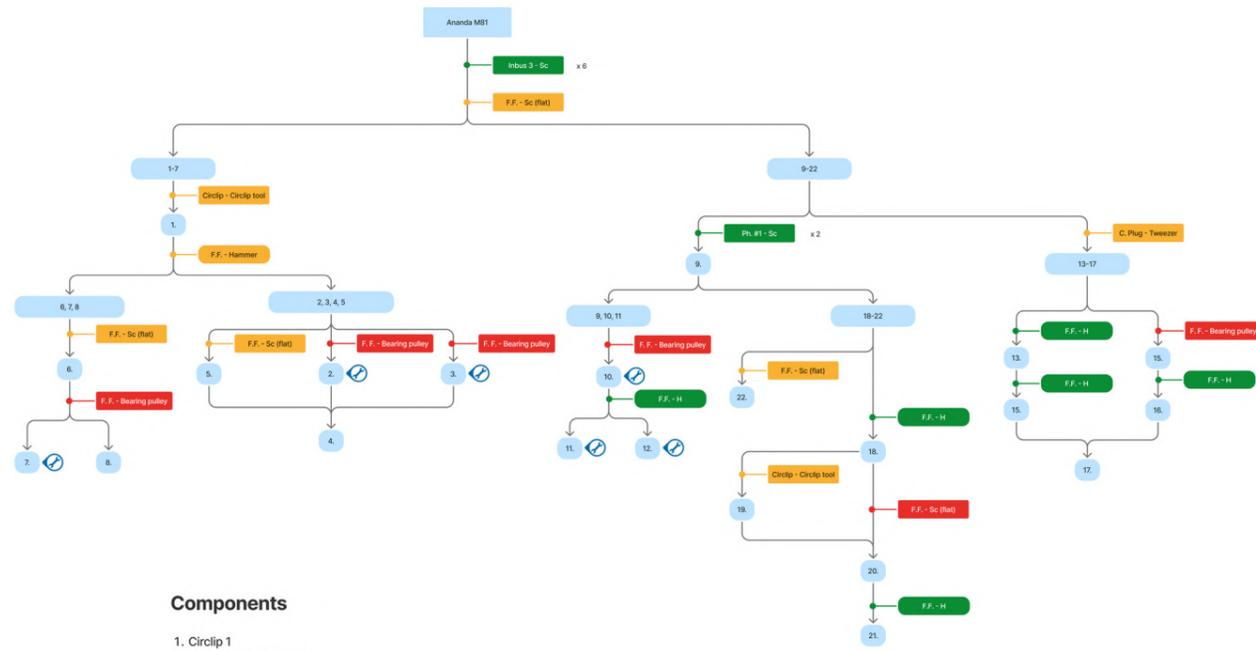
The interview addressed the role of manufacturer-provided diagnostic software in current e-bike maintenance practice. The software allows the technician to read out the complete system, including the motor, display, and battery. During regular service, the system is connected via USB, after which fault codes, system status, and available software updates can be reviewed. The software also generates a basic diagnostic report, primarily consisting of error codes and component status.

Based on the diagnostic outcome, two main follow-up paths are typically considered. If the motor is still under warranty, it is returned to the manufacturer for replacement or repair. If the motor is out of warranty, the technician often has limited options and may inform the customer that no further action can be taken within the standard service framework.

Although the software provides reliable system-level diagnostics, its output is limited to fault identification rather than actionable guidance for repair or refurbishment. This highlights the importance of linking diagnostic information to clear next steps and communicating these options effectively to bike mechanics. Mapping the system behaviour and making available follow-up options explicit were identified as key opportunities for improvement in the diagnostic process.

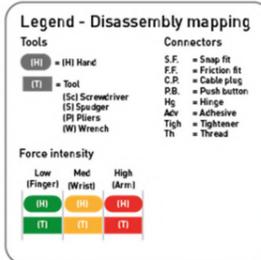
# APPENDIX D - DISASSEMBLY MAPS

## ANANDA M81

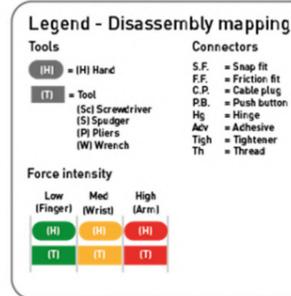
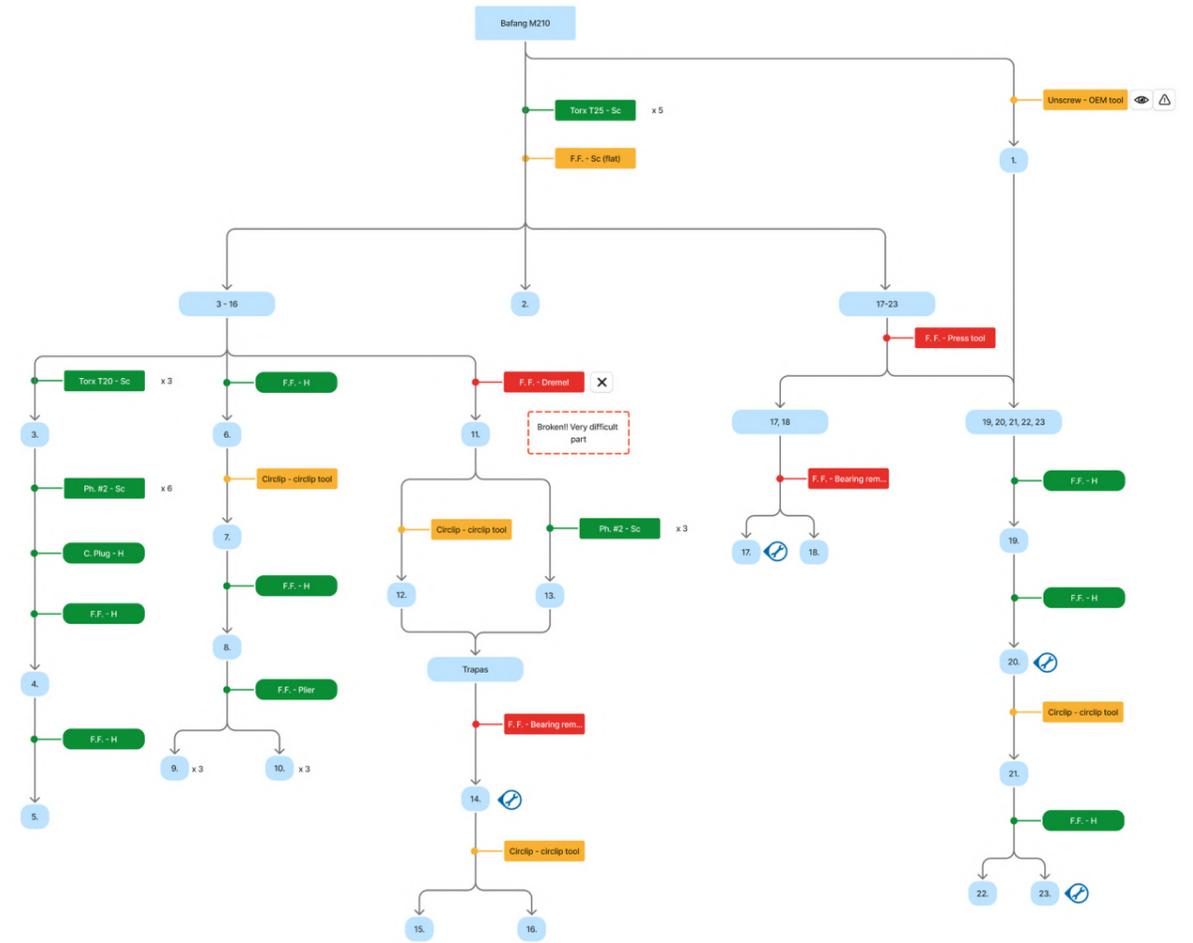


### Components

1. Circclip 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. Circclip 2
20. Metal cover
21. Spring ring
22. Seal ring



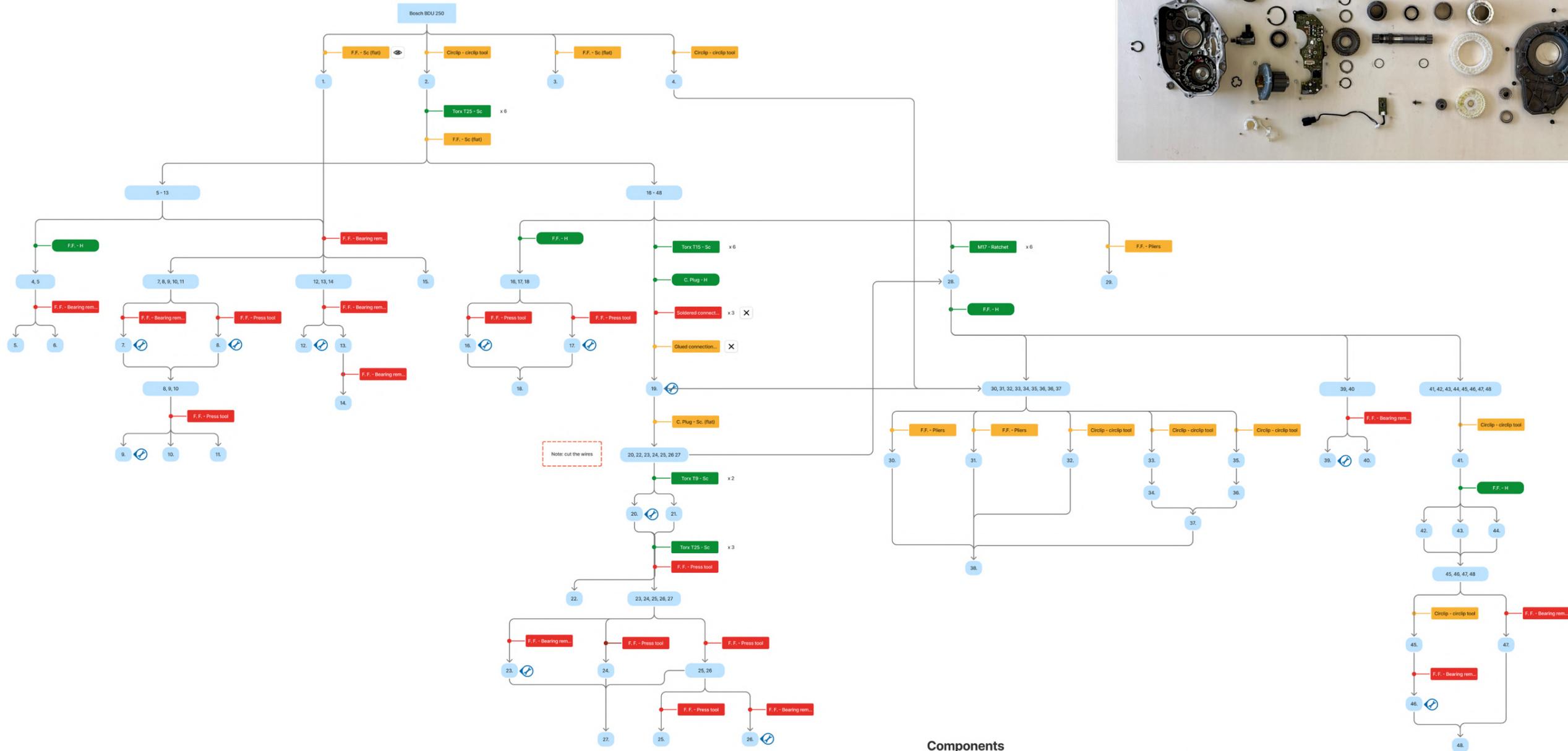
## BAFANG M210



### Components

1. Chaining
2. Water seal
3. Motherboard cover
4. Motherboard
5. Rubber connector protector
6. Trapas-ring 1
7. Circclip 1
8. Trapas-ring 2
9. Freewheel stop
10. Freewheel stop spring
11. Torque sensor
12. Circclip 2
13. Plastic cover
14. Bearing 6008 RS
15. Circclip 3
16. Crankshaft
17. Bearing 629RS
18. Casing right half
19. Seal ring
20. Bearing 69072RS1
21. Circclip
22. Freebody sub-assembly (incl. needle bearings)
23. Nylon Gear





**Legend - Disassembly mapping**

**Tools**

- (H) = (H) Hard
- (T) = Tool
- (S) = 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**

