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Application of Catena-X in Upstream Supply Chains within the Automotive Industry

A Case Study on How Catena-X Supports Circularity and Emission Reduction for an OEM and a Tier-1 Supplier

Master's thesis in Supply Chain Management

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SUMMARY

Due to increasing sustainability requirements and electrification of vehicles, automotive supply chains are becoming increasingly dependent on electronic components. While this development supports the transition toward more sustainable transportation, it also increases challenges related to Scope 3 emissions, supply chain transparency and circularity. Since environmental data is distributed across multiple supply chain tiers and often treated as commercially sensitive, companies struggle to obtain reliable primary data needed for accurate product carbon footprint calculations and sustainability initiatives. To address these challenges, collaborative data ecosystems, such as Catena-X, have emerged with the ambition to enable standardized and sovereign data exchange across the automotive value chain. Despite growing industry interest, there is still limited research regarding the practical challenges and benefits associated with Catena-X adoption, particularly within upstream automotive supply chains for electronic components. Thus, the thesis motivation originates from an ambition to increase the understanding of how Catena-X can support circularity and emission reduction opportunities while also addressing the challenges associated with ecosystem adoption and data exchange.

This case study aspires to investigate how the Catena-X ecosystem can support increased circularity and emission reduction opportunities within upstream automotive supply chains for electronic components. To fulfil the research objectives, a qualitative case study was conducted with an original equipment manufacturer (OEM), a Tier-1 supplier, additional upstream actors and representatives connected to the Catena-X ecosystem. The empirical material was collected through semi-structured interviews and complemented with secondary data consisting of academic literature, industry reports and publicly available Catena-X documentation. A theoretical framework was developed to support the analysis of empirical findings. The empirical data highlighted two main categories of challenges related to both sustainability management in general, and to Catena-X implementation specifically. Some highlighted challenges are, for example, organizational readiness, ecosystem maturity, data transparency, standardization, implementation costs, and low awareness regarding Catena-X and its practical applications. At the same time, the findings identified several perceived benefits related to improved standardization, increased data transparency, enhanced collaboration and support for emission management. Together, the findings and the discussion provide insights into both the opportunities and challenges associated with Catena-X adoption within automotive supply chains.

Keywords: Catena-X, Scope 3 emissions, Circularity, PCF, Data ecosystems, Automotive industry

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List of Abbreviations

A list of acronyms used throughout this master's thesis is presented below, listed in alphabetical order:

BoL	Beginning of Life
BOM	Bill of Material
CDP	Carbon Disclosure Project
CE	Circular Economy
CRM	Critical Raw Material
CSRD	Corporate Sustainability Reporting Directive
CX	Catena-X
DDS	Digital Data Space
ECU	Electronic Control Unit
ELV	End of Life Vehicle
EoL	End of Life
ESRS	European Sustainability Reporting Standard
EV	Electric Vehicle
GHG	Greenhouse Gas
IMDS	International Material Data System
IoT	Internet of Things
IT	Information Technology
LCA	Life Cycle Assessment
OEM	Original Equipment Manufacturer
PCBA	Printed Circuit Board Assembly
PCF	Product Carbon Footprint
RCD	Recovery Conscious Design
RQ	Research Question
SC	Supply Chain
SCD	Sustainability Conscious Design
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

1. Introduction

This chapter provides an overview of the context in which the thesis is situated. It identifies some of the problems that automotive industry companies currently face regarding emission accounting and circularity practices. Furthermore, the chapter presents the purpose of the thesis and the research questions that will guide the research. Finally, the delimitations are presented to clarify the scope of the thesis.

1.1 Background

1.1.1 Automotive electrification drives demand for electronic components

Driven by the global push for sustainability together with the emergence of new technologies, the automotive industry has undergone a swift transformation towards electric vehicle (EV) development (Liu et al., 2026). However, electrification should not be understood solely as a response to environmental objectives, but rather as a core component of broader industrial development. In this sense, electrification enables what Zhao et al. (2025) refer to as a data-centric evolution of the automotive sector. Zhao et al. (2025) explain how the access to and use of big data will transform industry standards regarding vehicle design, user experience, and manufacturing processes.

