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Sustainability & Circular Economy for electronic control units within the automotive industry

Master's thesis in Mobility Engineering

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DIVISION OF PRODUCTION SYSTEMS

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Abstract

The rapid evolution of the automotive industry, driven by advancements in technology and strict sustainability targets, demands the optimization of resources. Within this context, the exploration of remanufacturing, repair, and reuse strategies for electronic control units (ECUs) becomes critical. This thesis dives into the complex dynamics between OEMs and 1st-tier suppliers, focusing on the feasibility and implications of circular economy strategies in automotive electronics.

The study investigates two key aspects: the feasibility of implementing circular strategies for ECUs and the potential challenges. For the former, the work explores the hardware, software, and quality requirements together with the OEMs' expectation of "as good as new or better.". For the latter, the research studies the future implications of implementing circular strategies such as remanufacturing, repair, or reuse. Drawing on empirical data and the application of a robust analytical framework, this thesis provides key insights and strategic recommendations. Cybersecurity and hardware quality were identified as pivotal areas demanding innovative solutions. Further, it emphasizes the need for realistic expectations from OEMs, advocating for a necessary shift in the definition of "as good as new" within the circular economy framework for electronics.

The study highlights the increasing feasibility of circular strategies due to regulatory changes, innovation, and the transition to centralized hardware and software architectures.
The research offers critical contributions to the academic and practical discussion on automotive electronics sustainability. It introduces a new perspective on circular economy strategies, highlighting the importance of defining requirements, fostering compromise, and promoting innovation within a complex inter-organizational context. The recommendations presented in this work are intended to inform strategic decision-making for OEMs and first-tier suppliers, guiding them toward a more sustainable and efficient future.

Finally, this thesis provides a comprehensive roadmap for OEMs and suppliers for their sustainability journey, showing potential opportunities for future exploration. While not providing a full roadmap for the many issues confronting the automotive industry, it delivers essential insights into the field's current state and future directions. By doing so, it seeks to support further research and practical initiatives in automotive electronics remanufacturing, repair, and reuse, ultimately contributing to the realization of a sustainable automotive industry.

Keywords: current trends, challenges, opportunities, reuse, remanufacturing, repair, electronics, ECU, automotive, vehicle, sustainability, circular.

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Oscar Abel and Ola Groth, Gothenburg, June 2023

Contents

List of Abbreviations

ECU	Electronic Control Unit
ADAS	Advanced Driver Assistance Systems
OTA	Over-The-Air
SAFe	Scales Agile Framework
SW	Software
HW	Hardware
R&D	Research and Development
CE	Circular Economy
OEM	Original Equipment Manufacturer
ELV	End-Of-Life Vehicles
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
WEEE	Waste Electrical and Electronic Equipment Directive
SAE	Society of Automotive Engineers
AEC	Automotive Electronics Council
EOL	End-of-life
UNECE	United Nations Economic Commission for Europe
IATF	International Automotive Task Force
EPA	Environmental Protection Agency
E/E	Electrical and/or Electronic
DV	Design Verification
PV	Production Verification
TCAM	Telematic Connectivity Antenna Module
DPR	Design Pre-Requisitions
PCB	Printed Circuit Board
MCU	Microcontroller Unit
RAM	Random Access Memory
ROM	Read-Only Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
AUTOSAR	AUTomotive Open System ARchitecture

DVM	Design Verification Method
ISO	International Organization for Standardization
WoW	Way of Working
UK	Unknown

1. Introduction

In this chapter, the essential aspects of this research will be provided. The background, problem statement, aim, and research questions will be explored to offer comprehensive insights into the context of this study. The primary objective is to equip readers with the necessary information to develop a broad understanding of the research's context.

1.1. Background

The automotive industry has been undergoing significant transformations in recent years, largely influenced by the increasing focus on sustainability (Geng, 2019), rapid technological advancements (Meyer & Shaheen, 2017), and constantly evolving customer expectations (Kley, 2011).

This has led to the industry having to develop its strategy on how they handle manufacturing and the end-of-life management of its product. As the industry is currently in a shift where products are becoming fully electrified, another factor is added with challenges related to the management of electronic components. The automotive industry in Sweden is dependent on a lot of different suppliers which provide components and materials for the vehicles to be manufactured (Puiu, 2021). The high complexity put a significant challenge for the industry to implement circular economy principles, it requires a lot of effort to coordinate the entire value chain. One critical area is the management of ECUs. ECUs control all the electrical systems in a vehicle, for example, the engine, transmission, and braking system. The units are advanced and contain sensors, memory chips, and microprocessors. Due to the electrification of the world's fleets, the number of ECUs in every vehicle has increased.

Because ECUs are complex products it is a big challenge to recycle the units. One solution to overcome this problem is remanufacturing which means that a used product is restored to a like-new condition (Gunasekara, 2018). Remanufacturing can in the case of ECUs help to extend the life of the units which will reduce the need for new production and generated waste. The process for implementation of remanufacturing in this area also contains technical and economic challenges, but overall, this approach is a promising solution to the management of electronic components. As the industry is undergoing an electrical transformation the circular economy will be increasingly important and remanufacturing of ECUs will play a critical role when companies trying to reach their ambitions.

In the automotive industry, sustainability and circular economy principles are becoming increasingly important. The focus has switched from a hardware-centric towards a software-defined architecture. Development companies within the automotive sector highlight the new software-defined vehicle as a smartphone on wheels. Providing state-of-the-art features such as Advanced Driver Assistance Systems (ADAS) and Over The Air (OTA) software updates. OTA updates allow for continuous updates of software in the vehicle, even after it has left the factories through continuous SW deliveries developed according to the SAFe framework (SAFe, 2023). An increase in software features and centralization in the electrical architecture (E/E) means an increase in the complexity of the underlying hardware. An increase in complexity and centralization would suggest an increase in the cost of the ECU. Combining all these factors, would it affect the feasibility of remanufacturing, as illustrated in Figure 1?

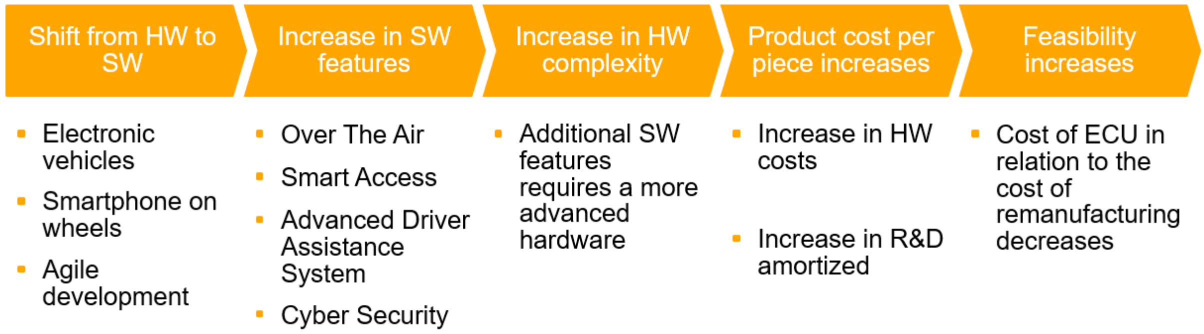

Figure 1. Market change – increasing feasibility for remanufacturing.

1.1.1. Industrial approach to this thesis

This thesis project is performed in collaboration with an industrial company called Company A. Company A produces 400,000 tons of products every year. In 2022, the Circular economy (CE) performance indicator reached 85%, increasing from 81% the year prior. This performance indicator is defined as the "Proportion of waste that has been sent for material recycling, thermal recovery or any other form of recycling or reuse."

Company A is a firm that has the vision of reaching their sustainability targets, of 100% closed resource loops and product cycles by 2050, this performance indicator must reach 95% by 2023. However, companies cannot achieve their goals individually, as the impact is generated through whole value chains. Company B is one of several important customers for Company A, and in their latest reports, they have promised closed loops by. This 10-year gap highlights a big problem as the development from their suppliers needs to be accelerated by at least 10 years, plus development.

This made Company A a suitable partner for the study of remanufacturing within the automotive industry. As mentioned, automotive electronics are becoming more complex, requiring more rare earth materials, for example, cobalt, and nickel (Ford, 2022). Companies like Company A, which are committed to closed resource -and product cycles must address the issue of scrapped ECUs.

1.2. Problem statement

Currently, the common practice of handling functionality issues within the automotive industry follows a linear economy approach. The first point of failure is that an issue is detected during the end-of-line testing at the OEM assembly plant. In this case, the problem is mostly solved by replacing the component that is most likely causing the issue. However, since the time is critical there is no time for a deep root cause analysis. The second is that the end customer, the driver of the vehicle, notices an issue or problem. The user would then drive the vehicle to a workshop which will determine the root cause of the issue and perform a software update or replace the ECU.

But in both cases above, neither the factory nor the workshop has the technical expertise to deep dive into the problem and choose the most time or cost-efficient solution. A portion of these parts are then delivered to the supplier for a deep analysis. Independent of the outcome from the analysis, the parts are scrapped, even if no issues are found. This can happen for several reasons, the wrong ECU was replaced, the ECU only needed a power reset for the software to restart or the issue is not within the ECU. The approach of scrapping all ECUs, independent of issue severity, leads to increased waste and an adverse environmental impact. The management of these returned components represents an opportunity to reduce waste, enhance resource efficiency, and contribute to the overall environmental performance of the industry.Therefore it's required to investigate why the ECUs can't be re-introduced to the market, and whether is there another way of working that could be implemented while still complying with today's standards and regulations?

1.3. Aim

This thesis aims to enable circular economy strategies of electronics control modules in the automotive industry.

The aim is divided into two objectives which together will provide evidence for enabling circular economy strategies. These objectives are required to be solved in chronological order. The first objective is to identify and evaluate how the automotive industry is managing reparations and scrapping of warranty returns. By evaluating the industry standards based on current regulations and global standards we can identify operational blockers and regulations preventing the implementation of CE strategies. The second objective is to define a technical proof of concept that would enable remanufacturing, repair, or reuse.

1.4. Research questions

To reach the aim of creating a proof of concept two questions needs to be answered. The carefully formulated questions summarize what is to be investigated from a broader perspective and are based on the goals set in section 1.3.

> *RQ1: What are the current trends and challenges in the remanufacturing, repair, and re-use of ECUs within the automotive industry?*

This is the main question of the thesis since it will define the steps of the research. To find and deep dive into the challenges that the industry and companies are facing regarding regulations, standards, and technical difficulties. Answering this question will allow for the creation of a strategy to overcome the challenges and inspire change in the industry.