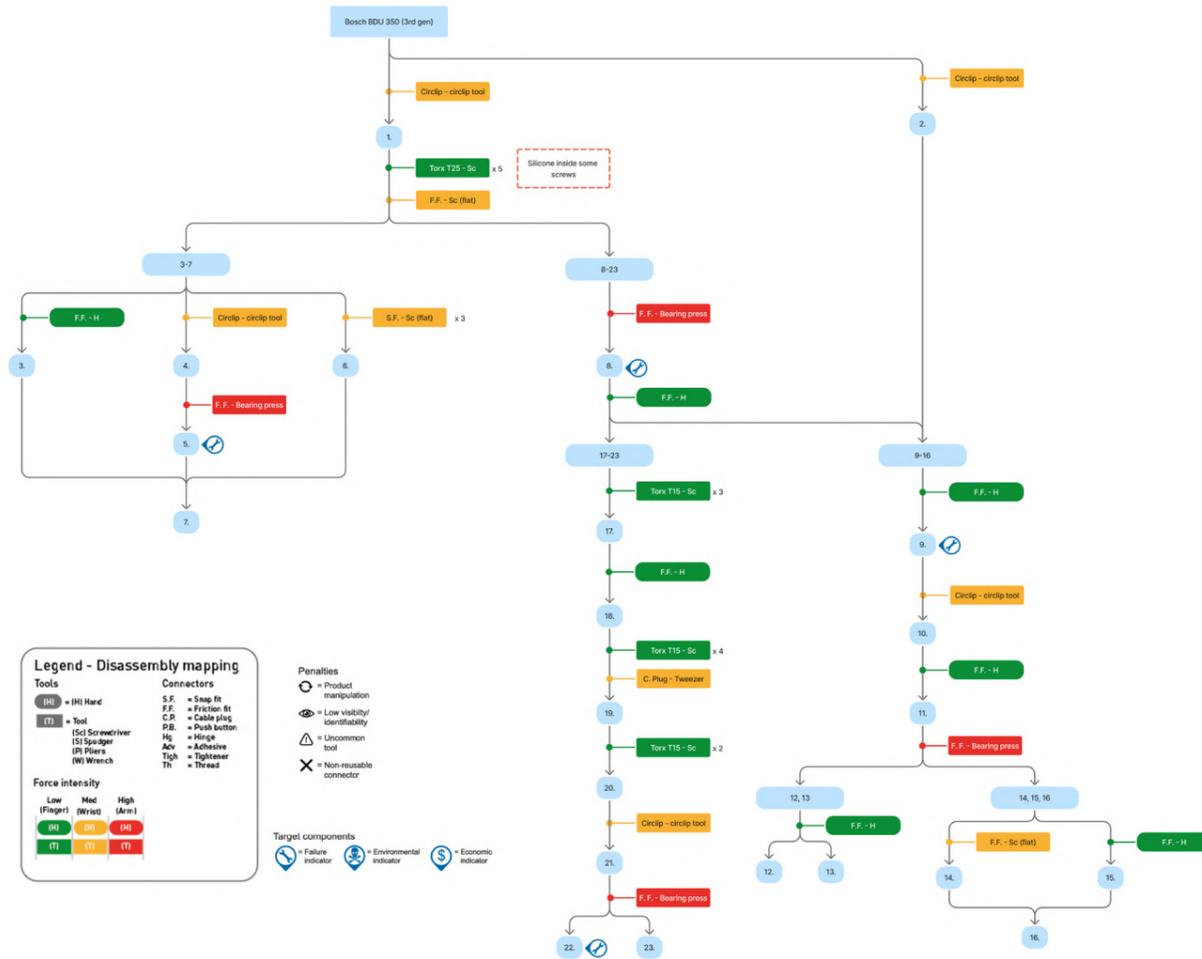
- ⦿ = Product manipulation
- 👁️ = Low visibility/identifiability
- ⚠️ = Uncommon tool
- ✗ = Non-reusable connector

**Target components**

- 🔍 = Failure indicator
- ♻️ = Environmental indicator
- 💰 = Economic indicator

**Components**

- |                      |                       |                                   |
|----------------------|-----------------------|-----------------------------------|
| 1. Plastic protector | 17. Bearing 4         | 33. Circclip 4                    |
| 2. Circclip 1        | 18. Metal base 2      | 34. Metal ring 2                  |
| 3. Foam ring         | 19. Motherboard       | 35. Circclip 5                    |
| 4. Circclip 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. Circclip 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. Circclip 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. Circclip 3        | 48. Gear assembly holder          |



**Legend - Disassembly mapping**

**Tools**  
 (H) = HI Hand  
 (T) = Tool  
 (S) = Screwdriver  
 (S) = Sprayer  
 (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

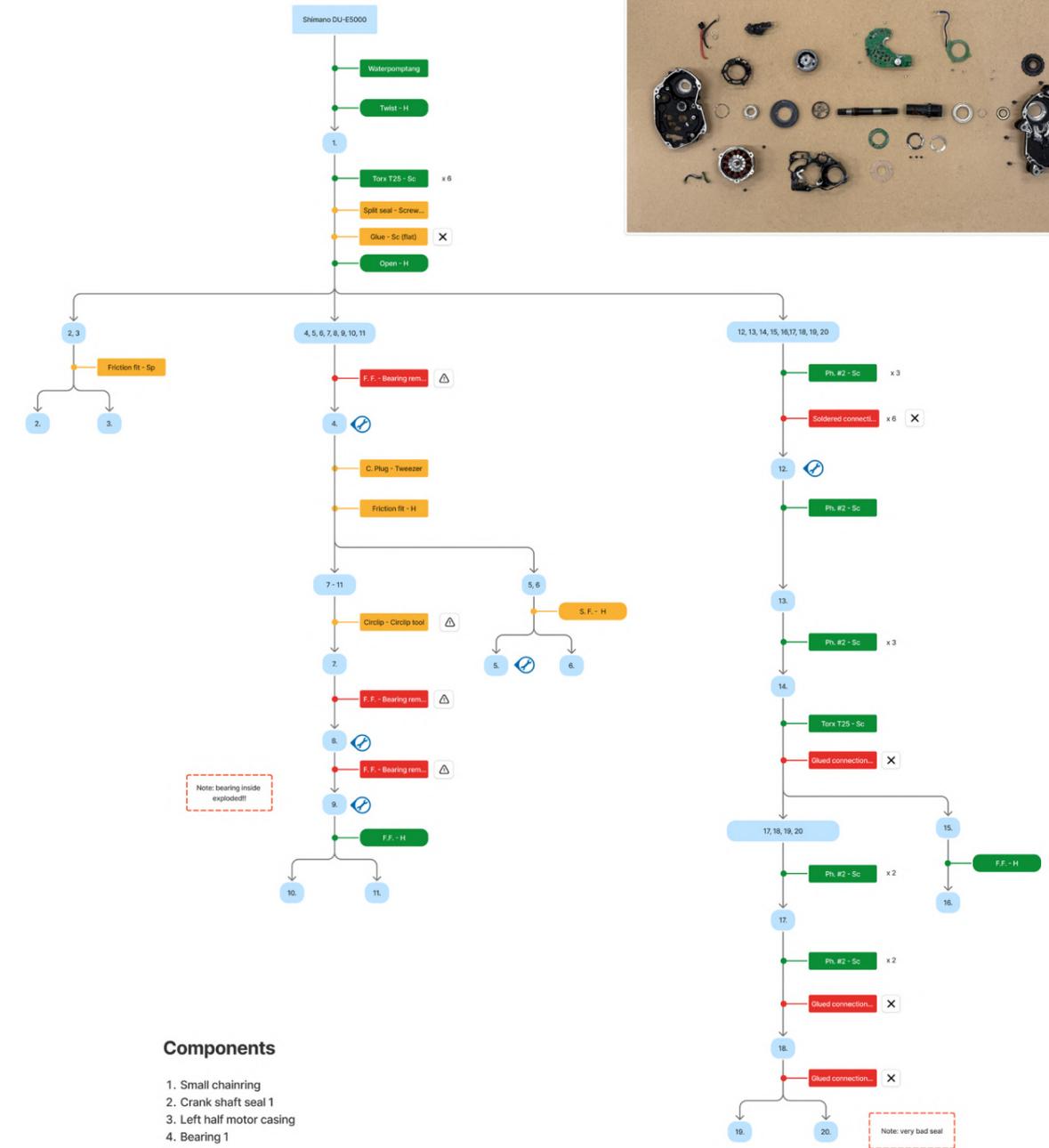
**Force intensity**  
 Low (Finger) (Wrist) (Arm)  
 Med (H) (M) (L)  
 High (T) (T) (T)

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

**Target components**  
 Failure indicator  
 Environmental indicator  
 Economic indicator

**Components**

1. Circlip 1
2. Circlip 2
3. Spring ring
4. Circlip 3
5. Bearing 6906-ZV (CW)
6. Plastic cover part
7. Casing half
8. Bearing 608-Z (CW)
9. Nylon gear, incl. freewheel mechanism
10. Circlip 4
11. Rubber ring
12. Rubber ring
13. Inner crankshaft
14. Rubber ring
15. Water seal
16. Outer crankshaft
17. Plastic motherboard protector
18. Connector plug
19. Motherboard
20. Torque sensor assembly (incl. plug)
21. Circlip 5
22. Bearing 18\*33\*8-ZV (CW)
23. Casing half



**Components**

1. Small chainring
2. Crank shaft seal 1
3. Left half motor casing
4. Bearing 1
5. Sensor
6. Plastic sensor mount
7. Circlip
8. Bearing 2
9. Bearing 3
10. Gear (with exploding bearing inside)
11. Crankshaft
12. Main PCB
13. Round sensor
14. Plastic motor cap
15. Metal casing
16. Electromotor
17. Small sensor
18. Cable connector 1
19. Cable connector 2
20. Right half motor casing

**Legend - Disassembly mapping**

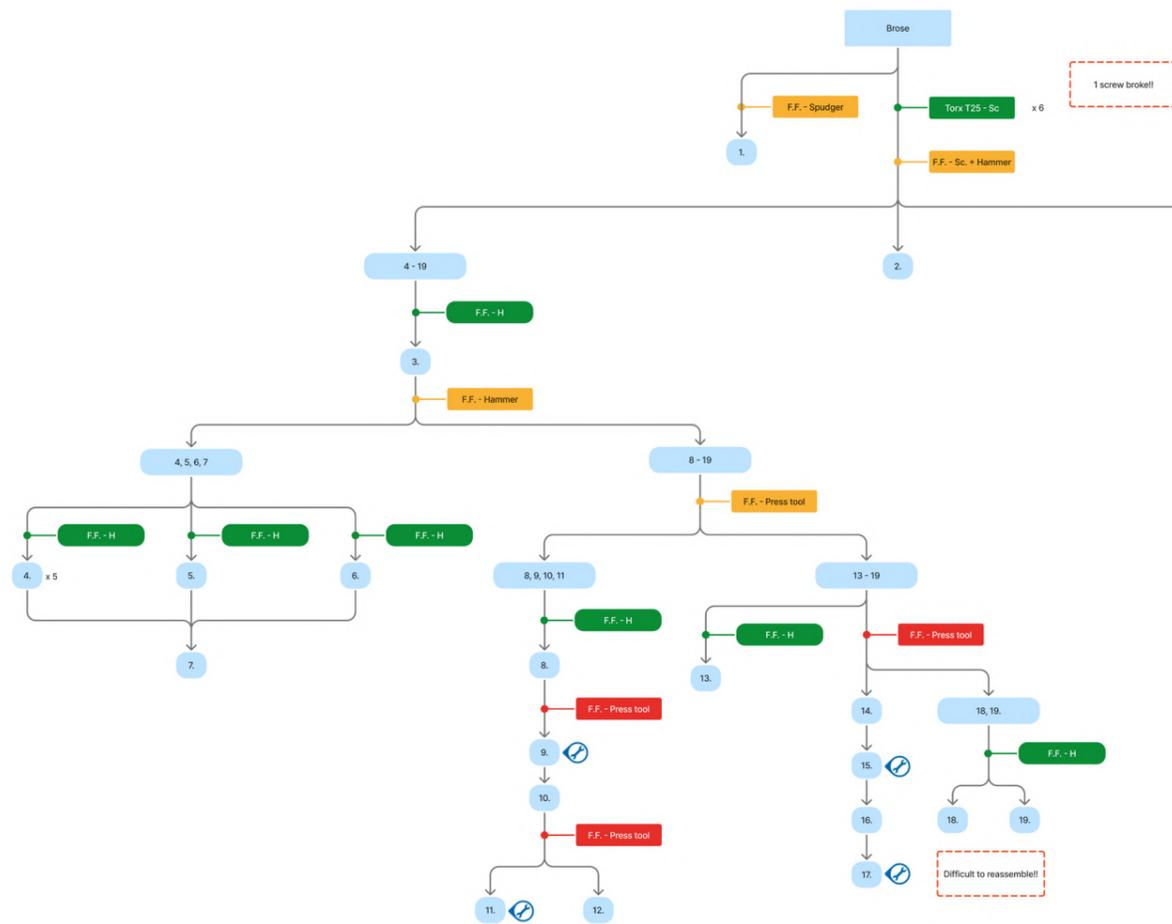
**Tools**  
 (H) = HI Hand  
 (T) = Tool  
 (S) = Screwdriver  
 (S) = Sprayer  
 (P) = Pliers  
 (W) = Wrench

**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) (Wrist) (Arm)  
 Med (H) (M) (L)  
 High (T) (T) (T)

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

**Target components**  
 Failure indicator  
 Environmental indicator  
 Economic indicator



**Components**

1. S-works cap incl. membrane
2. Gasket
3. Plastic grease retention peace
4. Thermal paste
5. Plastic ring
6. Seal ring
7. Casing
8. Freewheel bearing
9. Bearing 6805-ZV
10. Bearing spacer
11. Bearing 6805-ZV
12. Crankshaft
13. Ring
14. Metal ring
15. Bearing 6807-LBV
16. Metal spacer ring
17. Gear (metal)
18. Freewheel bearing
19. Torque sensor assembly
20. Spring ring
21. Seal ring
22. Small PCB
23. Plastic PCB holder
24. Motherboard
25. Torque sensor part
26. Connector (motor → motherboard)
27. Gearbox assembly
28. Rotor
29. Spring ring
30. Seal ring
31. Casing incl. stator assembly