Because of the increased demand for EVs, data analytics is becoming ever more important to monitor and enhance vehicle performance. This results in an increasing use of sensors and Internet of Things (IoT) modules. As the total number of sensors and IoT modules are growing, the number of Electronic Control Units (ECUs) will also likely increase due to the additional need for data processing and control. At the same time, the integration of technologies driven by data, such as sensors and IoT modules, is both environmentally and economically demanding due to high development and implementation costs, as well as the complexity of the materials and technologies involved (Zhao et al., 2025). These electronics are part of complex value chains involving multiple actors, material flows, and supplier tiers. This creates a sustainability paradox: the vehicles designed and developed to lead the transition toward sustainability also increase the dependence on complex electronics that both cause upstream emissions and are difficult to recirculate. More specifically, the ECUs and other electronic components enabling this transition generate substantial upstream green house gas (GHG) emissions and are difficult to recover, reuse, or recycle at the end of life (EoL) (Rosa & Terzi, 2023). Furthermore, the ECUs account for a substantial share of vehicle value, thus they are important both from an emission and circularity perspective, as well as from a technical and economic perspective (Rosa & Terzi, 2023). Rosa and Terzi (2023) further explain that automotive electronics can account for 30-50% of total vehicle cost depending on vehicle luxury level and thereby amount of ECUs, and ECUs have been estimated to embody 654 kgCO_2eq of GHG emissions per vehicle. ECUs are one of the main sources for valuable and often hard accessible critical raw materials (CRMs).

The increase in ECUs and other electronic components increases the dependency upstream along the supply chain (SC) for supply of critical and scarce subcomponents and materials (Rosa & Terzi, 2023). As environmental attention shifts toward production and upstream supply chains, companies therefore need more accurate data on component and material composition, supplier processes, and climate related impacts across the value chain (Kurdve et al., 2024). However, such data is difficult to obtain in practice because it is distributed across multiple actors, often treated as commercially sensitive, and rarely available in standardized formats.

1.1.2 Data Transparency Challenges in Supply Chains

The increased use of electronic components raises questions of supply chains' ability to reuse and recycle such components to reduce the automotive production's environmental footprint and achieve circularity (Zhao et al., 2025). EVs' emissions are connected to the manufacturing phase of the vehicle rather than vehicle usage (Wolff et al., 2020; Kurdve et al., 2024). This places greater emphasis on sustainable production practices to support circularity, but also on the supply chains' ability to effectively measure, trace, and report cradle-to-gate emissions across upstream production stages. Kurdve et al. (2024) further explain that effective emission control requires data from multiple actors along the supply chain across categories such as materials, supplier and higher tier-supplier information, location, transportation, and energy use.

Since a large share of automotive emissions occur outside the focal firms' direct operations, both upstream and downstream, the problem becomes primarily a Scope 3 issue (WRI & WBCSD, 2011). Thus, accurate GHG emissions accounting depends on data from suppliers and other upstream actors rather than only internal company data. Regulatory pressure further intensifies this problem. Under the EU's Corporate Sustainability Reporting Directive (CSRD), large companies are required to disclose Scope 3 emissions, making accurate upstream data collection no longer optional but legally mandated (European Commission, 2023). Research conducted by Lee (2011) shows that 26% of emissions are captured in Scope 1 and Scope 2, implying that the remaining 74% occur in Scope 3. This is especially relevant for electronics manufacturing supply chains where a large number of components and upstream material flows are involved (Huang et al., 2009-a).

Sesana et al. (2024) acknowledges a gap in terms of information sharing between Beginning of Life (BoL) and EoL actors. They explain that this absence of open data exchange prevents the optimization of EoL vehicle management processes and limits the improvement of vehicle design for easier disassembly and recycling. At the vehicle's EoL, when important information about its parts and materials is unavailable, it is difficult to make well-informed decisions about EoL strategies (Mügge et al., 2023). This becomes particularly evident in complex supply chains such as those in the automotive industry, which involve many globally distributed suppliers (Mügge et al., 2023).

The same upstream data is therefore useful for two connected sustainability goals. First, data about products, materials, and processes is needed to calculate more accurate product carbon footprints (PCFs.) Second, this data is needed to evaluate circularity strategies such as reuse, remanufacturing, and recycling, as well as to improve EoL management. Therefore, data transparency is not only treated as an emissions accounting issue in the thesis, but also as a necessity for enabling circularity.

Data can improve cost efficiency and supply chain resilience, and even enable circularity. Meanwhile, the automotive industry in particular struggles with limited data sharing, a lack of transparency, and accessibility to end-to-end data spanning over the value network (Mügge et al., 2023). The industry is defined by big actors, such as original equipment manufacturers (OEMs), that exert considerable influence over smaller firms in their supplier networks. But there are also influential Tier-1 suppliers that can play important coordinating roles across Tier-2 and further upstream suppliers, especially in supplier development related to sustainability goals (Brechtel, 2025). Yet, many firms refuse to share data with other actors in their supply chains because they view such exchange as a threat to their existing business (Brechtel, 2025). When primary data from Tier-n suppliers is incomplete or absent, secondary data made up of industry averages, databases, and emission factors are used instead (WRI & BCSD, 2011). In other words, without accurate upstream primary supplier data, PCF calculations become dependent on approximations and can be inaccurate.