> *RQ 2: What process improvements are required for remanufacturing, repair, and re-use of electronics to meet the standards of the automotive industry?*

With a clear picture of the regulations, standards, and current processes. Answering this question should support which processes can be used in reuse, repair, and remanufacturing operations to meet the standards, regulations, and quality levels of the automotive industry.

2. Theoretical framework

The primary aim of this chapter is to provide a frame of reference, which clarifies the definitions and concepts that are required for the understanding and answering of the research questions. The concept of circular economy is central to this thesis because the two strategies remanufacturing and repair are initiatives aligned with the circular economy in the automotive industry.

2.1. Circular economy

Today's industries mostly understand their environmental impact and that it can be linked to increasing demand for materials. Therefore, they are exploring alternative approaches to material supply and waste management. (Ferguson, 2009)

The European Commission has introduced a "circular economy strategy" which has further heightened awareness regarding the use of sustainable resources. Policies have been implemented that aim to minimize the environmental impact caused by end-of-life products. It also aims to reduce negative consequences that may arise, for example, conflicts when trading with rare minerals. In line with these commitments, the EU has decided on laws and regulations that will help shape the circular economy. The economic model aims to strive for the efficiency of resources, by creating a circular flow of products and materials. Certain regulations have been put in place to address the management of end-of-life vehicles (ELVs). (Directive 2015/614)

The EU has based its waste management preferences on the waste management hierarchy model, illustrated in Figure 2. When products reach the end of their life cycle, the hierarchy model prioritizes reuse and recycling as preferred strategies instead of options like recovery and landfilling. The reuse strategy extends the lifespan of products and components while recycling entails extracting materials from waste to further use. It's sometimes impossible to avoid landfilling but the industry should put efforts to minimize this alternative as much as possible. Because of already invested labor, time, or, energy in raw materials, the reuse of end-of-life products is highly preferable from both economic and environmental perspectives (Agrawal, 2015).

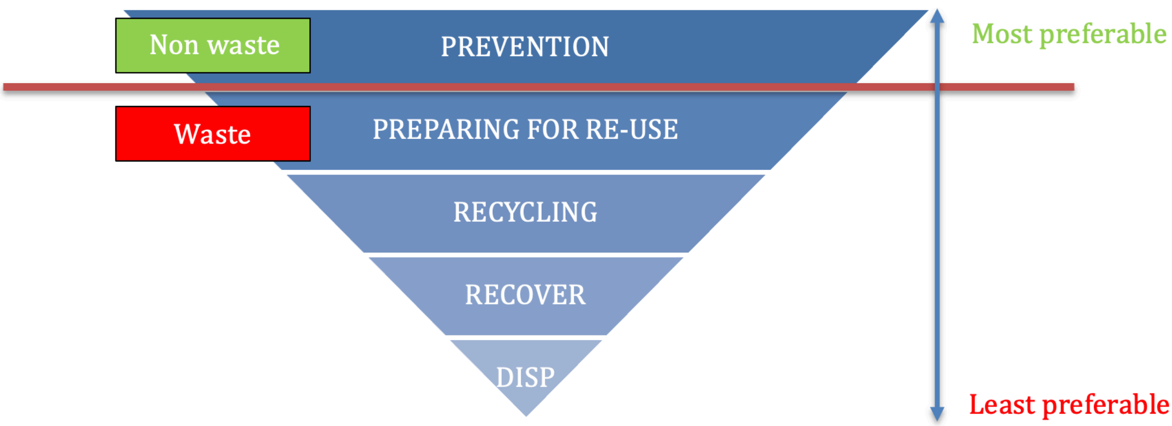

Figure 2. Waste management hierarchy model.

The reuse strategy can be applied in different forms, for example using car components as spare parts or utilizing them as resources for remanufacturing processes. Especially remanufacturing keeps a lot of the previously added value to the products which makes it a more efficient alternative compared to recycling. By sticking to the waste management hierarchy and putting the focus on reuse and recycling EU aims to optimize the use of resources, reduce waste, and minimize the environmental impact caused by end-of-life products. This approach is in line with the principles of circular economy and will work towards the goal to keep materials and products in life as long as possible. (Klaverkamp, 2017; Directive, 2008/98)

To summarize the circular economy strategy, as seen in Figure 4, it aims to extend the life of products, maximize the use of already extracted resources and minimize waste. The EU's plan to achieve this is to work with the waste management hierarchy, which emphasizes the importance of prioritizing reuse and recycling over recovery and landfilling. Reuse strategies which include remanufacturing offer an economic and environmental benefit by making use of the value embedded in end-of-life products.

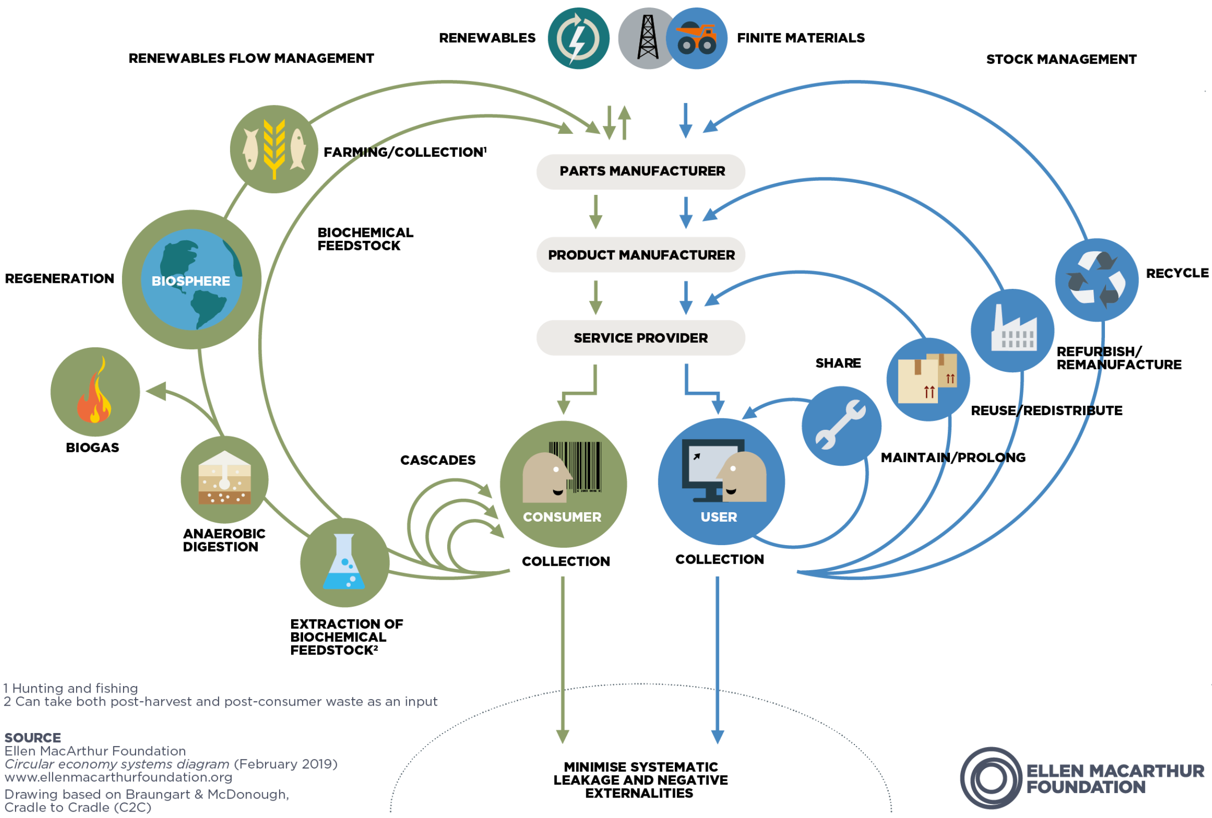

Figure 3. The butterfly diagram: Visualising the circular economy. By Ellen MacArthur Foundation.

2.2. Circular economy in the automotive industry

Remanufacturing means that used products are restored to a like-new condition to extend their useful life and minimize waste. According to (Gunasekara, 2018), the definition of remanufacturing is: “Returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product”. It is a key practice in circular economy principles and is widely adopted in the automotive industry. The process involves several key steps including disassembly, cleaning, inspection, sorting, reconditioning, and reassembly (Lieder, 2016).

During World War II, the focus on resources became an important issue for the first time. There was a lack of raw materials for weapon manufacture and also components for vehicles were missing. To solve the shortage problem of automotive components, they started to reuse parts, which led to automotive remanufacturing taking off in the USA and Great Britain. After the war, the lack of materials became a big problem for vehicle manufacturers, which led to them also starting to introduce remanufacturing of components. For example, Mercedes Benz started remanufacturing gearboxes and engines, among other things. Other vehicle manufacturers soon followed and also introduced remanufacturing into their processes (Casper, 2021).

The automotive industry is the largest in the world working with remanufacturing, the industry is responsible for 60% of all performed remanufacturing globally. 10% of all cars need a new engine during their lifetime, which is a contributing reason why the industry sees remanufacturing as an important component (Golinska-Dawson, 2011).

Remanufacturing is a complex recovery process, but it has a high potential impact on sustainable development. There are a lot of motives to implement the strategy and for developing countries, it is a great business opportunity, but there are also barriers. The barriers to implementing remanufacturing depend on different countries due to cultural, political, and social factors (Gunasekara, 2018).

Electronics belongs to an area with great opportunities when it comes to remanufacturing. In recent years, it has become a specialized subject within the automotive industry where a lack of competence has become a fact because it is not a traditional area within the automotive industry. The rapidly increased number of electrified cars has created a great need for technical competence to be able to implement remanufacturing processes. The increasing use of electrical components has also forced companies that work with remanufacturing to invest in skills, collaborate with companies that have skills, and expand their R&D to meet the new challenges. When the development of products progresses rapidly, it can be a challenge to argue for remanufacturing, as the costs of remanufacturing become very high when you need to keep pace with the development of products (Parker, 2015).

To extend the lifespan of a product, repair seems to be the most logical and straightforward approach if the purpose is to achieve a closed-loop system. In theory, this concept is simple, but not much research has been done on how this process relates to closed-loop frameworks. Repair aims to identify and correct specific issues in a product and then restore functionality and prolong the use of the product. One important aspect to take into consideration is that repaired products have a lower quality compared to remanufactured alternatives. This is because of the challenge to achieve the same level of performance and reliability as that of a newly manufactured product. Warranties are also something that differs between a repaired and a remanufactured product because the quality is difficult to guarantee when the product has not gone through the same comprehensive tests that the remanufacturing process contains. Sometimes even only certain parts of the product are covered by the warranty when it has been repaired (King, 2005).