**Legend - Disassembly mapping**

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

**Force intensity**

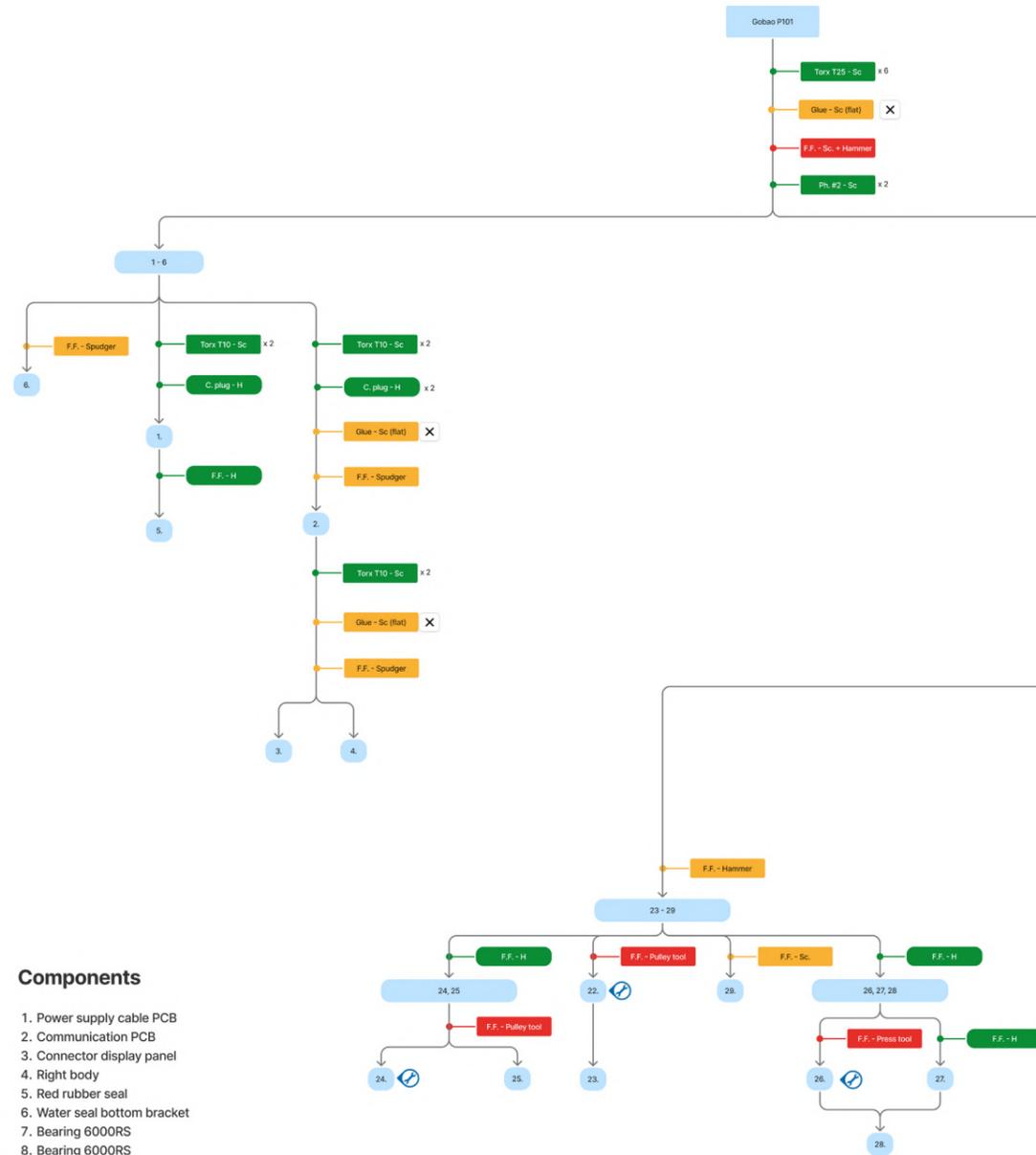
Low (Finger)	Med (Wrist)	High (Arm)
(H)	(H)	(H)
(T)	(T)	(T)

**Penalties**

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

**Target components**

- = Failure indicator
- = Environmental indicator
- = Economic indicator



**Components**

1. Power supply cable PCB
2. Communication PCB
3. Connector display panel
4. Right body
5. Red rubber seal
6. Water seal bottom bracket
7. Bearing 6000RS
8. Bearing 6000RS
9. Spacer
10. Big metal gear
11. Torque sensor part 1
12. Circlip 1
13. Spring ring
14. Circlip 2
15. Bearing 6805Z
16. Magnet
17. Torque sensor part 2
18. Plastic holder torque sensor
19. Crankshaft assembly
20. Main PCB
21. Casing and motor assembly
22. Bearing 61808 RS
23. Big gear assembly
24. Bearing 608Z
25. Nylon gear
26. Bearing 6201Z
27. Freewheel bearing
28. Metal gear including axle
29. Seal ring

**Legend - Disassembly mapping**

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

**Force intensity**

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

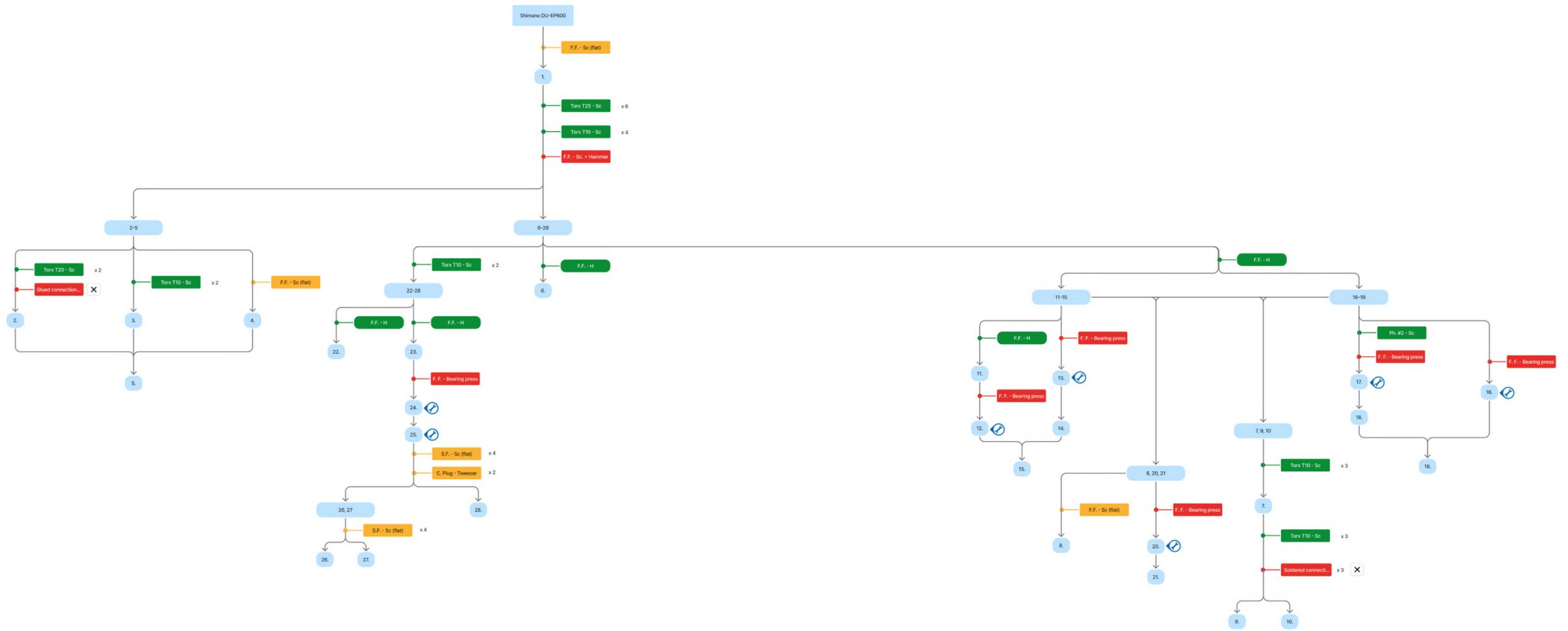
**Penalties**

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

**Target components**

- Failure indicator
- Environmental indicator
- Economic indicator





**Components**

- 1. Plastic outer protection ring
- 2. Plastic connector
- 3. Small PCB
- 4. Seal ring
- 5. Casing half
- 6. Cable spacer
- 7. Plastic motherboard protector
- 8. Seal ring
- 9. Motherboard
- 10. Casing incl. motor
- 11. Spring ring
- 12. Bearing 608-Z (NMB)
- 13. Bearing 608-Z (NMB)
- 14. Freewheel mechanism
- 15. Axle incl. gear
- 16. Bearing 608-Z (NMB)
- 17. Bearing 608-Z (NMB)
- 18. Nylon gear
- 19. Axle incl. gear
- 20. Bearing 6907-Z (NSK)
- 21. Crankshaft freewheel hub
- 22. Torque sensor
- 23. Spring ring
- 24. Bearing 6805-Z (NTN)
- 25. Magnet (ring)
- 26. Plastic sensor holder
- 27. Torque sensor
- 28. Crank shaft incl. freewheel mechanism

**Legend - Disassembly mapping**

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

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

**Penalties**

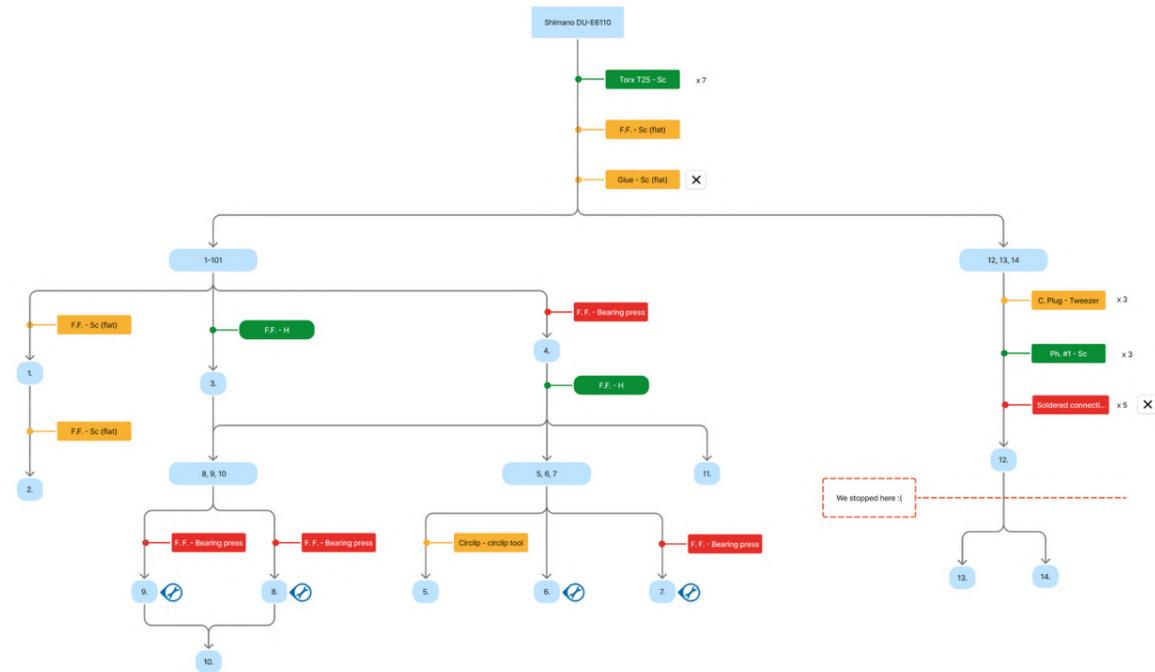
- ⌚ = Product manipulation
- 👁️ = Low visibility/identifiability
- ⚠️ = Uncommon tool
- ✖️ = Non-reusable connector

**Target components**

- 🚫 = Failure indicator
- ♻️ = Environmental indicator
- 💰 = Economic indicator



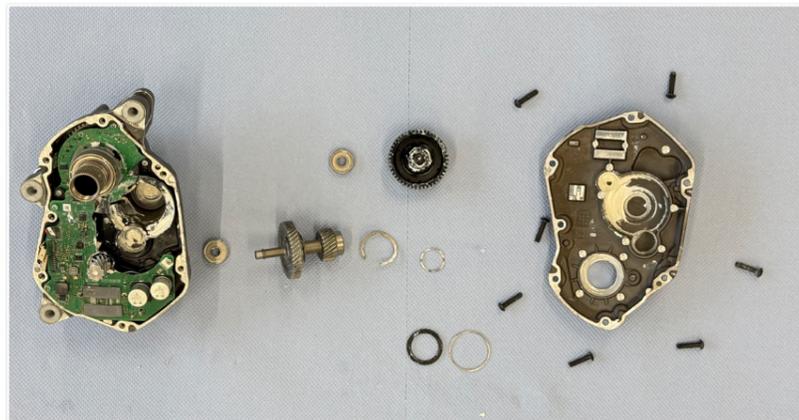


**Components**

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

**Legend - Disassembly mapping**

<b>Tools</b>	<b>Connectors</b>	<b>Penalties</b>
(H) = (H) Hand	S.F. = Snap fit	⊙ = Product manipulation
(T) = Tool	FF. = Friction fit	👁 = Low visibility/identifiability
(Sc) = Screwdriver	C.P. = Cable plug	⚠ = Uncommon tool
(S) = Spudger	P.B. = Push button	✗ = Non-reusable connector
(P) = Pliers	Hg. = Hinge	
(W) = Wrench	Adv. = Adhesive	
	Tigh. = Tightener	
	Th. = Thread	
<b>Force intensity</b>		<b>Target components</b>
Low (Finger)	Med (Wrist)	👁 = Failure indicator
(L)	(M)	♻ = Environmental indicator
(L)	(M)	💰 = Economic indicator
High (Arm)	(H)	
(H)	(H)	