1.1.3 Data ecosystems like Catena-X can enable data exchange

As a result of the industry's current data-centric evolution, together with the greater focus on circularity and reducing PCFs, the idea of establishing collaborative, open data ecosystems are becoming increasingly attractive. "/…/ there is an increasing need for a platform or network to facilitate the exchange and management of essential supply chain data among companies and throughout different product lifecycle phases" (Mügge et al., 2025).

A data ecosystem can be understood as a "complex socio-technical network" in which autonomous actors collaborate to produce, provide, and consume data through a shared digital infrastructure. Unlike traditional centralized digital platforms, data ecosystems keep data distributed rather than stored in a single location controlled by one firm. This decentralized form of collaboration is enabled by data spaces. The data spaces provide the technical infrastructure required for interoperability, data sovereignty, and standardization. Because all participants follow the same rules, companies can continue using their own computer systems. They are not required to buy all technology from a single provider but only need to connect to the network through specific data space connectors. The data spaces themselves are in turn designed on four principles: data sovereignty, equality, decentralization, and governance. The data ecosystem is the network of partners working together, while the data space is the technical environment and ruleset enabling sovereign data exchange (Brechtel, 2025).

Catena-X is an initiative developed for the automotive industry (Brechtel, 2025). Mügge et al. (2025) proceeds to explain how the Catena-X ecosystem allows for data sharing among actors in the value chain and thus enables supply chain transparency as well as standardization. Catena-X aims to develop a collaborative and open data ecosystem. It also promotes sovereign data exchange across the entire multi-tiered value chain and supports the development of key technologies and solutions for sustainability and circular economy (CE). According to Mügge et al. (2025), this can include support for determining appropriate circular economy strategies at the component level. Catena-X also claims to support the aggregation of component-level PCF data in order to enable the calculation of end products' PCF (Brechtel, 2025).

1.2 Empirical Problem Description

Regulatory pressure and industry focus on sustainability continue to increase. Companies in the automotive industry face challenges in managing Scope 3 emissions and implementing circular practices in upstream supply chains for electronic components. A central issue is the limited availability and quality of primary data from suppliers. Many firms rely on secondary data and industry averages because suppliers often consider primary data sensitive or revealing. The lack of transparency between tiers in the supply chain reduces the accuracy of PCF calculations and limits the ability to identify emission reduction opportunities.

Meanwhile, circularity practices within the automotive electronic supply chains remain underdeveloped. R-strategies such as reuse, remanufacturing and recycling are associated with additional costs and operational complexity, and are not yet viewed as standard practice within the industry. Strict quality and safety requirements from the OEM further complicate the implementation of circular solutions, particularly for complex components such as ECUs.

Another key challenge is the lack of coordination and alignment across the supply chain actors. Although circularity opportunities exist at the Tier-1 level, they are not fully utilized in practice. This suggests that existing capabilities across the supply chain are not being leveraged effectively.

Together, these challenges highlight a gap between the increasing demand for transparency, emission reduction and circularity, and the current capabilities of supply chain actors to deliver on these requirements. This raises the need to explore new approaches that can enable improved data sharing, coordination and implementation of circularity strategies in complex, multi-tier supply chains. In this context, the thesis explores the potential of the Catena-X ecosystem as a means to address and bridge this identified gap.

Although Catena-X offers a promising technical framework, it is still unclear how well its functions match and manage the specific data problems and circularity barriers present in the case companies' upstream supply chains.

1.3 Purpose

The purpose of this thesis is to explore how the Catena-X ecosystem can support circularity and emission reduction opportunities within upstream automotive supply chains for electronic components. It also examines the challenges, benefits and conditions influencing ecosystem adoption and sustainability-related data exchange.

1.4 Research Questions

To serve the purpose, two research questions (RQs) have been formulated, presented below with their respective aim.

RQ1: *What challenges exist for the adoption of the Catena-X framework for emission data transparency and increased circularity within the automotive supply chain among the case companies?*

RQ1 aims to identify and analyze the organizational, supply chain and ecosystem-related challenges and conditions that influence the adoption and practical implementation of Catena-X among the case companies. These include technical, organizational, economic and interfirm challenges across the multi-tiered supply chain. Together, these factors influence the companies' ability to use the ecosystem to improve data transparency, PCF management and circularity support.

RQ2*: How does shared product and material data, as defined by Catena-X, support reduction of Scope 3 emissions and strategies for increased circularity, such as reuse, remanufacturing and recycling, for the investigated case companies in upstream electronic supply chains?*

RQ2 aims to explore how the management, structuring, and exchange of data enabled by Catena-X can support improved emission data transparency, PCF management and circularity practices within upstream automotive supply chains.