3. Methodology

The Methodology chapter described the research strategy and outlines the important steps to evaluate and triangulate toward an answer to our research questions. The selected methodology is a case study, based on the book, Case Study Research: Design and Methods by Yin (2003). The case study approach, specifically the Yin method, is a valuable research strategy for conducting in-depth investigations of complex processes with a real-world connection (Baxter & Jack, 2008). Figure 4 illustrates the methodology framework.

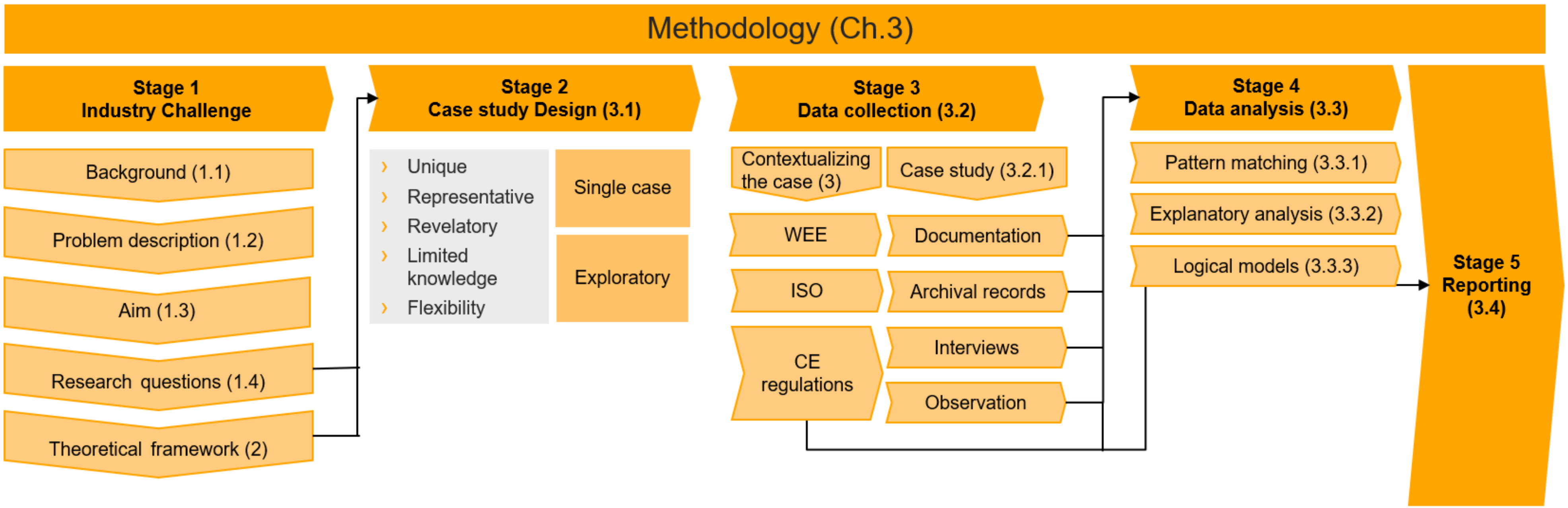

Figure 4. Methodology roadmap.

3.1. Case study design and selection

The case study will investigate a single product, developed by a 1st tier supplier which is then delivered to a specific OEM. The product and its requirements are unique both from an OEM and a 1st tier supplier perspective as it's developed for one customer and one purpose. In section 4 the ECU is described in detail. Due to its technological advancement, it has a complex hardware architecture as well as state-of-the-art software inside. Choosing a product that includes complex hardware and state-of-the-art software is a decision taken to represent the high and increasing complexity of automotive electronics (Meyer & Shaheen, 2017). Using a **single case,** figure 5**,** study to get an in-depth understanding of a product, inaccessible to external researchers, provides the 3rd rationale for the single case study approach, revelatory case (Yin, 2003)

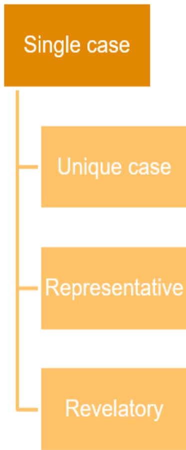

Figure 5. Case study design - Single case

An **Exploratory approach**, Figure 6, to the case study is preferable in cases where the topic has never been addressed and existing theories do not apply (Creswell, 2009). In this case, the fact that the product is unique and has never been studied before suggests an Exploratory approach to the study. Creswell (2009) advocates an exploratory approach when there is limited knowledge of the subject. As a result of the limited knowledge, the approach requires flexibility since the results can be varying and can suggest changes in both the methodology and reporting of the results.

Figure 6. Case study design - Explanatory

3.2. Data collection methods

The data collection process for this study is designed to give a comprehensive and in-depth understanding of the potential for remanufacturing, repair, and re-use of automotive ECUs. To ensure the validity and reliability of the findings a combination of data collection methods is proposed by Yin (2003) for case study research. Each method is described in detail and adapted for an engineering study in the section below.

3.2.1. Case study

A systematic review of internal reports, guidelines, and standards related to ECUs, their manufacturing process, and quality assurance will be conducted. This aims to identify the applicable policies, processes, and challenges for the implementation of circular strategies. In Figure 7 the complete picture of the case study analysis is visualized.

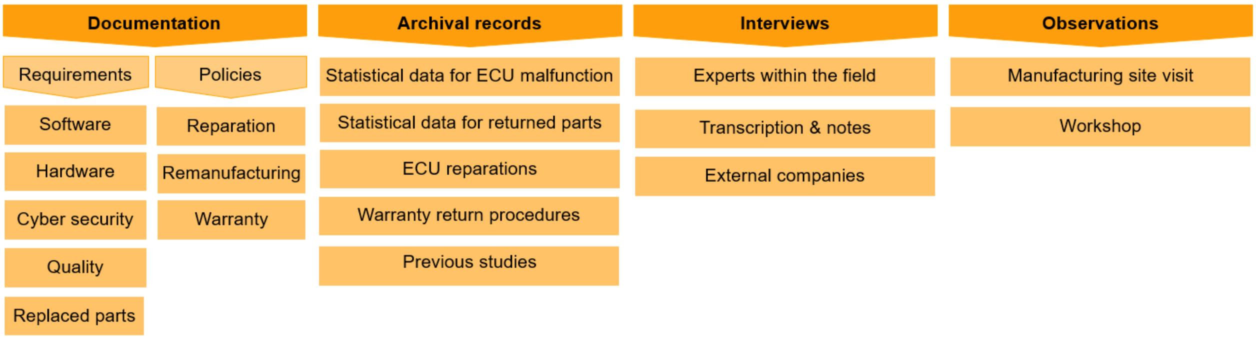

Figure 7. Case study design and data collection.

Documentation
The documentation that was reviewed consists of two categories. Internal requirements, and Policies. Requirements in this context are provided by the OEM to the 1st tier supplier, unique for each product. The policies are internal guidelines and rules that each project and product must comply with.

Archival records
Archival records consist of quantitative data, established processes, and past investigations done within similar areas. This includes the collection and examination of data from the ECU production, repair, and fail rates for the ECU in question. By analyzing the records, the research can identify trends and patterns related to the ECU technology, repairability, and feasibility of CE strategies.

Interviews
To get more insight into the current practices, challenges, and opportunities, a set of semi-structured interviews, table 1, was conducted following the Yin (2003) method. The interviewee was sent a document with a short background description and a list of questions to be answered before the interview date. This document can be found in Appendix A. The interviews were carried out as a discussion around the questions as it allows for flexibility and the opportunity to explore topics beyond the predetermined questions, enabling interviewees to provide their personal insights and unique perspectives. A diverse range of experts from OEMs and 1st tier suppliers was interviewed. The interviews will, if allowed, be audio recorded and transcribed for analysis. If the interviewee does not comply with the audio recording, notes will be taken and analyzed.

Table 1. Expert review.

Interviewee Function	Data collection method	Company function
Quality management	Transcription	Automotive tier 1 supplier
Circular Lead engineer	Transcription	Automotive OEM
Technical Leader CE	Notes	Automotive OEM
Service Part management	Transcription	Automotive tier 1 supplier
CE management	Transcription	Automotive tier 1 supplier

Observations

Yin (2003) emphasizes the importance of observations in case study research as they might provide valuable insight into real-world practices and processes. Following this recommendation a visit, to Company A's manufacturing site in Eastern Europe, was conducted. To further verify the data collected a workshop was organized at the OEM to complement the documentation and archival records.

3.2.2. Contextualizing the case

To better understand the case study and interpret the complex connections it's important to examine the relationship and contextualize the case (Flyvbjerg, B., 2006). The automotive industry, as all industries, is bound by requirements and regulations. It's important to highlight how these regulations fit and synergize within the boundaries of this case study. The sectors for regulations that are taken into consideration for this are shown in Figure 8.

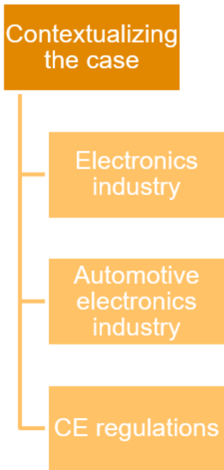

Figure 8. Contextualizing the case.

3.3. Data analysis techniques

In line with Yin's (2003) recommendation for case study research, this study will use Pattern Matching, Explanatory analysis, and Logical models to analyze the collected data, figure 9. The selected techniques aim to provide a comprehensive and understandable result. By combining the strengths of the two approaches the analysis seeks to uncover the relevant patterns, relationships, and other potential factors that could influence the reliability and conclusions made from the collected data.

Figure 9. Data analysis techniques.

3.3.1. Pattern Matching

The technique, of pattern matching, is used to compare to observe the empirical patterns in the collected data with the expected patterns derived from relevant theories and concepts. This specific technique aims to identify similarities and discrepancies between collected data. If the patterns match, it strengthens the validity of the case study, while discrepancies help identify areas that require further investigations or changes to the theoretical framework (Yin, 2003).

3.3.2. Explanatory analysis

The explanation-building technique involves an iterative process to construct a comprehensive explanation of the case study by refining initial theoretical propositions or hypotheses (Yin, 2003). In this research, explanation building will be used to unravel the intricate interactions between OEMs and 1st tier suppliers, as well as to examine the factors and constraints that might impact the implementation of circular economy principles within the automotive industry.

3.3.3. Logical models

Logical models consist of creating visual representations that depict the relationships between various variables, events, or factors in a case study (Yin, 2003). These models are a complement to clarify the complex interactions and provide a structured framework for analyzing the data. In the context of this thesis, logical models will be employed to illustrate the interdependencies between the OEM, 1st tier suppliers, and the automotive industry.