## APPENDIX E - MOTOR COMPARISON

Step/subassembly	Part	Bosch BDU 250	Bosch BDU350	Bafang M210	Brose Specialized	Shimano DU-E5000	Shimano DU-EP600	Shimano DU-E6110	Ananda M81	Gobao P101
Splitting casing	TX25	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
	Inbus 3	No	No	No	No	No	No	No	Yes	No
	Philips #2	No	No	No	No	No	No	No	No	Yes
	Circlip(s)	Yes	Yes	Yes	No	Yes	No	No	No	Yes
	Friction fit	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Non-reversible seal	No	No	No	No	Yes	Yes	Yes	No	Yes
	Reversible seal	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
Casing half assembly 01	Seal ring	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Connectors	No	No	No	No	No	Yes	No	No	Yes
	Small PCB	No	No	No	No	No	Yes	No	No	Yes
Casing half assembly 02	Motor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Seal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Connectors	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
	Motherboard cover	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No
	Soldered motherboard	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
	Seperate motherboard	No	Yes	Yes	Yes	No	No	No	No	No
	Thermal paste	No	Yes	Yes	Yes	No	No	No	No	Yes
Crankshaft assembly	Crankshaft	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Metal gear	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
	Plastic gear	Yes	Yes	Yes	No	No	No	No	No	No
	Freewheel hub	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Torque sensor	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Bearings	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Circlips	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes
Transmission (motor to crankshaft)	Metal gears	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes
	Nylon gears	Yes	No	No	No	No	No	No	Yes	Yes
	Searate gear stations	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
	Complete gear assembly	No	No	No	Yes	No	No	No	No	No
Number of parts	TX25	9	5	5	6	6	6	7	0	6
	TX20	0	0	3	0	0	2	0	0	0
	TX15	6	9	0	0	0	0	0	0	0

TX10	0	0	0	0	0	14	0	0	6
TX9	2	0	0	10	0	0	0	0	7
Inbus 3	0	0	0	0	0	0	0	6	0
Philips #2	0	0	9	0	11	1	3	2	0
Circlip(s)	7	5	3	0	1	0	1	2	2
Bearings	8	3	3	3	3	6	4	4	5
Metal gears	3	0	0	1	2	3	4	1	3
Plastic gears	2	1	1	0	0	0	0	1	1
Total parts	48	23	23	31	20	28	12	21	29

Specifications

Type of seal	Transparent silicone seal line	Transparent silicone seal line	Separate gasket	Separate gasket	Glued, very bad	Glued, very bad	Glued, very bad	Black silicone seal ring	Glued, hard to remove
Bearing types	N.t.b.	6906 ZV 608 Z 18*33*8 ZV	6008 RS 629RS 69072RS1	2x 6805 ZV 6807 LBV	N.t.b.	4x 608 Z 6907 Z 6805 Z	4x 608 Z	2x 6907 RS 61903 RS 6901RS	2x 6000 RS 6805 Z 61808 RS 608Z

Points of interest	Risk of water ingress	Medium	Low	Low	Low	High	High	High	Medium	Low
	Motherboard removable	No	Yes	Yes	Yes	No	No	No	No	Yes
	Crankshaft removable	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
	Bearings accessible	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes

Conclusion	Chances for repair	Medium	High	Low	High	Medium	Medium	Low	Medium	High
------------	--------------------	--------	------	-----	------	--------	--------	-----	--------	------

### HotSpot Mapping Datasheet

#### General project information

Brand name	Bosch Gen3
Product category	E-bike motor
Authors	Dion Vijverberg
Date	Oct-25
Location	Delft

#### Overall HotSpot Results

<b>Total:</b>		<b>Average:</b>	
- time to disassemble	320 sec	- time per step	10,7 sec/step
- number of tasks	39	- force	4 [1=low .. 5=high .. 10=extreme]
- number of steps	30	- accessibility	2 [1=clear .. 5=moderate .. 10=difficult]
- number of tools	4	- positioning	2 [1=easy .. 5=moderate .. 10=difficult]

Step number	Name	General		Activity				Accessibility			Functional		Material		HotSpot Indicators					Notes	
		Subassembly?	Part of ...	Type of activity	Required tool	Tool size	Task frequency	Total time to disconnect (sec)	Force	Accessibility	Positioning	Failure Likelihood	Functional relevance	Material group	Weight (g)	Time	Activity	Priority part	Environmental		Economic
1	Circlip	no		Remove	Pliers		1	5	level 2	level 1	level 1	level 0	level 0	Stainless Steel	5		▶				
2	Circlip	no		Remove	Pliers		1	5	level 2	level 1	level 1	level 0	level 0	Stainless Steel	5		▶				
3	Left half casing	yes	main assembly	Unscrew	Screwdriver	TX25	5	50	level 1	level 0	level 0	No to low precision			▶						
4	Left half casing	yes	main assembly	Remove	Screwdriver	Flat	1	10	level 1	level 1	level 1	Moderate precision				▶					
5	Spring ring	no		Remove	Hands		1	5	level 0	level 0	level 0	level 0	level 0	Stainless Steel	2						
6	Circlip	no		Remove	Pliers		1	5	level 2	level 1	level 1	level 0	level 0	Stainless Steel	5		▶				
7	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2	level 0	level 1	level 2	level 2	Mixed materials mainly	50	▶	▶	▶			
8	Plastic cover	no		Remove	Screwdriver	Flat	1	10	level 1	level 1	level 1	level 0	level 0	Thermoplastic	20		▶				
9	Left half casing	no		Remove	Hands		1	0	level 0	level 0	level 0	level 0	level 1	Aluminium	500				▶	▶	
10	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2	level 0	level 1	level 2	level 2	Mixed materials mainly	25	▶	▶	▶			
11	Crankshaft	yes	main assembly																		
12	Nylon gear	no		Remove	Hands		1	5	level 0	level 0	level 0	level 1	level 2	Thermoplastic	100			▶			
13	Circlip	no		Remove	Pliers		1	5	level 2	level 1	level 1	level 0	level 0	Stainless Steel	5		▶				
14	Rubber ring	no		Remove	Hands		1	5	level 0	level 0	level 0	level 0	level 0	Rubber	2						
15	Inner crankshaft	yes	Crankshaft	Remove	Proprietary tool		1	20	level 2	level 0	level 0	No to low precision			▶	▶					
16	Rubber ring	no		Remove	Hands		1	5	level 0	level 0	level 0	level 0	level 0	Rubber	2						
17	Inner crankshaft	no		Remove	Hands		1	0	level 0	level 0	level 0	level 0	level 2	Steel	300				▶		
18	Outer crankshaft	yes	Crankshaft	Remove	Hands		1	0	level 0	level 0	level 0	No to low precision									
19	Rubber ring	no		Remove	Lever / Prybar		1	10	level 0	level 0	level 0	level 0	level 0	Rubber	2						
20	Water seal	no		Remove	Hands		1	5	level 0	level 0	level 0	level 0	level 0	Foam	2						
21	Left half casing	no		Remove	Hands		1	0	level 0	level 0	level 0	level 0	level 1	Aluminium	500				▶	▶	
22	Right half casing	yes		Remove	Hands		1	0	level 0	level 0	level 0	No to low precision									
23	Plastic cover	no		Unscrew	Screwdriver	TX15	3	30	level 0	level 0	level 0	level 0	level 0	Thermoplastic	20	▶					
24	Connector plug	no		Unplug	Hands		1	10	level 0	level 0	level 0	level 0	level 0	Thermoplastic	20						
25	Motherboard	no		Unscrew	Screwdriver	TX15	3	30	level 0	level 0	level 0	level 0	level 2	PCB	200	▶			▶	▶	
26	Motherboard	no		Unplug	Pliers		1	10	level 0	level 0	level 0	level 0	level 2	PCB	200				▶	▶	
27	Torque sensor	no		Unscrew	Screwdriver	TX15	3	30	level 0	level 0	level 0	level 1	level 2	Other Electronics	20	▶		▶			▶
28	Circlip	no		Remove	Pliers		1	5	level 2	level 1	level 1	level 0	level 0	Stainless Steel	5		▶				
29	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2	level 0	level 1	level 2	level 2	Mixed materials mainly	50	▶	▶	▶			
30	Right half casing	no		Remove	Hands		1	0	level 0	level 0	level 0	level 0	level 1	Aluminium	1500				▶	▶	

## HotSpot Mapping Datasheet

### General project information

Brand name	Bosch Gen3
Product category	E-bike motor
Authors	Dion Vijverberg
Date	Oct-25
Location	Delft

### Overall HotSpot Results

<b>Total:</b>		<b>Average:</b>	
- time to disassemble	340 sec	- time per step	10 sec/step
- number of tasks	50	- force	● 3 [1=low .. 5=high .. 10=extreme]
- number of steps	34	- accessibility	● 1 [1=clear .. 5=moderate .. 10=difficult]
- number of tools	4	- positioning	● 2 [1=easy .. 5=moderate .. 10=difficult]

Step number	Name	General		Activity				Accessibility			Functional		Material		HotSpot Indicators					Notes
		Subassembly?	Part of ...	Type of activity	Required tool	Tool size	Task frequency	Total time to disconnect (sec)	Force	Accessibility	Positioning	Failure Likelihood	Functional relevance	Material group	Weight (g)	Time	Activity	Priority part	Environmental	
1	Left half casing	yes	main assembly	Unscrew	Screwdriver	TX25	6	60	level 1 - level 0 - level 0	No to low precision					▲					
2	Left half casing	yes	main assembly	Remove	Screwdriver	Flat	1	10	level 1 - level 1 - level 1	Moderate precision						▶				
3	Gasket	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 1 - Thermoplastic	5									
4	Plastic cover	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 0 - Thermoplastic	10									
5	Left half casing 2	yes	Left half casing	Remove	Screwdriver		1	10	level 1 - level 0 - level 0	No to low precision										
6	Thermal paste	no		Remove	Hands		4	5	level 0 - level 0 - level 0	level 0 - level 1 - Foam	4									
7	Seal ring	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 1 - Rubber	2									
8	Crankshaft	yes	main assembly	Remove	Hands		1	0	level 0 - level 0 - level 0	No to low precision										
9	Inner crankshaft	yes	Crankshaft	Remove	Lever / Prybar		1	5	level 1 - level 0 - level 0	No to low precision										
10	Freewheel bearing	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 1 - level 2 - Mixed materials mainly	50					▶	▶	▶		
11	Bearing	no		Remove	Lever / Prybar	Small	1	20	level 2 - level 0 - level 1	level 2 - level 2 - Mixed materials mainly	50	▶	▶			▶	▶	▶		
12	Bearing spacer	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 1 - Steel	5									
13	Bearing	no		Remove	Lever / Prybar	Small	1	20	level 2 - level 0 - level 1	level 2 - level 2 - Mixed materials mainly	50	▶	▶			▶	▶	▶		
14	Crankshaft	no		Remove	Hands		1	0	level 0 - level 0 - level 0	level 0 - level 2 - Steel	300						▶			
15	Outer crank shaft	yes	Crankshaft	Remove	Hands		1	0	level 0 - level 0 - level 0	No to low precision										
16	Metal ring	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 1 - Steel	2									
17	Bearing	no		Remove	Lever / Prybar	Small	1	20	level 2 - level 0 - level 1	level 2 - level 2 - Mixed materials mainly	50	▶	▶			▶	▶	▶		
18	Metal ring	no		Remove	Hands		1	0	level 0 - level 0 - level 0	level 0 - level 1 - Steel	2									
19	Gear	no		Remove	Hands		1	0	level 0 - level 0 - level 0	level 1 - level 2 - Steel	2						▶			
20	Freewheel bearing	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 1 - level 2 - Steel	50						▶			
21	Torque sensor	no		Remove	Hands		1	0	level 0 - level 0 - level 0	level 0 - level 2 - Main functionality	100									
22	Right half casing	yes	main assembly	Remove	Hands		1	0	level 0 - level 0 - level 0	No to low precision										
23	Spring ring	no		Remove	Hands		1	5	level 0 - level 0 - level 0	level 0 - level 0 - Steel	2									
24	Seal ring	no		Remove	Lever / Prybar		1	5	level 1 - level 0 - level 0	level 0 - level 1 - Rubber	5									
25	Motherboard	yes	Right half casing	Unscrew	Screwdriver	TX9	5	50	level 0 - level 0 - level 0	No to low precision					▶					
26	Motherboard	yes	Right half casing	Unplug	Hands		1	5	level 0 - level 0 - level 0	No to low precision										
27	Motherboard	yes	Right half casing	Remove	Screwdriver	Flat	1	10	level 0 - level 0 - level 0	No to low precision										
28	Small PCB	no		Remove	Screwdriver	flat	1	10	level 1 - level 0 - level 0	level 0 - level 2 - PCB	15							▶	▶	
29	PCB holder	no		Remove	Hands		1	0	level 1 - level 0 - level 0	level 0 - level 0 - Thermoplastic	10									
30	Motherboard	no		Remove	Hands		1	0	level 1 - level 0 - level 0	level 0 - level 2 - PCB	200							▶	▶	
31	Torque sensor	no		Remove	Hands		1	10	level 0 - level 0 - level 1	level 0 - level 2 - PCB	20							▶	▶	
32	Connector part	no		Remove	Lever / Prybar		1	10	level 1 - level 0 - level 0	level 0 - level 1 - Thermoplastic	10									
33	Gearbox	no		Unscrew	Screwdriver	TX9	5	50	level 0 - level 0 - level 0	level 1 - level 2 - Steel	400	▶					▶	▶		
34	Right half casing	no		Remove	Hands		1	0	level 0 - level 0 - level 0	level 1 - level 2 - Mixed materials mainly	1500						▶	▶	▶	

# HotSpot Mapping Datasheet

## General project information

Brand name	Shimano DU-E5000
Product category	E-bike motor
Authors	Dion Vijverberg
Date	Oct-25
Location	Delft