3.4. Reporting

While reporting and documenting this study, it is necessary to acknowledge the constraints on the level of detail that can be provided due to confidentiality agreements and intellectual property. These agreements restrict specific, proprietary information and certain sensitive details and will therefore not be disclosed within this report. However, every effort has been made to present the findings in a manner that is as comprehensive as possible while respecting these restrictions. While this does limit the depth of the details in certain areas, it should not undermine the overall validity and reliability of the research findings.

4. Contextualizing the case

The relationship between the industry and the surrounding requirements is an important part understand. It adds complexity and constraints that the automotive industry needs to operate within. Company B and Company A, like all OEMs and suppliers, operate within these frameworks of regulation, standards, and directives. These regulations are in place to support a safe and sustainable product. Figure 10 presents a simplified nested diagram of the relationship, and the section below describes the major actors relevant to this study. The dotted line represents the boundaries of the case study.

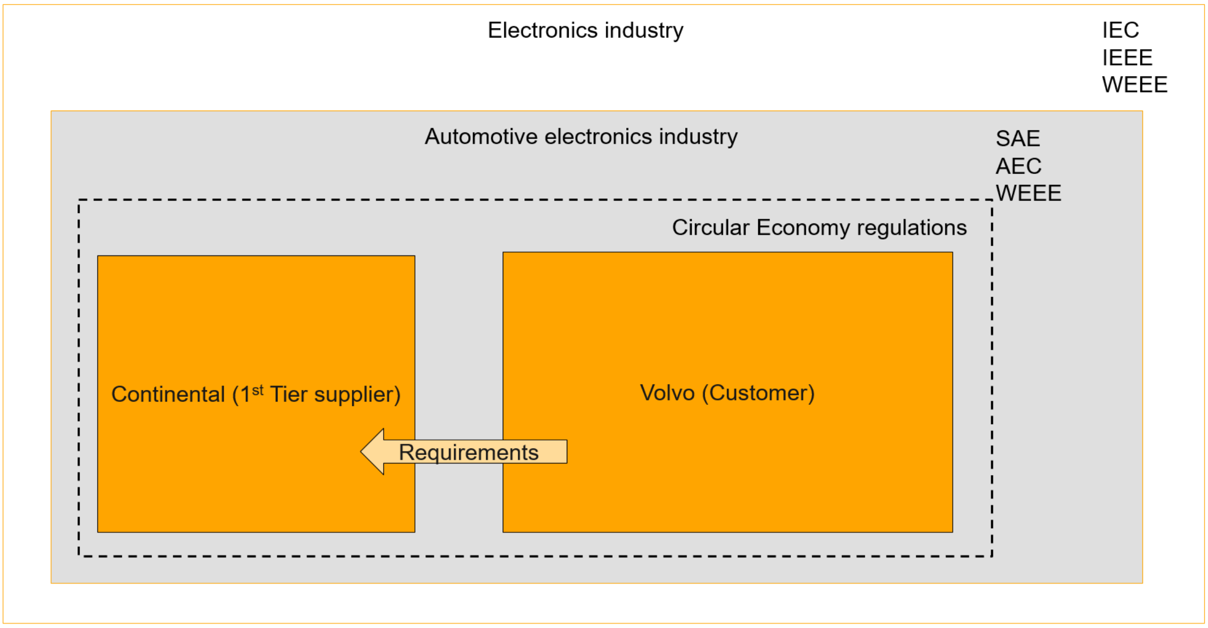

Figure 10. Contextualizing the case.

4.1. Electronics industry

The electronics industry is primarily guided by several international standards and regulations, which significantly shape the way this industry operates. The International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) are key organizations that develop and manage standards for electrical and electronic technologies globally. Their directives and regulations set benchmarks for risk and quality management, and other key aspects of electronics design and manufacturing (IEC, 2023; IEEE, 2023). In addition, the Waste Electrical and Electronic Equipment Directive (WEEE) impacts businesses involved in the lifecycle of electrical and electronic equipment, by mandating rules for their proper disposal and encouraging recycling and reuse, thus shaping the environmental sustainability practices within the industry (WEEE, n.d).

4.2. Automotive electronics industry

In the automotive electronics segment, regulations and directives are similarly influential but are more specifically targeted toward vehicle technology. The Society of Automotive Engineers (SAE) and Automotive Electronics Council (AEC) establish standards for the design, manufacture, and performance of automotive electronics. These guidelines ensure the safety, reliability, and durability of these components, given their critical role in vehicle functionality (SAE, 2023; AEC, n.d). The WEEE likewise applies here, guiding manufacturers to consider sustainable design- and EOL management practices for automotive electronics. These regulations encourage a shift towards more sustainable and circular models in the automotive electronics sector, prompting manufacturers to consider product lifecycle from development to EOL including disposal (WEEE, n.d)

4.3. Circular economy regulations

The wide range of regulations for the industry and their subsections form the standards and requirements that the OEM and suppliers need to follow. However, the OEMs do have the freedom to implement their targets and standards which are stricter than the global regulations and guidelines. Regulations such as ELV, UNECE, IATF, EPA, EU, and WEEE provide the minimum for what needs to be achieved while OEMs like Company B have a reputation within the industry to be a quality-driven company it's not uncommon to provide requirements to their suppliers which are beyond the global regulations. The regulations mentioned do not necessarily specifically mention circular economy but have an influence on the OEM and suppliers that restricts the use by defining the risk, quality, and reliability management of ECUs.

This study will not deep dive into each regulation but considers it important to understand how global organizations impact the feasibility of circular operations.

5. Case Description & empirical data collection

Company B is a global actor in the automotive industry with global production and is known worldwide for their high quality and safety standards. Company A's Automotive sector of is one of the leading suppliers of automotive products. Throughout the years they have developed several products for the Company B vehicles. In this case, we study one of these ECUs, the telematics module, which is an advanced smart antenna module (figure 15). We study the structure of the collaboration, the ECU, and the ways of working within the project.

5.1. Structure of collaboration

The interaction between an OEM and a supplier during the development can be described in three stages. Product definition, development, and production. This flow is visualized in Figure 11. These stages are a simplification of the process. In practice, it is a much more convoluted and iterative process, see section 5.1.1, often involving multiple rounds of design revisions, testing, and approval before the final product is ready for production. The timeline for an automotive project is, depending on the product, three years. contingent on the complexity of the product and the requirements of the OEM.

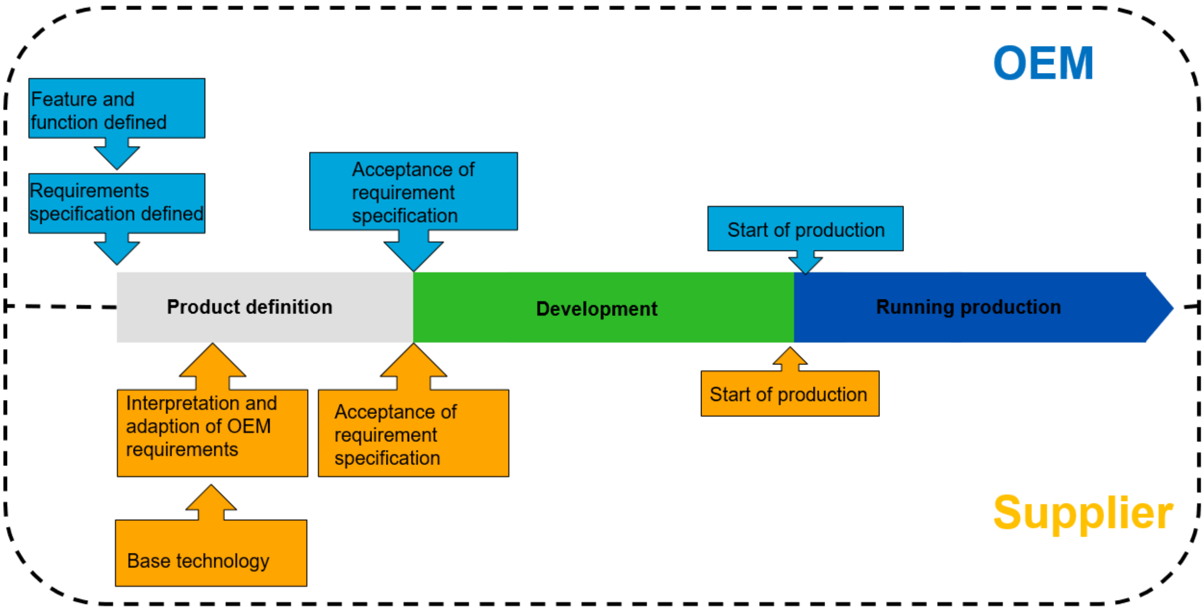

Figure 11. OEM Supplier relationship.

Product Definition: This stage shows the collaboration of the product development process where the OEM outlines the desired specifications for the product, including its functionality, mechanical attributes, performance metrics, and overall design. These specifications are subsequently delivered to the supplier. The supplier, in response, collects these requirements, critically evaluates them in the context of their manufacturing capabilities and resource availability, and compares them to their requirements for the already defined base architecture. The supplier concludes their understanding and interpretation of the requirement and sends it back to the OEM to ensure both parties have a mutual understanding of the final product.

Development: Following the mutual agreement on the requirements of the product, the development phase is started. This phase contains several activities, including product design, prototyping, testing, and verification. The process is iterative and requires several loops. ECUs are interconnected, meaning that the definition of one ECU often has an impact on another ECU. This often leads to changes along the way as the requirements mature for the overall E/E architecture. The OEM and the supplier maintain a symbiotic relationship during this stage. They are consistently communicating to ensure the product is evolving in line with the predetermined and evolving specifications. Continuous and late changes present pressure on the budget and timeline of the project. To maintain the project trajectory and accommodate any necessary adjustments, frequent reviews, and checkpoints are scheduled throughout the development stage.

Production start: Upon the successful completion of the development phase and approval of the final product design verification (DV) by the OEM, the production phase is activated. This phase encompasses the manufacturing process, quality control measures, packaging, and delivery of the product to the OEM. As the last stage before mass production start, the supplier performs a production verification (PV), which is evaluated according to the OEMs specification. Throughout the production process, the OEM and the supplier maintain a close-knit communication to certify the product is manufactured in compliance with the agreed-upon specifications, with any production issues being mitigated swiftly.

5.1.1. Agile way of working

As a company, Company B has in 2017 transitioned from the classic waterfall processes to the Scaled Agile Framework (SAFe). This section will present the Company B and Company A ways of working for the development of the studied ECU. The agile framework describes a process where the companies work with continuous improvements and continuous implementation of features. The product, which is already out on the market, still requires updates in terms of bug fixing, cyber security updates, and implementation of new features. The list of updates is not exclusive but showcases the general highlights for postproduction development. As the project is a running project these software updates are deployed using OTA (see section 5.2.2.1) if they are part of the application software (see section 5.2.2). If updates are done to the base software, the implementation must be deployed at the supplier manufacturing site. The transition to the agile way of working is a result of the evolving software architecture in the automotive industry. Transitioning from a conventional vehicle to a smartphone on wheels poses challenges in development that need to be addressed by moving toward software-driven systems engineering. (McKinsey, 2020)

5.2. ECU description

This case study has selected the TCAM, Telematic Connectivity Antenna Module, as the subject of interest. The telematics module represents the high complexity and advanced technology that is now a standard part of today’s connected vehicles.

5.2.1. Hardware

The hardware requirements are delivered to the supplier as an extensive list of requirements called “Design Pre-requisites” (DPR). In the DPR is every attribute request from the OEM ranging from individual component performance to mechanical design.

As stated above the hardware design is defined by the requirements provided by the OEM in collaboration with the supplier. The function and features define the electronic architecture (E/E) of the ECU while the mechanical requirements determine the design.

The automotive ECU typically contains six key elements,

1. PCB
2. MCU
3. Memory (RAM+ROM+EEPROM+ flash memory)
4. Connectors (Communication channels)
5. Mechanical housing and components
6. Feature-specific modules (for example, antennas for GPS applications)

The mechanical design, i.e., the shape and dimension of the ECU is constrained to the available space in the vehicle and optimized for size, weight, and cooling performance.
In figure 12 the ECU is displayed in an exploded view, the TCAM has more components than described in the list above due to its functions such as emergency call, GPS, Wi-Fi, and connectivity features.

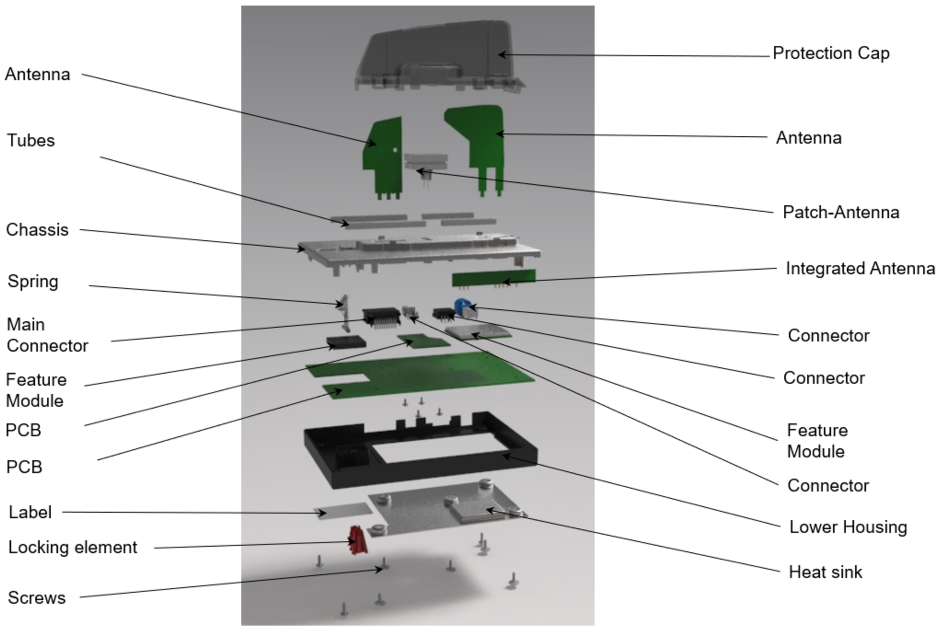

Figure 12. Exploded view of the TCAM.

5.2.2. Software

Electronic Control Unit (ECU) is typically composed of two layers: the base software layer and the application software layer. The base software layer also referred to as the firmware or base tech layer, provides the basic functions to control the hardware of the ECU. This layer is usually standardized across various ECUs and forms the interface between the hardware and the application software. The base software includes services such as diagnostic communication, memory management, and basic input/output control. It is often developed by standardized software frameworks for automotive software such as AUTOSAR (AUTomotive Open System ARchitecture) but configurated to fit the specific OEM architecture.

The application software layer contains the specific functionality of the ECU. This layer is responsible for implementing the desired features and controls according to the specification of the vehicle manufacturer. It interprets the data received from the base software layer, executes the necessary calculations, or processes, and sends commands back to the base software layer to control the vehicle's hardware. This layer often contains control algorithms, fault detection, isolation routines, and calibration data (Navet et al., 2018).

Separating the software into these two layers allows for modularity and reusability in software design, which can reduce development time and costs. It also facilitates software updates and upgrades, as changes in the application software can be made without impacting the base software, and vice versa.

These requirements received from the OEM are decomposed into specific and implementable requirements. This process is illustrated with an example in Figure 13. In the figure two steps are shown, the decomposing would continue until it reaches a level that is implementable by code into the software.

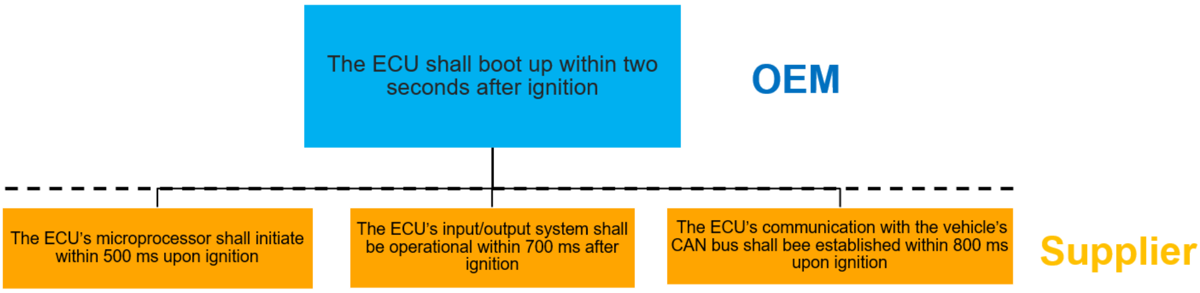

Figure 13. Decomposing requirement example.

5.2.2.1. Over the air

Over-the-air (OTA) is the technology that allows for wireless transmission of data between vehicles and databases, the modern vehicles are using 4G/5G network connection to download data from OEM's cloud databases. This technology reduces the need for customers to visit workshops since the new software can be downloaded wirelessly instead of via physical cable. (Vector, n.d).

5.2.3. Testing and verification

The requirements for both hardware and software define what needs to be developed and how the product should function. To verify that it works as intended and all requirements are implemented as requested a Design Verification Method (DVM) is specified. The DVM is specific for each ECU and contains the tests mapped to the requirement or requirements it should verify. It's usually two sets of DVMs developed for a product, one at the OEM and one at the supplier. These two DVMs are based on the high-level requirements from the supplier and the decomposed requirements from the supplier. Each requirement needs a test case to verify that it satisfies the requirement criteria. Note that one test case can cover several requirements.

5.3. Current ECU lifecycle management practices

The lifecycle of the ECU is defined in several documents of confidential nature. Table 2 presents an overview of the documentation that describes the policies and standards affecting ECU lifecycle management.

Table 2. Documentation related to ECU lifecycle.

Evidence #	Source	Purpose
1	Company B	Design Pre-requisitions - The document provides the requirements and guidelines for the design of the Telematics module from 2016. It covers requirements for both software and hardware with most of the requirements related to software. The requirements incorporate both internally developed requirements and global standards.
2	Company B	Technical cleanliness requirements – The document provides the requirements necessary to achieve satisfactory cleanliness in the manufacturing and workshop area. Including areas for repair. This document reflects the ISO standard *ISO SS-EN 14644-1.*
3	Company B	Packaging requirements – The document describes the requirements for packaging the products delivered to Company B.
4	Company A	Manufacturing concept – The document describes the manufacturing process at Company A for the telematics unit. It's presented as a detailed PowerPoint presentation with each step of the production carefully described.
5	Company A	Logistical concept – The document describes the logistical workflow and distribution globally. It also highlights the requirements for global export to verify that all documentation is available.
6	Company A	Warranty service request – The document describes and summarizes all requirements established by Company B regarding warranty-claimed parts. It describes timings, markets, and projections of volume.
7	Company A	Returned part analysis concept – The document describes the user guide for analysis based on the warranty service request by Company B. It specifies the analysis step by step and is an input to the final deep analysis concept
8	Company A	Warranty claim analysis report – The document analyzed is a report from a faulty ECU containing all tests and results specified in the analysis concept.
9	Company A	Fault analysis summary report – The document is a summary by the warranty service team. It's a list of all ECUs received in the year 2022 specifying the status, actions, and conclusion of the analysis process.
10	Company B	Return printout – The document is a printout of the Company B system for all parts returned to Company A in the year 2022 from one specific plant at Company A.

5.4. Remanufacturing, repair, and re-use practices

This section highlights the purpose of the documentation included in the investigation that defines the current remanufacturing, repair, and re-use practices. Through analysis of these documents, we aim to understand the implications they have for the implementation of circular strategies and extending the useful life of the ECUs. The collected documents are summarized and presented in Table 3 to provide a clear overview of each document. This evidence-based analysis will be further described in Chapter 6.

Table 3. Archival records related to circular strategies.

Evidence #	Source	Purpose
11	Company A	Recovery of ECU – The document describes a step-by-step guide on how to recover the telematics unit if it has malfunctioned, returning the software to its supplier factory state.
12	Researcher	Notes from a factory visit
13	Researcher	Notes from Workshop
14	Company A	Re-work concept – The document describes an investigation done for another OEM that considered remanufacturing as a solution to a quality problem.
15	Company A	Zero re-work concept – The document describes a template for which electronic components are applicable for re-work during manufacturing if a problem has occurred. It outlines the cause of the failure and the approved solutions.

5.5. Software, Hardware, and Cyber security requirements

Documentation that could potentially affect the implementation of circular strategies was categorized into three sections, software, hardware, and cyber security. Cyber security can be considered a part of the software, but it's here separated as it has a major significance to the topic. In Table 4 the documents concerning requirements are presented.