## Overall HotSpot Results

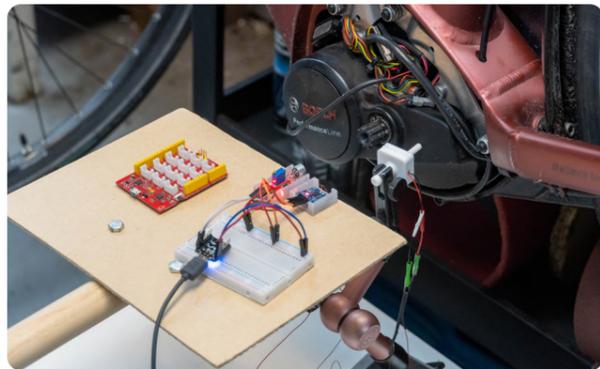
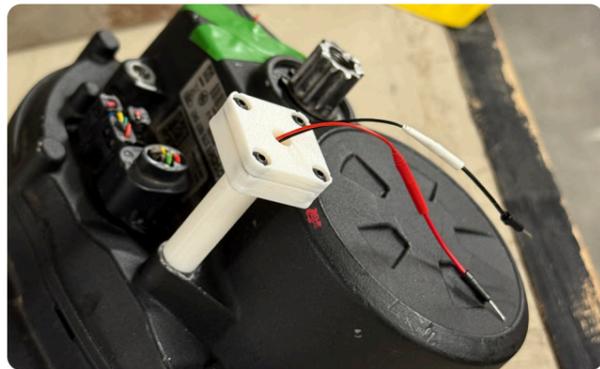
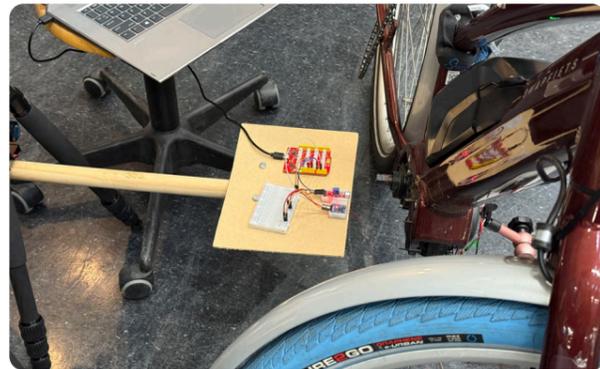
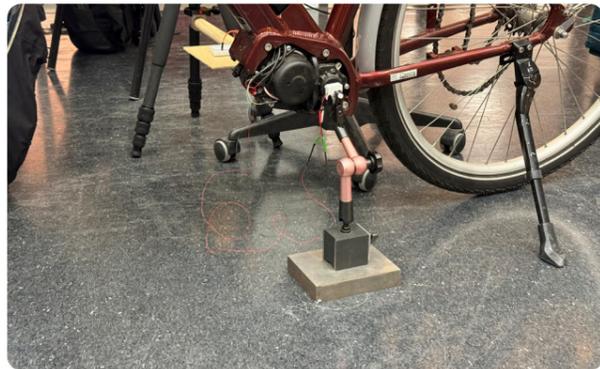
<b>Total:</b>		<b>Average:</b>	
- time to disassemble	165 sec	- time per step	10,3 sec/step
- number of tasks	22	- force	5 [1=low .. 5=high .. 10=extreme]
- number of steps	16	- accessibility	2 [1=clear .. 5=moderate .. 10=difficult]
- number of tools	4	- positioning	5 [1=easy .. 5=moderate .. 10=difficult]

General		Activity			Accessibility			Functional		Material		HotSpot Indicators					Notes				
Step number	Name	Subassembly?	Part of ...	Type of activity	Required tool	Tool size	Task frequency	Total time to disconnect (sec)	Force	Accessibility	Positioning	Failure Likelihood	Functional relevance	Material group	Weight (g)	Time		Activity	Priority part	Environmental	Economic
1	Left half casing	yes	main assembly	Unscrew	Screwdriver	TX25	6	60	level 1 - level 0	level 0	No to low precision					▶					
2	Left half casing	yes	main assembly	Remove	Screwdriver	Flat	1	10	level 1 - level 1	level 1	Moderate precision						▶				
3	Seal ring	no		Peel off	Lever / Prybar		1	5	level 1 - level 0	level 1		level 1 - level 1	Rubber	5							
4	Left half casing	no		Remove	Hands		1	0	level 0 - level 0	level 0		level 0 - level 1	Aluminium	500				▶	▶		
5	Crankshaft	yes	main assembly	Remove	Hands		1	0	level 0 - level 0	level 0	No to low precision										
6	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2 - level 0	level 1		level 2 - level 2	Mixed materials mainly	50	▶	▶	▶			▶	
7	Torque sensor	yes	Crankshaft	Unplug	Pliers	Small	2	5	level 0 - level 0	level 2	High precision						▶				
8	Torque sensor	yes	Crankshaft	Remove	Hands		1	5	level 1 - level 1	level 2	High precision						▶				
9	Plastic holder	no		Remove	Hands		1	10	level 1 - level 0	level 2		level 0 - level 0	Thermoplastic	10		▶					
10	Torque sensor	no		Remove	Hands		1	0	level 0 - level 0	level 2		level 2 - level 2	PCB	15			▶	▶		▶	
11	Circlip	no		Remove	Pliers		1	5	level 2 - level 1	level 1		level 0 - level 0	Stainless Steel	5		▶					
12	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2 - level 0	level 1		level 2 - level 2	Mixed materials mainly	50	▶	▶	▶			▶	
13	Bearing	no		Remove	Lever / Pryba	Small	1	20	level 2 - level 0	level 1		level 2 - level 2	Mixed materials mainly	50	▶	▶	▶			▶	
14	Gear	no		Remove	Hands		1	5	level 1 - level 0	level 1		level 1 - level 2	Steel	100			▶				
15	Crankshaft	no		Remove	Hands		1	0	level 0 - level 0	level 0		level 0 - level 2	Steel	300				▶			
16	Right half casing	no		Remove	Hands		1	0	level 0 - level 0	level 0		level 1 - level 2	Mixed materials mainly	2000			▶	▶		▶	

## APPENDIX G - TEST SETUP

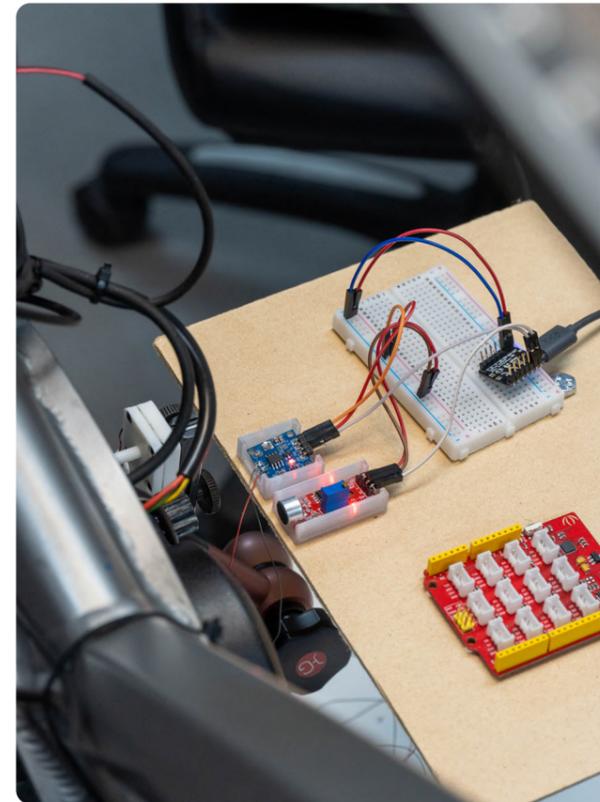
### ITERATIONS

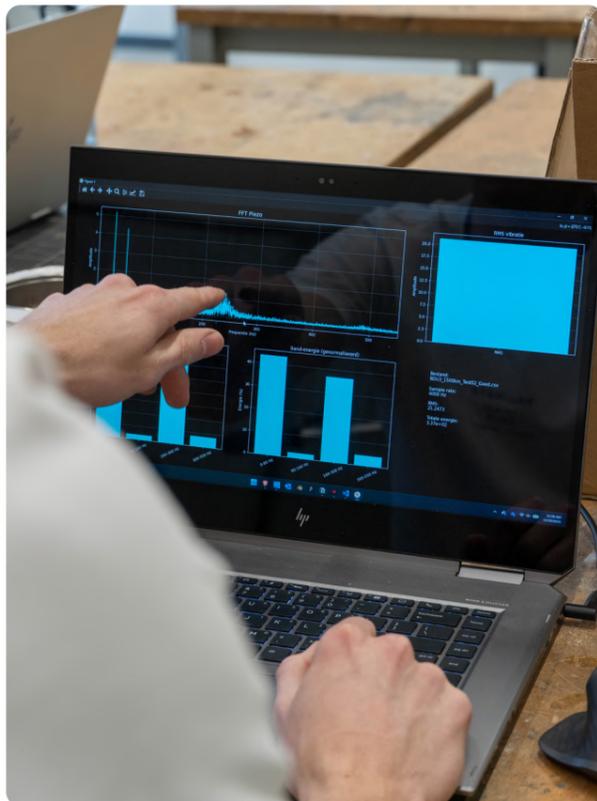
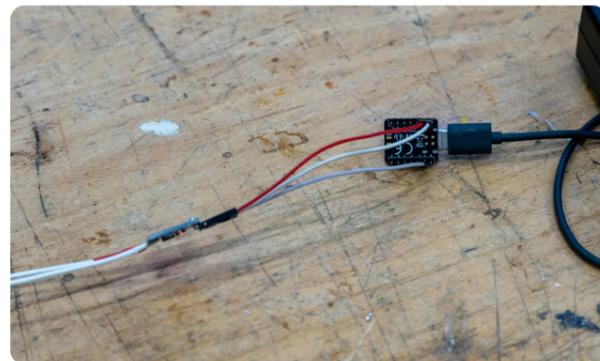
Prototype and piezo mounting iterations



### EXTRA PHOTOS

Bosch BDU 350 test





## APPENDIX H - PROTOTYPE SOFTWARE

### ARDUINO CODE

```
const int MIC_PIN = A0;
const int PIEZO_PIN = A1;

const int MIC_BASELINE = 530;
const int PIEZO_BASELINE = 15;

unsigned long lastMicros = 0;
const unsigned long SAMPLE_INTERVAL = 100;

void setup() {
  Serial.begin(230400);
}

void loop() {
  unsigned long now = micros();
  if (now - lastMicros >= SAMPLE_INTERVAL) {
    lastMicros = now;

    int micRaw = analogRead(MIC_PIN);
    int piezoRaw = analogRead(PIEZO_PIN);
    int micAmp = micRaw - MIC_BASELINE;
    int piezoAmp = (piezoRaw - PIEZO_BASELINE)*5;

    Serial.print(micAmp);
    Serial.print(",");
    Serial.println(piezoAmp);
  }
}
```

### PYTHON SCRIPT FOR DATA COLLECTION AND VISUALISATION

```
import serial
import numpy as np
import pyqtgraph as pg
from PyQt6 import QtWidgets, QtCore
import time
import csv
from datetime import datetime

# === Serial setup ===
ser = serial.Serial("COM4", 230400)

# === Buffers ===
buffer_size = 1000
mic_buffer = np.zeros(buffer_size)
piezo_buffer = np.zeros(buffer_size)

# === Smoothing instelling ===
SMOOTH_WINDOW = 5

# === Flags en opslag ===
save_flag = False
save_data = [] # opgeslagen rijen [timestamp, mic, piezo]
```

```

# === PyQt GUI setup ===
app = QtWidgets.QApplication([])

container = QtWidgets.QWidget()
layout = QtWidgets.QVBoxLayout()
container.setLayout(layout)

win = pg.GraphicsLayoutWidget()
win.setBackground('k')
layout.addWidget(win)

# ===== GRAPH 1: MICROFOON =====
plot_mic = win.addPlot(title="Microphone (A0)")
plot_mic.setYRange(-25, 25)
plot_mic.showGrid(x=True, y=True)
plot_mic.setLabel('left', 'Amplitude')
plot_mic.setLabel('bottom', 'Samples')
curve_mic = plot_mic.plot(
    mic_buffer, pen=pg.mkPen('c', width=2), antialias=True)

# ===== GRAPH 2: PIEZO =====
win.nextRow()
plot_piezo = win.addPlot(title="Piezo (A1)")
plot_piezo.setYRange(-25, 200)
plot_piezo.showGrid(x=True, y=True)
plot_piezo.setLabel('left', 'Amplitude')
plot_piezo.setLabel('bottom', 'Samples')
curve_piezo = plot_piezo.plot(
    piezo_buffer, pen=pg.mkPen('c', width=2), antialias=True)

# ===== KNOP =====
button = QtWidgets.QPushButton("Save 10s (Mic + Piezo)")
button.setStyleSheet(
    "background-color: cyan; color: black; font-size: 14px; font-weight: bold;"
)
layout.addWidget(button)

# === Update functie ===
def update():
    global mic_buffer, piezo_buffer, save_flag, save_data

    while ser.in_waiting:
        try:
            line = ser.readline().decode("utf-8", errors='ignore').strip()

            # Verwacht: "mic,piezo"
            parts = line.split(",")
            if len(parts) != 2:
                continue

            mic_val = float(parts[0])
            piezo_val = float(parts[1])

            # Schuif buffers
            mic_buffer[-1] = mic_buffer[1:]
            mic_buffer[-1] = mic_val

            piezo_buffer[-1] = piezo_buffer[1:]
            piezo_buffer[-1] = piezo_val

            # Opslaan?