Table 4. Requirement data

Evidence #	Source	Purpose
16	Company B	Design Pre-requisition – The document describes the same content as the DPR in Table 2, however, this DPR is applicable for another ECU developed in 2022.
17	Company B	SW base tech – The document specifies the software base tech requirements for the telematics module. See section 5.2.2
18	Company B	SW Application – The document specifies the software application requirements for the telematics module. See section 5.2.2

19	Company A	Cyber Security Summary – The document is a summary of the decomposed cyber security requirements applicable to the telematics module.
20	Company A	Technical cleanliness concept – The document provides the final technical cleanliness concept developed by Company A based on their internal requirements and the requirements received from Company B
21	Company A	Quality concept – The document describes the process of qualifying the part for production including design and production verification. It also describes the key performance indicators for reliability predictions.

6. Data analysis and findings

This chapter covers the process of analyzing data collected in Chapter 5. As the automotive industry strides towards sustainable practices, understanding the dynamics between OEMs and suppliers becomes essential. The qualitative and quantitative data identify key patterns like cyber security requirements, quality standards, and the feasibility of circular economy strategies. This analysis shows the current situation and reveals opportunities for innovation within the automotive industry. Following the analysis, we present practical recommendations for OEMs and 1st tier suppliers. These insights aim to bridge the gap between sustainability goals and operational strategies. This exploration serves as a steppingstone toward a deeper understanding of the potential for circular strategies concerning automotive electronics.

6.1. Description of current ECU lifecycle and WoW

Through the data collected from relevant documents, contracts, and internal presentations it is possible to describe the lifecycle of the ECU, see Figure 14. The section below is a result of the analysis that was performed which describes each step starting from the manufacturing at the supplier until the end of life and the alternative routes for the ECU during its lifetime.

1. The ECU is manufactured and delivered to the OEM factory for assembly into the vehicle.
2. If the ECU fails the EOL testing in the manufacturing site, it might be subject to a rework or retesting and is therefore again introduced to the manufacturing workflow. There are quality policies in place that prohibits certain rework operations due to risk for either the manufacturing equipment or the quality of the part.
3. If the ECU requires a prohibited operation, the ECU is considered scrap and will reach its end of life, and is subject to recycling.
4. After successful assembly into the vehicle at the OEM factory the vehicle is sent to the final customer.
5. If the ECU fails during the end-of-line testing at the assembly site, the ECU is replaced with a new one and considered scrap.
6. If the ECU fails during the end-of-line testing a portion of the malfunctioning ECU are sent to the warranty center of the supplier for a deep analysis. This analysis will determine if there is a systematic failure and determine the party responsible for the failure. If there is a systematic issue with the ECU, the analysis report is sent to the development team for quality updates to prevent reoccurrence.
7. Once the expected lifetime of the vehicle has been reached, the ECU has reached its EOL.
8. If there is an issue during the usage of the vehicle, the user will take the vehicle to a workshop. The workshop will perform a diagnostic investigation and replace the faulty ECU.
9. The ECU that has been replaced is now considered scrap and is now subject to recycling
10. Like step 6, a portion of the faulty ECUs are sent to the warranty center.
11. Ultimately, all ECUs that reach the warranty center independent of failure will be considered scrap and subject to recycling.

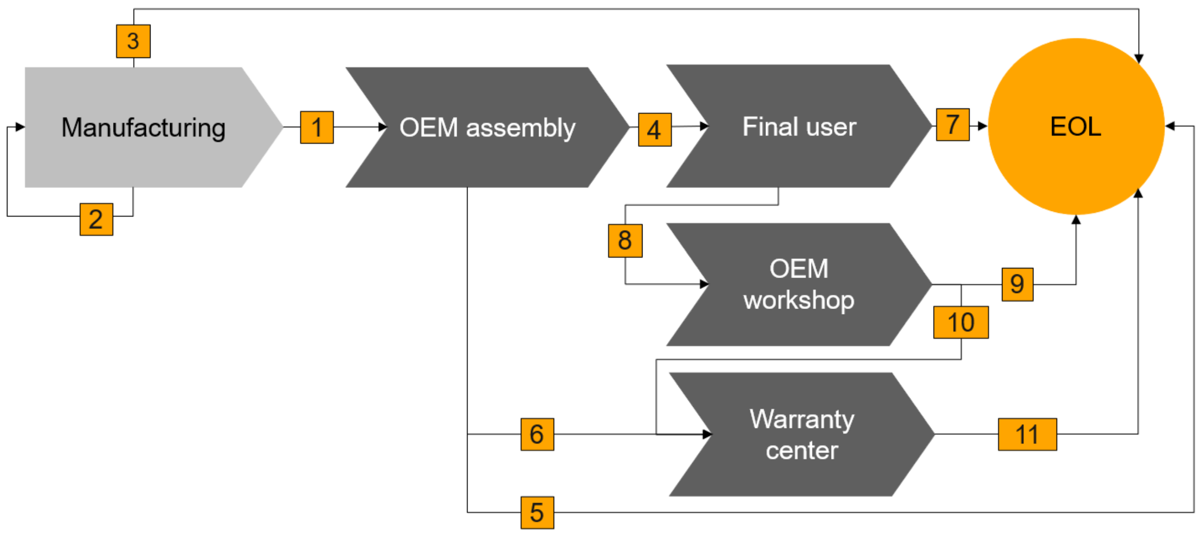

Figure 14. ECU lifecycle & alternatives.

6.2. Barriers to implement circular strategies

As a result of the analyzed files, several possible barriers to the implementation of circular strategies have been identified. In the following section, these barriers are divided into three sections, hardware, software, and cyber security.

6.2.1. Hardware

The analyzed documentation defines the final product that is found in the DPR. The new product is then evaluated through the PV testing process. According to the quality concept, PV testing is the benchmark that the OEM expects for the serial-produced parts they should receive in the future. However, for a part that is remanufactured, repaired, or re-used the same quality standard is expected. Which presents the first barrier.

1. The OEM expects that all products received fulfill the requirements set for the PV testing.

During the production at the supplier, there can be mistakes or failures resulting in an unwanted ECU performance. These failures are categorized into an internal pre-defined template. This template then shows which actions are allowed to be performed and considered as a part of the "Zero re-work concept". These defined actions can be considered a policy to avoid damage to the machines and to ensure the full functionality of the product. This policy shows a clear technical limitation to the process of remanufacturing.

2. There are significant technical difficulties in reworking the electronics hardware without risk of critical damage.

The Technical cleanliness concept and requirements are defined to make sure that there are no contaminations of the product during production. This is connected to a global standard regulation from ISO 14644-1. The requirement defines the cleanliness of the production location, from maintenance to particle size allowed on the factory floor. However, it also states that the area for reparation, or repair area, is also under the same requirements. This is a restriction to the process since disassembling a product can release particles from the ECU itself, breaking the cleanliness requirement.

3. Technical cleanliness requirements are applicable also for reparation areas, preventing disassembly operations.

The last finding is a combination of requirements, interview responses, and observational data. The telematics module was disassembled during the workshop, providing more insight into the disassembly process, and an issue appeared early in the process. As ECUs are getting more advanced and require more energy, they are also getting warmer. This requires that ECUs have a heat sink, figure 15, for heat dissipation. A heatsink is in this case combined with a cooling paste that hardens over time, making it act as a glue holding the aluminum sheet in place. Removing this plate, took “quite a lot of effort” and in the end it bent, see Figure 18.

Figure 15. Heatsink after removal

4. The design of the ECU does not allow for disassembly without risk of damage to the housing and possibly the PCB.

6.2.2. Software requirements

Based on the evidence collected, no barriers to the software requirements were found.

6.2.3. Cyber Security requirements

Cybersecurity requirements serve as important safeguards against physical, network, and cloud-based cyber-attacks. Furthermore, they provide necessary standards for functional safety and provide guidelines on the ECU's response in the event of a critical failure. This section presents cybersecurity barriers found in the comprehensive analysis of regulatory frameworks and standards.

Universal compliance with these cybersecurity requirements is a prerequisite for selling commercial vehicles in certain markets. For instance, in the European Union (EU), the United Nations Economic Commission for Europe (UNECE) states these requirements (UNECE, 2020). An examination of the UNECE WP.29 outlines the requisite criteria that must be followed to get certification within the EU. The decomposition of the UNECE's complex regulations translates to several ECU requirements. One of these requirements states that ECU should disable the physical interface to the PCB permanently after software download. This implies that in the event of a critical software failure, restoring the ECU to its original state becomes an impossibility.

5. Cyber security requirement permanently disables the physical interface of the PCB preventing any recovery attempts in case of critical software failure.

6.3. Opportunities for reuse, repair, and remanufacturing of ECUs

As the opposite of section 6.2, this section will describe the opportunities given by regulation, innovation, and evolvement of the automotive industry discovered in the case study.

6.3.1. Software updates

The analysis of replaced ECUs gave a clear indication of which area to focus on. As seen in Figure 16, 73% of the issues found were related to software, while 8% were related to hardware (HW), 9% shows no fault found (NFF) and for 10% of the ECUs, a single category of failure could not be determined also called unknown (UK).

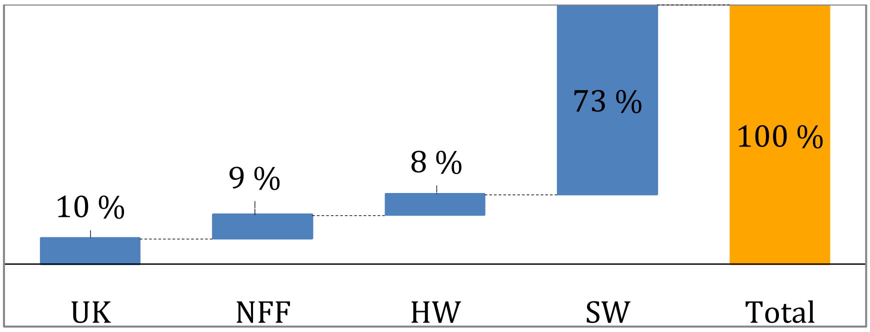

Figure 16. ECUs returned in 2022.

Based on the finding of the statistical data the opportunity for re-use or repair can be found in the requirements for the software and the archival records retrieved from the case study. They present four ways to download software to the ECU

Supplier factory - Performing a software download, or "flashing" is performed in the supplier factory with needle adaptors connected directly to the PCB. This process can load the base software.

Development – During the development, there is a need to restore and recover the ECU if faulty software has been flashed or downloaded to the ECU. This is done with specialized tools and the interface to the hardware is a USB connection from the PC to the CAN network of the ECU. This process can load the base and application software.

On-Board-Diagnostics (OBD) - software download is the most common way of downloading software and is used both in the aftermarket and in the assembly plant. This process can update the application software.

Over The Air (OTA) – Over-the-air updates are a relatively new way of updating the software of an ECU. The vehicle is connected to a cloud server from where it can download and distribute the software to the ECU. This process can update the applications software

The development process, described above, is a way to restore the ECU and has been tested on one of the malfunctioning ECUs. This process could restore the ECU to function properly again. However, it should be noted that a full functionality test was not performed but the previous symptoms were not present after the software recovery.