```

```

        if save_flag:
            timestamp = datetime.now().strftime("%H:%M:%S.%f")[:-3]

            mic_str = str(mic_val).replace('.', ',')
            piezo_str = str(piezo_val).replace('.', ',')

            save_data.append([timestamp, mic_str, piezo_str])

        except:
            continue # laat de GUI doorlopen

# --- smoothing voor plot ---
smooth_mic = np.convolve(mic_buffer, np.ones(
    SMOOTH_WINDOW)/SMOOTH_WINDOW, mode='same')
smooth_piezo = np.convolve(piezo_buffer, np.ones(
    SMOOTH_WINDOW)/SMOOTH_WINDOW, mode='same')

curve_mic.setData(smooth_mic)
curve_piezo.setData(smooth_piezo)

# Timer
timer = QtCore.QTimer()
timer.timeout.connect(update)
timer.start(10)

# === Save functie (10 sec) ===
def save_10_seconds():
    global save_flag, save_data
    save_flag = True
    save_data = []
    print("Saving mic + piezo for 10 seconds...")

    # Stop automatisch na 10 seconden
    QtCore.QTimer.singleShot(10000, finish_save)

def finish_save():
    global save_flag, save_data
    save_flag = False

    filename = f"mic_piezo_{int(time.time())}.csv"
    with open(filename, 'w', newline='') as f:
        writer = csv.writer(f, delimiter=',')
        writer.writerow(["timestamp", "mic", "piezo"])
        writer.writerows(save_data)

    print(f"CSV opgeslagen: {filename} met {len(save_data)} samples")

# Connect knop
button.clicked.connect(save_10_seconds)

container.show()
app.exec()

```

#### PYTHON SCRIPT FOR DATA ANALYSIS

```

import pandas as pd
import numpy as np

```

```

import matplotlib.pyplot as plt

# =====
# INSTELLINGEN
# =====
CSV_FILE = "ShimanoDU-E5000_Test02_Slecht1.csv"
Fs = 4000 # sample rate in Hz

bands = [(0, 80), (80, 160), (160, 300), (300, 550)]

# =====
# DATA INLADEN
# =====
df = pd.read_csv(CSV_FILE, sep=";",)

piezo = pd.to_numeric(
    df["piezo"].astype(str).str.replace(',', '.'),
    errors='coerce'
).values

piezo = piezo[~np.isnan(piezo)]

# =====
# RMS BEREKENEN (tijdsdomein)
# =====
piezo_dc = piezo - np.mean(piezo)
rms = np.sqrt(np.mean(piezo_dc**2))

# =====
# FFT FUNCTIE
# =====

def compute_fft(signal, Fs):
    N = len(signal)
    window = np.hanning(N)
    signal_win = signal * window
    X = np.fft.rfft(signal_win)
    freqs = np.fft.rfftfreq(N, d=1/Fs)
    amplitude = np.abs(X) * 2 / N
    return freqs, amplitude

freqs, amp = compute_fft(piezo_dc, Fs)

# =====
# BAND-ENERGIE BEREKENEN
# =====
band_energy = []
band_labels = []

for f_low, f_high in bands:
    idx = (freqs >= f_low) & (freqs < f_high)
    energy = np.sum(amp[idx]**2)
    band_energy.append(energy)
    band_labels.append(f"{f_low}-{f_high} Hz")

band_energy = np.array(band_energy)
total_energy = np.sum(amp**2)
band_energy_norm = band_energy / total_energy

# =====

```

```

# DASHBOARD FIGUUR
# =====
plt.style.use("dark_background")
fig = plt.figure(figsize=(14, 9))

# ---- FFT ----
ax1 = plt.subplot2grid((2, 3), (0, 0), colspan=2)
ax1.plot(freqs, amp, color="cyan", linewidth=1.2)
ax1.set_xlim(0, 550)
ax1.set_title("FFT Piezo", fontsize=14)
ax1.set_xlabel("Frequentie (Hz)")
ax1.set_ylabel("Amplitude")
ax1.grid(True, linestyle="--", alpha=0.4)

# ---- RMS ----
ax2 = plt.subplot2grid((2, 3), (0, 2))
ax2.bar(["RMS"], [rms], color="cyan")
ax2.set_title("RMS vibratie")
ax2.set_ylabel("Amplitude")
ax2.grid(True, axis="y", linestyle="--", alpha=0.4)

# ---- Band energie (absoluut) ----
ax3 = plt.subplot2grid((2, 3), (1, 0))
ax3.bar(band_labels, band_energy, color="cyan")
ax3.set_title("Band-energie (absoluut)")
ax3.set_ylabel("Energie")
ax3.tick_params(axis='x', rotation=30)
ax3.grid(True, axis="y", linestyle="--", alpha=0.4)

# ---- Band energie (genormaliseerd) ----
ax4 = plt.subplot2grid((2, 3), (1, 1))
ax4.bar(band_labels, band_energy_norm * 100, color="cyan")
ax4.set_title("Band-energie (genormaliseerd)")
ax4.set_ylabel("Energie (%)")
ax4.tick_params(axis='x', rotation=30)
ax4.grid(True, axis="y", linestyle="--", alpha=0.4)

# ---- Tekstvak met kernwaarden ----
ax5 = plt.subplot2grid((2, 3), (1, 2))
ax5.axis("off")

textstr = (
    f"Bestand:\n{CSV_FILE}\n\n"
    f"Sample rate:\n{Fs} Hz\n\n"
    f"RMS:\n{rms:.4f}\n\n"
    f"Totale energie:\n{total_energy:.2e}"
)

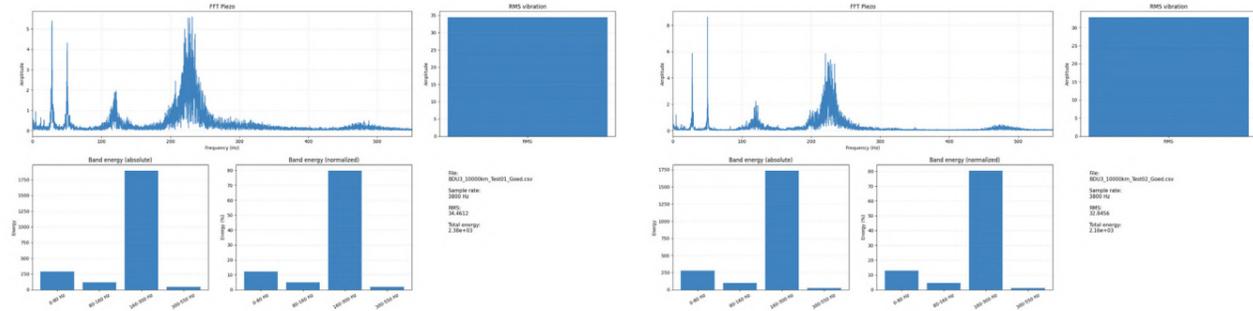
ax5.text(0.05, 0.95, textstr, va="top", fontsize=11)

plt.tight_layout()
plt.show()

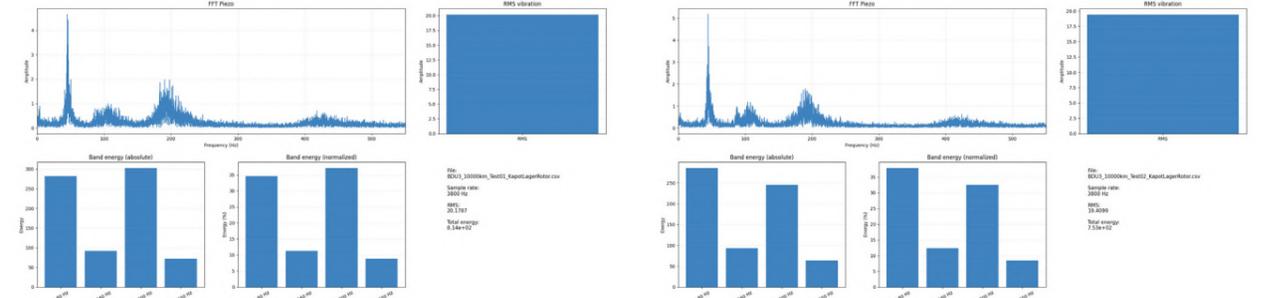
```

# APPENDIX I - TEST RESULTS

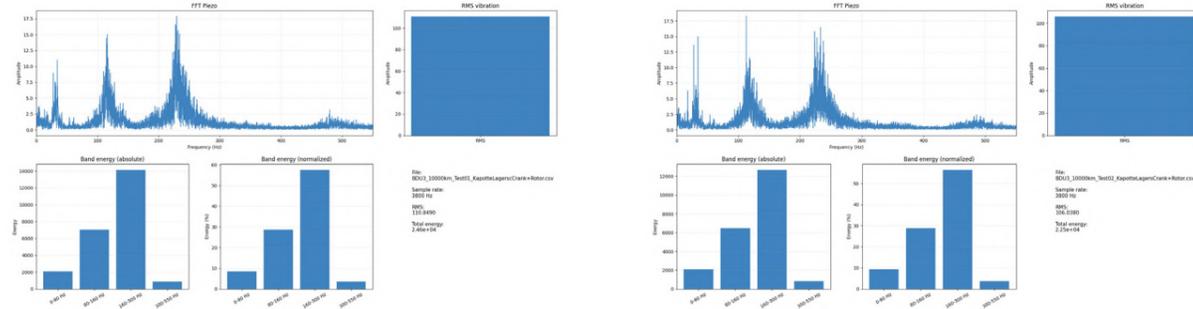
## BOSCH BDU 350 - 10000 KM - GOOD CONDITION



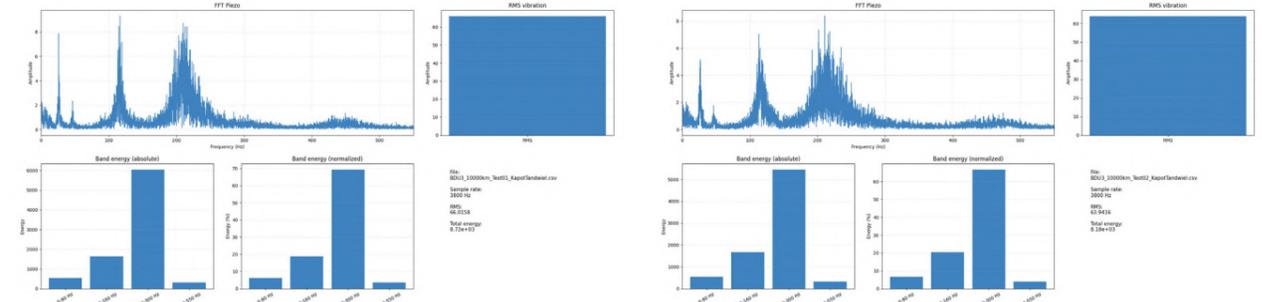
## BOSCH BDU 350 - 10000 KM - DAMAGED ROTOR BEARING



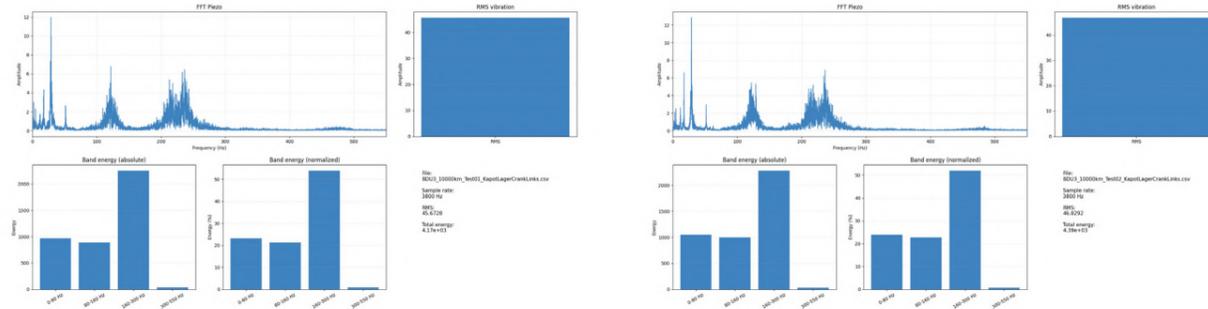
## BOSCH BDU 350 - 10000 KM - ALL BEARINGS DAMAGED



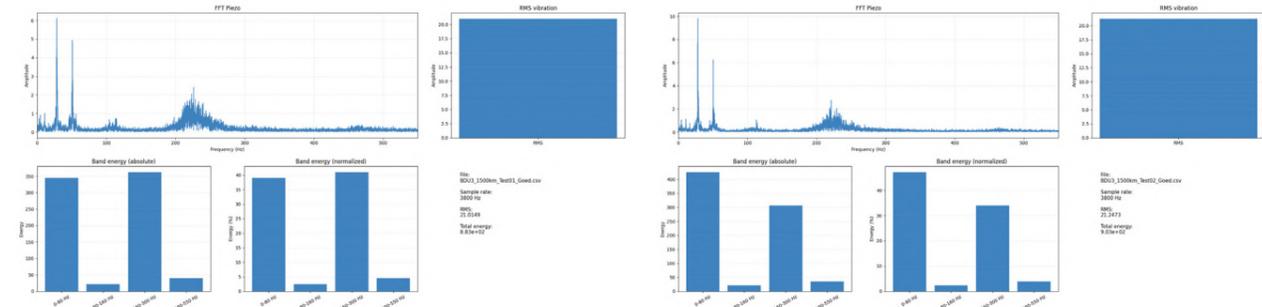
## BOSCH BDU 350 - 10000 KM - DAMAGED GEAR