6.3.2. Market demand and OEM targets

The research provides a clear indication from the industry to move towards a sustainable feature by implementing circular strategies. The published sustainability report from both Company A and Company B shows that they have the ambition to reach 100% closed resource loops. In addition, the global regulations provide clear guidelines (perhaps add some sources here) and requirements that force the industry to act. It can be seen in the two DPRs analyzed that the second DPR from 2022 includes requirements for re-used plastic and requirements for serviceability. This part was not included in the DPR from 2016.

As stated in the interviews by experts in the field, the requirement for remanufacturing and repair processes will become mandatory for all ECUs in the future. As of today, the ECUs eligible for remanufacturing are roughly around 11%. By defining this as a criterion for sourcing a supplier it will accelerate the development of circular practices at the suppliers.

6.4. Potential of closed loop lifecycle

This section will be based on the finding to explore the potential of closed-loop lifecycles. It will use the data presented above and provide an analysis of the environmental saving and potential for financial incentives.

6.4.1. Environmental aspects

According to the data discussed in section 6.3.1, it appears that a large majority of ECUs, as much as 73%, are scrapped exclusively due to software failure. If we extend this to include ECUs that show no identifiable failure, this figure rises to 82%. This is an important finding when investigating the potential for circular strategies. In light of these figures, an opportunity presents itself in the form of ECU repair, specifically focused on software issues. If a reliable and effective method for repairing software failures on ECUs could be established it would drastically reduce the need for part replacement and consequently, the need for new material.
Such a strategy would have a twofold benefit. First, it would directly contribute to reducing waste generation, a primary goal of sustainability. Second, it would lead to more efficient resource usage. The continued utilization of already-produced hardware would conserve the resources that would otherwise be used to manufacture new ECUs.
This approach does, however, rely on the feasibility of ECU software repair. Such repair mechanisms would need to be both reliable and cost-effective to be a viable alternative to the current practice of part replacement. Furthermore, it must be noted that this strategy only addresses ECUs discarded due to software issues and does not apply to units scrapped due to hardware failures or at vehicle end-of-life.
Therefore, the potential reduction of scrapped parts by 82% represents a best-case scenario. Still, this potential reduction would be a noteworthy achievement in the targets for greater sustainability within the automotive industry.

6.4.2. Financial opportunities

Incorporating circular economy strategies can together with hardware centralization bring several new financial opportunities for the OEM and the supplier. Based on the presented findings and interview data a list of possible financial opportunities is presented below

Reduced the need for new material: By reusing, repairing, or remanufacturing existing ECUs, OEMs can significantly reduce the costs associated with new material procurement. This reduction can be especially significant considering the current global supply chain issues and rising costs of raw materials.

Cost savings from decreased waste: The cost of waste management, both in terms of financial expenditure and regulatory compliance, can be reduced by implementing circular strategies. This leads to a decrease in waste because there is no need to manufacture new hardware if it is possible to do a rework of an old one and it will remove the cost to scrap the faulty part.

Future-proofing and cost efficiency with OTA updates: By employing centralized hardware architectures and enabling OTA updates, OEMs can reduce the cost associated with hardware replacements for new feature additions. This future-proofing strategy not only reduces costs but could also enhance customer satisfaction and improve their market position.

Competitive Advantage and Market Differentiation: As sustainability and environmental responsibility become increasingly important to consumers, businesses that adopt circular economy principles can differentiate themselves in the marketplace, potentially gaining a larger market share. Suppliers that can provide remanufacturing or repair for the ECUs are more likely to get sourced.

Regulatory Compliance: By adopting practices that are in line with environmental regulations companies can avoid potential fines and penalties, and future-proof their operations against expected stricter regulations.

7. Discussion

This thesis has provided an in-depth exploration of the complex dynamics between an OEM and a 1st tier supplier in the automotive industry, with a focus on the feasibility of remanufacturing, repairing, and re-using ECUs. The research has combined multiple data sources, including interviews and real industrial data, and has used a case study methodology to ensure a comprehensive understanding of the topic.

7.1. RQ1: What are the current trends and challenges in the remanufacturing, repair, and re-use of ECUs within the automotive industry

Our findings have revealed that the ambitious targets for implementing circular economy strategies in the automotive industry include various trends which present both opportunities and challenges. A key trend identified in this study is the industry's move towards ECU centralization, this means that you use a few high-performance ECUs that control all software functions in the vehicle instead of having several small ECUs. This shift to centralize the functionalities into fewer ECUs simplifies the diagnosis and repair process, making it more efficient. It also enhances the remanufacturing efficiency and increases opportunities for reuse. Despite its apparent advantages, centralization also comes with its own set of challenges, such as dealing with more complex ECUs that house numerous functionalities. Housing several functions within one ECU can add additional risk for remanufacturing, repair, and re-use as more functions need to be fully tested after such operations.

Additionally, we observed an increasing focus on cybersecurity requirements, driven by the growing complexity of the connected vehicle (UNECE, 2020). While such security measures are essential for safeguarding vehicles and users, they create significant challenges for the reprogramming of ECUs, thus impacting remanufacturing, repair, and reuse strategies.

According to an expert in the field who was interviewed for this study, the diversity in incoming software and hardware quality presents another challenge. Implementing a one-size-fits-all solution for circular strategies becomes difficult due to the varying quality of malfunctioning parts. Therefore, ensuring the same functionality and quality as a new part necessitates that remanufactured or repaired ECUs undergo similar production and quality testing processes as new units which would add complexity, time, and cost to the process.

Another notable challenge lies in the mismatch between the expectations from OEMs and the reality. The conventional standard for remanufactured parts being as good as new or better might work well for mechanical components but creates significant hurdles for ECUs (Gunasekara, 2018). Electronics should have a separate set of requirements as they are, mostly, hidden within the vehicle and should therefore not be applicable for visual requirements. It's also a challenge highlighted during the interviews to determine the warranty aspect of a remanufacturing, repair, and re-use process as it is a recovery and not a renewal of the components. To extend the warranty of the ECUs you would need to replace the "first-to-break" component and define it based on new criteria which will be significantly more complex than for mechanical components.

7.2. RQ2: What process improvements are required for remanufacturing, repair, and re-use of electronics to mee the standards of the automotive industry

In response to the second research question, our study has demonstrated the significant potential and challenges in utilizing emergent trends and practices within the automotive industry to drive circular economy strategies. A key trend is the birth of OTA updates (Vector, n.d), a technology that is reshaping the maintenance and repair landscape in the automotive industry. OTA updates have crucial implications for the viability of circular strategies. Primarily, they facilitate the remote diagnosis and rectification of software issues. This drastically reduces the need for physical removal, repair, or replacement of ECUs, thereby minimizing waste and extending the lifespan of the ECU. This aligns closely with the principles of the circular economy (Ellen MacArthur Foundation, n.d). Moreover, OTA updates provide a way for continuous improvement to the vehicle's system, even after it has left the factory. This has the potential to significantly reduce the need for hardware replacements, favoring instead a focus on software enhancements that can extend the useful life of the ECUs. It also allows companies to collect data to prevent issues for other vehicles by working proactively to improve their software.
However, it's worth noting that OTA updates have limitations as well. They can only be used to update the application layer of the software, meaning if the base software fails, a more complicated process, like the original development process, needs to be implemented in the ECU lifecycle. This presents significant challenges in the remanufacturing and repair of ECUs, as they would require more than just an application layer software update.
The increasing complexity of software and integration of multiple functionalities within single ECUs also present challenges. They can complicate the diagnosis and repair process and create barriers to the re-use and remanufacturing of the ECUs. It also means that if one functionality of the centralized ECU is malfunctioning the whole ECU needs to be replaced if it’s not designed for remanufacturing, repair, or re-use.

An additional key finding relates to the unexploited potential in the aftermarket treatment of the ECU. We have observed a pressing need for a substantial rethinking and restructuring of the current ECU aftermarket processes to exploit the benefits of circular strategies. Limited ECU diagnostics and knowledge at the OEM contribute to a high number of NFF and SW-related returns. This results in a wasteful cycle of unnecessary replacements. This scenario presents an opportunity to reconsider current processes and invest in repair. Considering the results of the statistical analysis, repair of the software shows the most potential for financial success. Future strategies could focus on re-flashing the ECU, rather than replacing the entire unit by implementing another alternative into the lifecycle according to step 9 in Figure 17. Step 9 would be an alternative flow for all parts excluding the ECUs that will go to deep analysis. While the potential savings here can be noteworthy, such strategies should be approached cautiously, due to the cybersecurity requirements that are a crucial concern in today's digital age and would require additional analysis by experts in cyber security and ECUs.

As mentioned before, only a portion of the replaced ECUs are sent in for analysis at the warranty return center. Based on the statistical analysis, 73% are related to SW and 9% are showing no failure. Assuming that the statistical analysis is representative a simple calculation would show that repairing 73%+9% of the 90% remaining ECUs which are currently stored or scrapped would reduce the total number of scrapped ECUs by 75% (Eq.1) $Potential\ scrap\ reduction = (0{,}74 + 0{,}09) * 0{,}90 = 75\%$ (1)

It’s still of high importance that the 10% goes to the warranty center to determine systematic faults and failures to proactively improve the HW and SW quality. A simplified way of this process is described in Appendix A under Topic 3. Deep diving into the full and detailed process can present a compliance issue and cyber security risk.

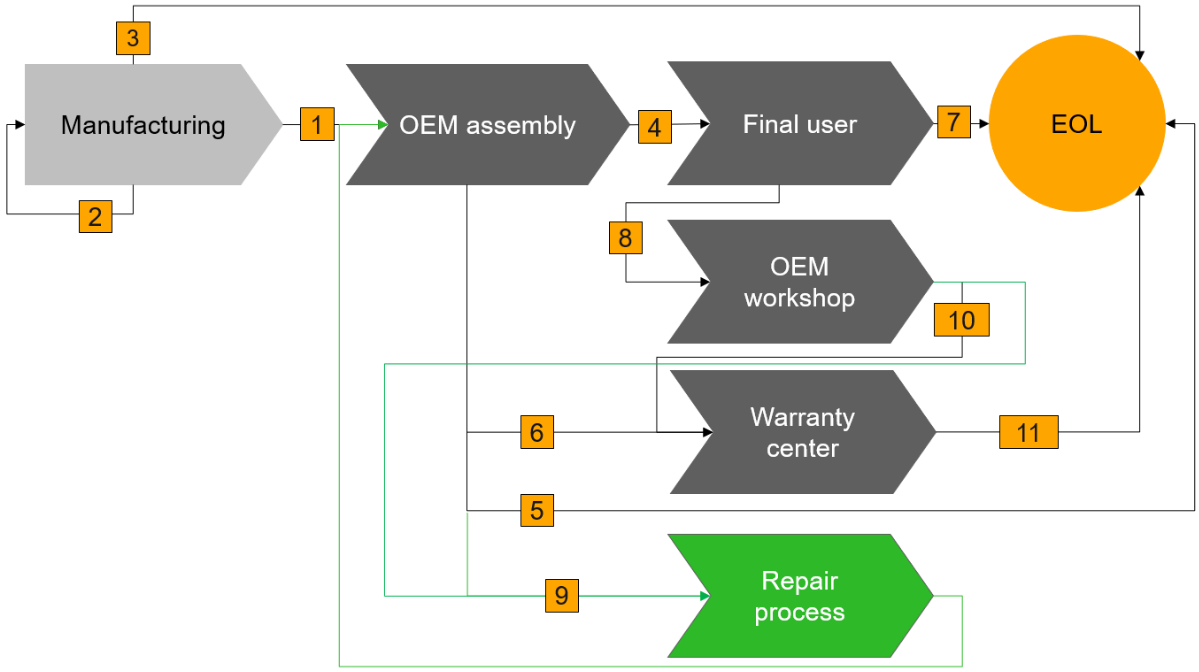

Figure 17 – Introducing repair to the ECU lifecycle

7.3. Recommendations for the OEMs and 1st Tier Suppliers

The sections below outline the concluding recommendations for the OEMs and 1st Tier Suppliers to reach their sustainability targets

Cyber security requirements

This research would highlight the need for innovative solutions to complex issues, it's clear that in certain areas "time to market" is more important than innovation and high-tech solutions. But a new and improved technical solution could potentially remove this constraint and enable operations to extend the ECU lifetime.

Incoming quality & hardware quality requirements

As a recommendation for OEMs and 1st tier suppliers, this research would focus on the risk analysis for ECUs eligible for remanufacturing, repair, and re-use as a first step toward a circular economy. We conclude that the risk of failure prevents OEMs and 1st tier suppliers to investigate the alternative deeply before excluding it as an option. A way to support this process is to consider the option of remanufacturing during the design process of the ECU and using the concept of "Design for Remanufacturing".

Unrealistic expectations from the OEM

To prepare for the new era of ECUs, the automotive industry must be willing to adapt their requirements for remanufactured, repaired, and reused parts. By focusing on communication and compromise to reach a solution that is possible, acceptable, and safe for the end customer.

Feasibility

The facts show a clear increase in feasibility for circular strategies. Given the potential for these operations, we recommend that OEMs and suppliers revisit the option to repair and re-use ECUs already on the market. As the solution to reduce waste might already be available, as suggested in section 6.3.2.

7.4. Limitations and future research directions

The research conducted was based on a single case study. Although we sought to gather a comprehensive understanding of the feasibility of circular strategies in the automotive industry, we acknowledge that our findings might not be generalizable to all settings. Future research should aim to conduct similar investigations across multiple companies and possibly several ECUs to further validate the evidence found in this research.
There is also a gap in research on case studies with real industrial data. This gap largely results from the lack of deep technical expertise in the product for external researchers. Future research should focus on bridging this gap, providing more concrete and quantifiable data to experts within the companies to improve the design and investigate the implementation of circular strategies.

Another limitation that is considerable when using industrial data is concerning compliance and confidentiality. The protection of internal information is crucial for companies to protect their business models, processes, and technical data. Ensuring compliance is a problem for external researchers who can only base their findings on publicly available data and therefore can damage the validity of the study (Yin, 2003). This data is usually not painting the whole picture and may require a lot of speculation to prevent further development.

In this case study we have had access to privileged and confidential information and have done our utmost to avoid any compliance issues. We ensured to remain within legal boundaries, even though this sometimes meant dealing with broader brushstrokes rather than minute details. Furthermore, due to the sensitivity and confidentiality of internal information related to operational processes and data, we were only able to use non-specific, aggregated data in our analysis. Consequently, while we present a comprehensive picture, certain fine-grained insights may not have been included due to these limitations.

Moreover, the issues identified are more from an organizational perspective than from a technological one. Risk management and willingness to compromise will be an important parts for both the OEM and suppliers to reach their sustainability targets.

One additional challenge was highlighted by an expert in the connectivity area during the factory visit. The challenge posed was related to homologation for telematic ECUs that require unique homologation for certain markets. Homologation is the government-issued certificate required to sell the vehicle. This topic was, in this thesis, not investigated therefore might present additional blockers to implementing circular strategies.

Lastly, the underutilization of the aftermarket potential in ECU treatment represents an exciting area for future process improvements. Further research could investigate how this process could be designed to repair ECUs and improve the sustainability of the automotive industry more effectively.

8. Conclusions

In the quest to optimize resource use, the automotive industry stands on the brink of a significant shift. The practices of remanufacturing and recycling are set to take center stage in the coming years, moving the industry towards a circular economy. This thesis took a deep dive into this transformative space, exploring the intricate dynamics between an Original Equipment Manufacturer (OEM) and a first-tier supplier, with a sharp focus on the practicality of remanufacturing, repairing, and reusing electronic control modules.

Our exploration brought several intriguing insights to the surface, all of which contribute to a fresh perspective on the practicality of a circular economy in the automotive industry. These include the urgency of cybersecurity requirements, the associated risks of maintaining quality standards in remanufacturing and recycling processes, the necessity to recalibrate OEM expectations for refurbished parts, and the growing feasibility of circular strategies, which are driven by regulatory changes, technological innovations, and a trend towards more centralized, software-focused hardware architectures.

Informed by these findings, we propose a set of strategic recommendations for both OEMs and first-tier suppliers, aiming to bolster their sustainability endeavors in the sphere of automotive electronics manufacturing and remanufacturing. These recommendations span from fostering innovative, swift cybersecurity solutions to engaging in thorough risk analysis for ECUs eligible for circular strategies, adjusting OEM expectations for remanufactured, repaired, and reused parts, and reevaluating the possibilities of repairing and reusing ECUs already in the market.

Through this study, we have attempted to contribute significantly to the academic discourse around the application of the circular economy within the automotive industry. This work unravels the realities of the relationship between OEMs and suppliers, spotlighting the importance of clear definitions of requirements, a spirit of compromise, and the propulsion of innovation. While we may not have arrived at a definitive solution, we hope this research serves as a roadmap for OEMs and suppliers, nudging them to begin their deeper investigations into this field teeming with potential. We hope that this work helps shape the future of industry moving towards sustainable practices.

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Appendix A – Expert review template

Introduction and purpose

The automotive industry is facing growing pressure to adopt sustainable practices and reduce its environmental impact. One way to achieve this is through 3R (repair, remanufacturing, and re-use) strategies, which can help extend the life of products and reduce waste.

In this interview, we will be speaking with representatives from the automotive industry about their approach to the circular economy and the “3R:s” for ECU’s (electronic control units). We will also discuss your current use of re-used, re-paired or remanufactured components, the challenges you face in implementing circular strategies, and your future initiatives to advance sustainability and circular economy practices.

Furthermore, we will explore the potential of a concept that provides repair, remanufacturing, and re-use services for ECU’s. We will discuss the financial benefits of implementing circular strategies and the competitiveness of companies that provide these services. Finally, we will address the challenges and blocking points that might be faced during the implementation of such a concept, and where an operation like this should take place.

Note: The interview will be anonymous, no name or company will be mentioned unless this is a request.

Topic 1 – General “3R:s” strategy

The automotive industry is a significant contributor to global carbon emissions, and as concerns around climate change and resource depletion continue to grow, there is a growing demand for sustainable solutions in the sector. 3R (Repair, remanufacturing, and re-use) strategies are essential components of a circular economy, and many companies in the automotive industry are embracing these principles to reduce waste and extend the life of their products.

- *What is your company's approach to circular economy and the “3R:s” for ECU’s?*
- *Does your company currently work with re-used, re-paired or remanufactured ECU’s or other electronics?*

Topic 2 – Concerns “3R:s” strategy

One of the main concerns when implementing repair, remanufacturing, and re-use strategies is ensuring that the quality of re-used, re-paired or remanufactured components. Do they meet the same standards as new components? Companies must ensure that these components undergo thorough testing and inspection to ensure that they function properly and safely.

There may also be concerns around the competitiveness of companies that choose to implement these strategies. Companies that invest in sustainable practices and circular economy initiatives may face additional costs that their competitors do not, which could impact their competitiveness in the short term.

- *How does your company ensure that re-used, re-paired or remanufactured components meet the same quality standards as new components, and do they follow the same requirements as a new component?*
- *Are there any known challenges that your company faces for the implementation of circular strategies? Is there also a solution to these challenges?*
- *The implementation of circular economy can but isn’t always a profitable business, how does your company ensure the financial benefit and how important is it?*
- *What future initiatives does your company have to further advance their sustainability and circular economy practices?*

- *Would a concept that provides this service (without any profit or loss) be of interest and how do you think it would affect the "competitiveness" of the company that provides the service?*

Topic 3 – Verification of technical solution

A statistical analysis was performed indicating that most parts are failing due to software-related issues revealing that there is no need to alter or repair the hardware. Doing software recovery is a known process used in development. Implementing a similar operation for the aftermarket is possible and could also be automated to minimize the manual handling. Manual handling is always a risk and automating the process could retain the overall quality of the product.

After collection of the units, they would be shipped to a joint location to be "recovered". The recovery process uses the following steps.

1. Unit to be placed in fixture by robot, possible optical inspection
2. Robot to place electrical connections in place (12V+CAN bus connection)
3. Script from microcomputer hold the "factory state SW" from supplier. It would erase all content from the ECU and reflash it to its original state.
4. If the flashing is successful the ECU will undergo a series of testing, do by the same microcomputer to verify the SW integrity and functionality.
5. If the unit fails the flashing, it will be sorted out as "unrepairable by SW".
6. When it fails or passes the sequence, the microcomputer will instruct the robot to post a new label on the ECU stating that it's been "repaired" or "failed".
7. The robot will then pack the ECU for shipment back to the OEM or into a "failure" box.

This operation is a simplification of the process, there are more steps to ensure traceability and quality.

- *In your opinion, is it possible to implement a concept like the one presented above? What challenges or blocking points do you see?*
- *In your opinion, where should an operation like this take place?*

Topic 4 – Known strategies for the "3R:s"

- *Is there to your knowledge any company that provides this service for ECU's?*

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