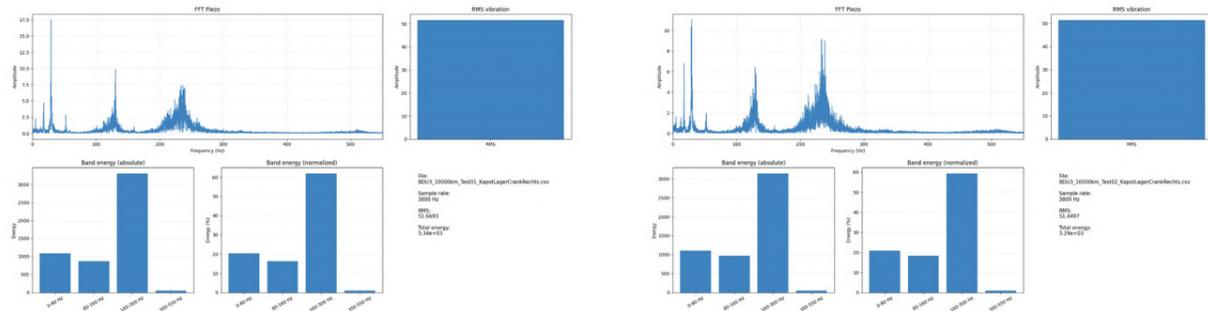
## BOSCH BDU 350 - 10000 KM - DAMAGED LEFT CRANKSHAFT BEARING



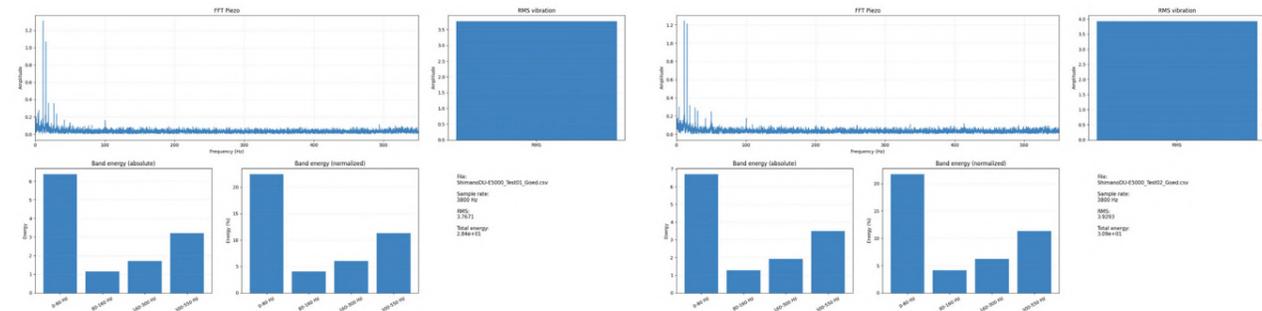
## BOSCH BDU 350 - 1500 KM - GOOD CONDITION



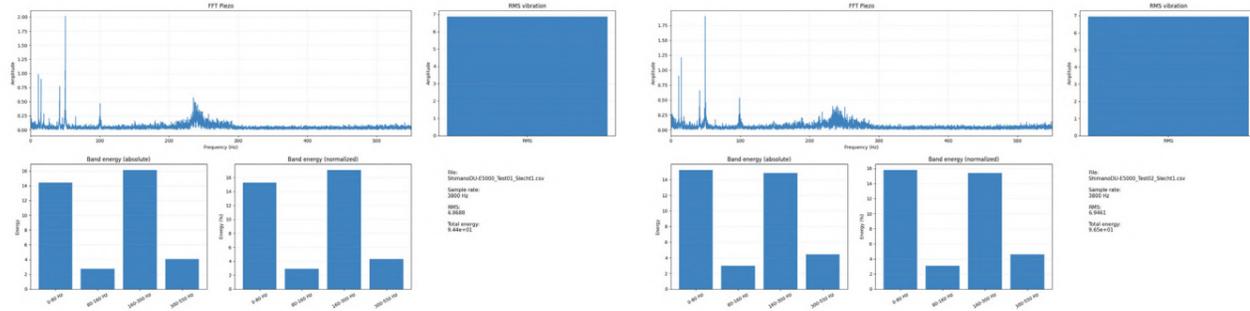
## BOSCH BDU 350 - 10000 KM - DAMAGED RIGHT CRANKSHAFT BEARING



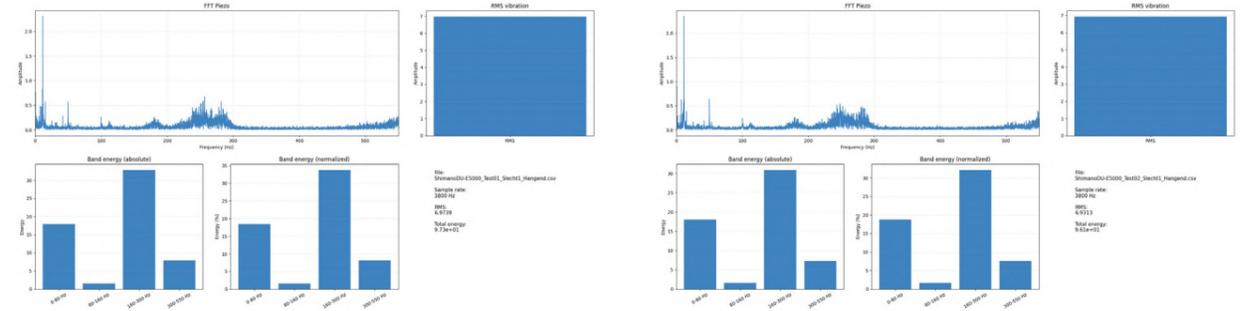
## SHIMANO DU-E5000 - GOOD CONDITION - STANDING



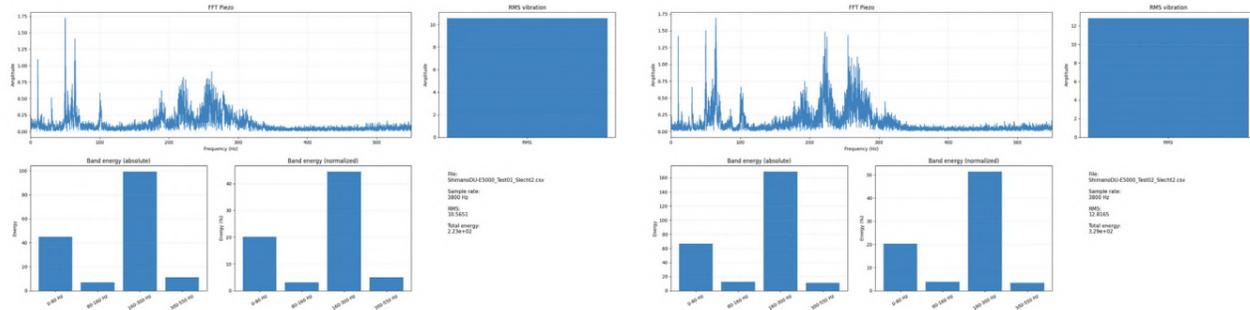
### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 01 - STANDING



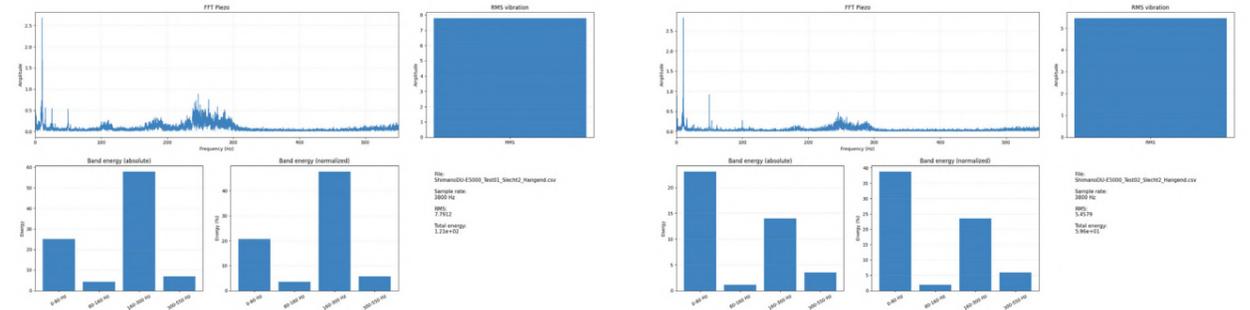
### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 01 - HANGING



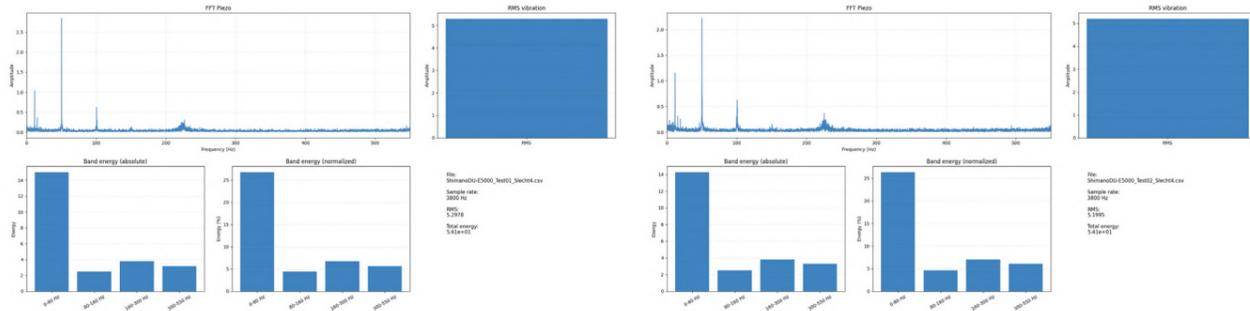
### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 02 - STANDING



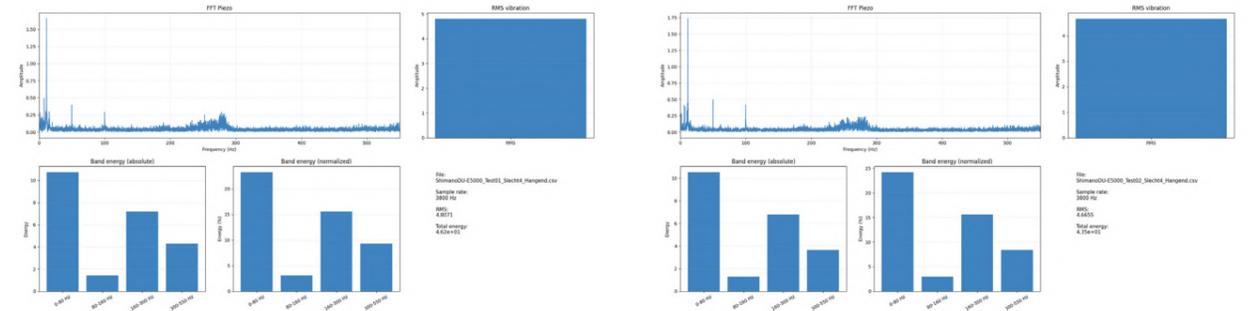
### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 02 - HANGING



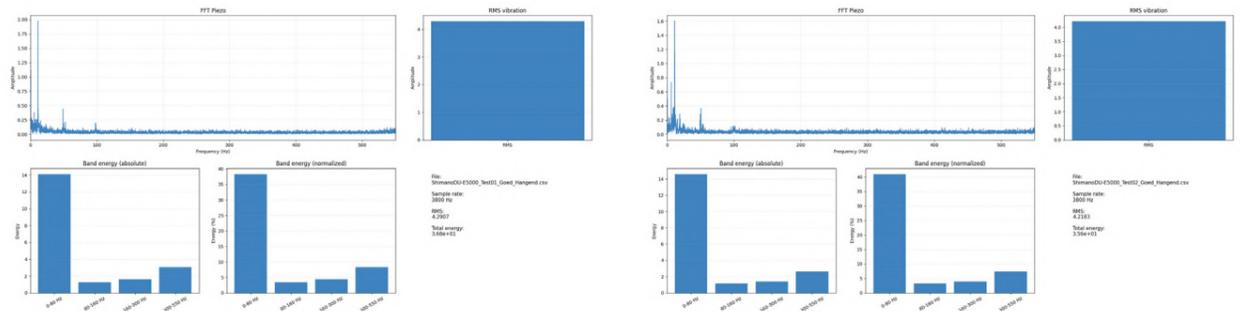
### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 03 - STANDING



### SHIMANO DU-E5000 - WITH MECHANICAL DAMAGE 03 - HANGING

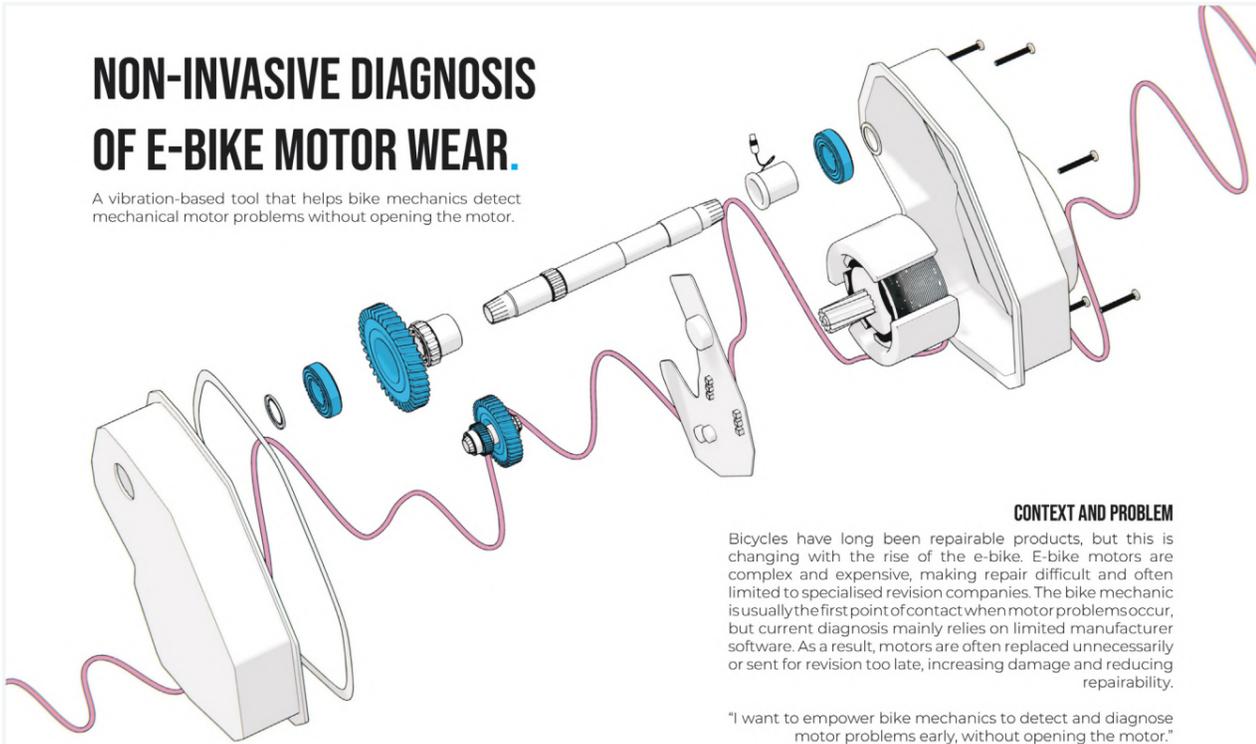


### SHIMANO DU-E5000 - GOOD CONDITION - HANGING



# NON-INVASIVE DIAGNOSIS OF E-BIKE MOTOR WEAR.

A vibration-based tool that helps bike mechanics detect mechanical motor problems without opening the motor.



### CONTEXT AND PROBLEM

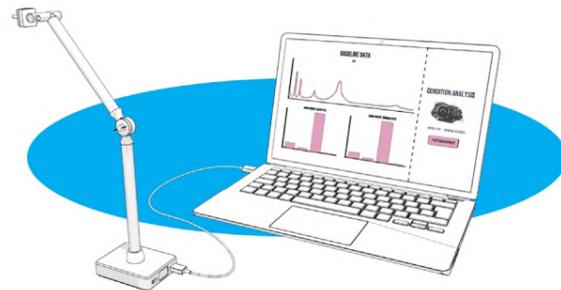
Bicycles have long been repairable products, but this is changing with the rise of the e-bike. E-bike motors are complex and expensive, making repair difficult and often limited to specialised revision companies. The bike mechanic is usually the first point of contact when motor problems occur, but current diagnosis mainly relies on limited manufacturer software. As a result, motors are often replaced unnecessarily or sent for revision too late, increasing damage and reducing reparability.

"I want to empower bike mechanics to detect and diagnose motor problems early, without opening the motor."

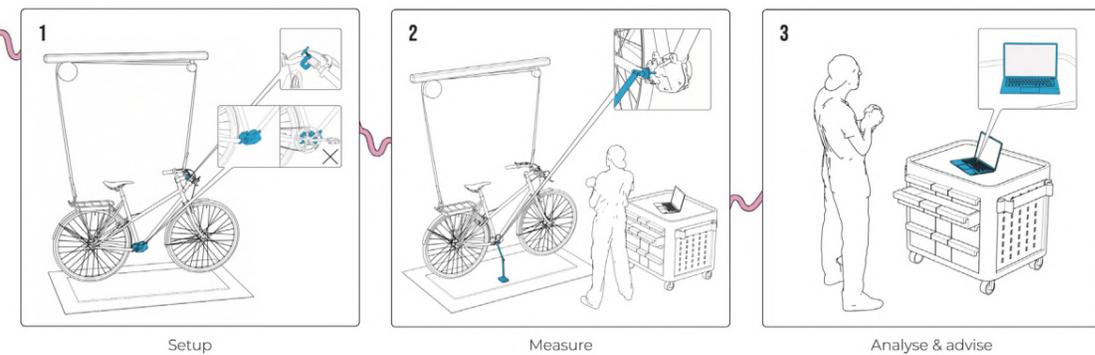
### SOLUTION

This project proposes a vibration-based diagnostic tool for non-invasive assessment of e-bike motor condition. A piezoelectric sensor is positioned against the motor housing while the bicycle is suspended and the motor runs on walk-assist. The sensor captures vibration signals that reflect the internal mechanical behaviour of the motor.

The recorded data is analysed by software and compared with baseline measurements from healthy motors of the same type. Complex vibration data is translated into a clear indication of motor condition and a recommendation for follow-up action. This supports bike mechanics in making objective, well-founded decisions and helps identify mechanical wear at an earlier stage.



### PROCEDURE



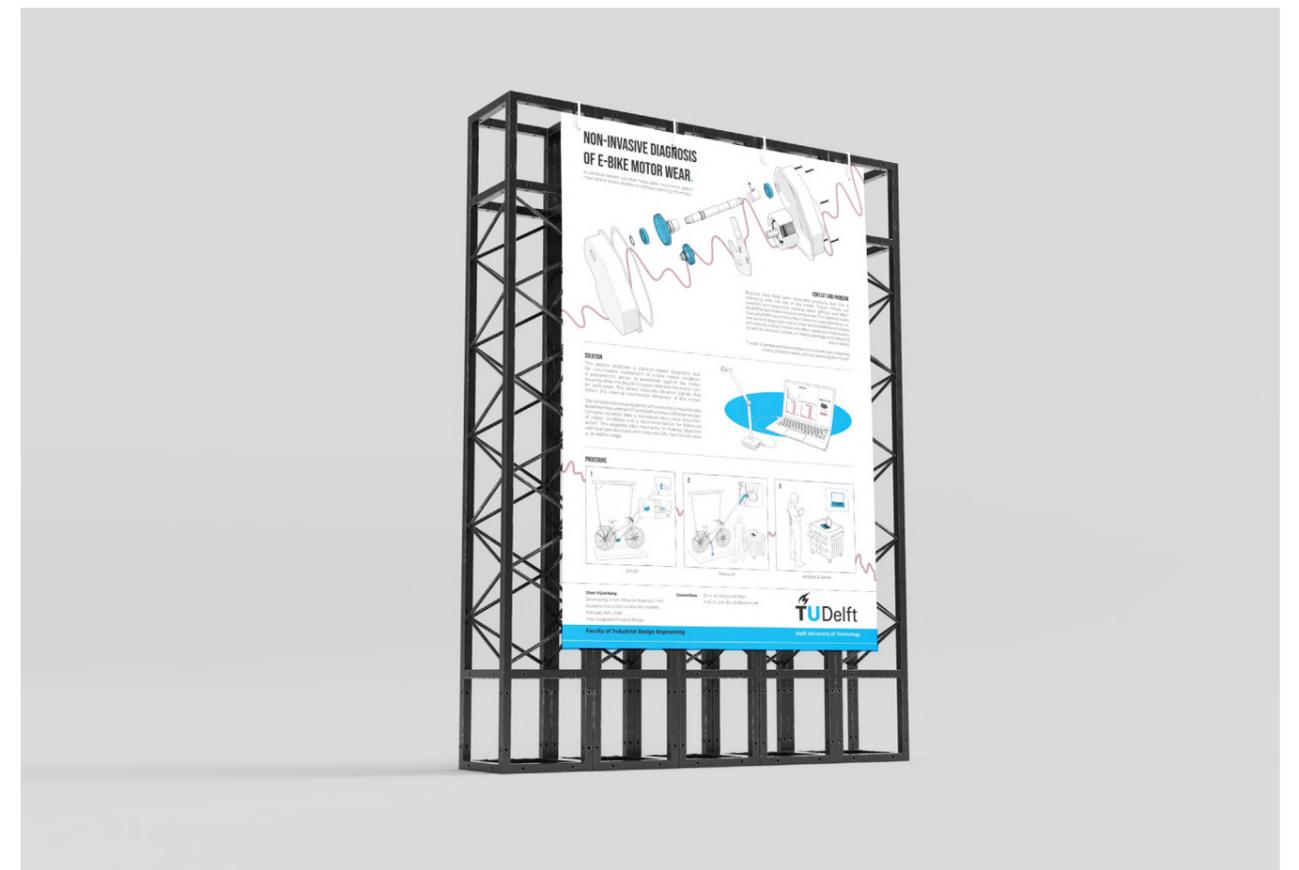
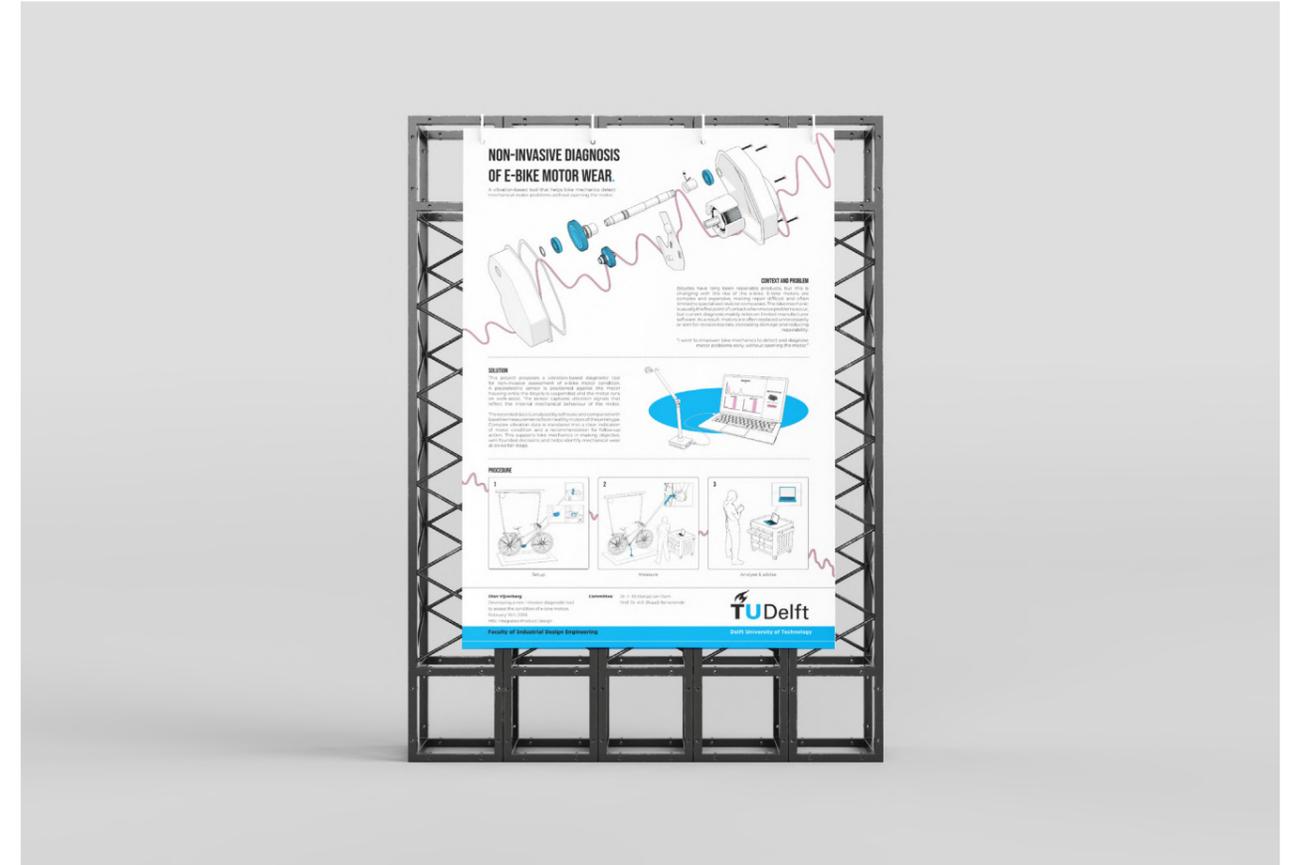
**Dion Vijverberg**  
Developing a non-intrusive diagnostic tool to assess the condition of e-bike motors.  
February 16th, 2026  
MSc Integrated Product Design

**Committee** Dr. ir. SS (Sonja) van Dam  
Prof. Dr. A.R. (Ruud) Balkenende



Faculty of Industrial Design Engineering

Delft University of Technology



## DESIRABILITY VALIDATION PREPARATION

### Setup

Validation method: Semi-structured interviews

Participants:

- 1 bike mechanic
- 1 revision company

Tool: A visual poster used as a discussion and explanation aid

Objective: To evaluate the clarity, relevance, and perceived value of the concept

### Interviews

Bike mechanic

Objective: To assess whether the concept fits into daily workshop practice and whether it supports the mechanic's work.

Approach: The poster was printed and discussed using a predefined set of questions.

Questions:

- Does the mechanic recognize that mechanical motor issues are difficult to diagnose? Do they encounter motors with mechanical problems?
- Does the mechanic experience uncertainty when advising customers?
- Would an objective measurement support their diagnosis?
- Would the concept help in communication with customers?
- Could the procedure fit within a regular service appointment?
- Is the procedure logical and feasible?
- What would be an acceptable cost?
- How often would the tool be used?
- Are there aspects that should be changed or improved?

Revision company

Objective: To assess whether the concept supports the revision process and business model.

Questions:

- Could an objective measurement also support their diagnostic process?
- Do they see value in building and maintaining baseline data?
- Who should manage this data? Would they be willing or able to do so?
- Would they offer such a tool or service to bike mechanics?