1.5 Delimitations

The case study in this report is mainly focused on an OEM in the automotive manufacturing industry and one of its Tier-1 suppliers. The report explores the potential for increased circularity and reduced emissions associated with a lighting component provided by the Tier-1 supplier. More specifically, the thesis aims to investigate the component's ECUs. By only focusing on a limited selection of companies for the case study, the result may not be fully applicable for the entire automotive industry. It may not even be applicable for all upstream suppliers in the focal companies' supply chain.

Furthermore, the thesis focuses on circularity within the case companies' automotive supply chains, rather than on circularity in supply chains more generally. Therefore, the findings may have limited generalizability to other industries.

The thesis will focus on ECUs in upstream supply chains. The thesis does not include the emissions created in the vehicles' use phase. The possibility of reducing PCF and increasing circularity is therefore somewhere in the chain from cradle-to-gate or at EoL.

Furthermore, this thesis is limited by the scope of its empirical data collection. The number of interviews conducted is relatively restricted, and not all relevant functions within the studied organizations have been represented. Consequently, the findings may not fully capture all internal perspectives or the complete extent to which Catena-X is being implemented or evaluated within the case companies.

2. Frame of Reference

This chapter presents the theoretical framework that serves as a basis for the thesis. It reviews the literature on Scope 3 emission reductions and circularity strategies in upstream electronic supply chains. The chapter also provides an information on data sharing, digital data spaces and data ecosystems.

2.1 Emissions Management in Automotive Electronic Supply Chains

This section aims at presenting how the automotive industry works with emission accounting, Scope 3 emissions, PCF, data collection, best practices, and key challenges of calculating accurate Scope 3 emissions in upstream supply chains.

2.1.1 Corporate GHG Accounting and Reporting Requirements

This section explores why companies report emissions and outlines the reporting requirements they face.

Why companies report emissions

As the impact of climate change has become increasingly evident in recent years, governments, corporations and individuals have grown more concerned about the contribution of their activities to climate change. Many organizations are involved in discussions regarding climate change and measuring their GHG emissions from products to identify strategies to mitigate their impacts (Huang et al., 2009-b). Carbon emissions are recognized as one of the critical factors in supply chain management, as suppliers in the chain are significantly affected by stakeholder requirements and emissions regulations (Lee, 2011).

As demand from customers and other stakeholders grows, both within and beyond the automotive industry, many OEMs are pursuing substantial reductions in carbon emissions (Fugger et al., 2025). The use of carbon accounting supports the companies in reducing GHG emissions (Sial et al., 2024), and to identify strategies to reduce their climate impacts (Huang et al., 2009-a).

Measuring and reporting carbon footprint is no longer used solely for reporting purposes, but increasingly functions as a strategic business tool. The information generated through carbon accounting provides companies with insight into their internal operations and can help them identify inefficiencies, reduce costs, and redesign products based on their full life cycle impact (Lee, 2011). Furthermore, integrating carbon accounting into a company's business strategy could lead to increased consumer trust, improve customer loyalty, and improve the overall image of the company (Sial et al., 2024). Ideally, companies would like their GHG inventory to serve multiple purposes. The GHG Protocol Corporate Standard by the World Resource Institute

(WRI) and World Business Council for Sustainable Development (WBCSD) (2004) is designed to support the main business goals of companies.

GHG Protocol Standards

The GHG Protocol Corporate Standard is a comprehensive accounting and reporting framework that provides companies with guidelines and standards on how to prepare a GHG inventory, meaning the quantified and reported accounting of a firm's GHG emissions. There are many different positive side effects of converging toward a common standard. Businesses for example, experience reduced costs from meeting information requirements, while for others, it enhances transparency and consistency, and makes the data more comparable over time (WRI & WBCSD, 2004).

The GHG Protocol Corporate Standard is accounting standards rather than a verification standard. It presents five guiding principles that the accounting has to be based on in order to be considered a true and fair representation of the company's emissions. The principles are relevance, completeness, consistency, transparency and accuracy (WRI & WBCSD, 2004).

Climate targets and requirements

In 2023 the EU adopted commission proposals to reduce net gas emissions by 55% by 2030, compared to 1990 levels (European Commission, n.d.-a). This is part of the work of making the EU the first climate-neutral continent by 2050 (European Commission, n.d.-b). According to EU law, companies above a certain size are required to provide information on identified risks and opportunities from both social and environmental issues, and what impact their activities have on people and the environment. This helps all groups of stakeholders to evaluate the company's sustainability performance (European Commission, 2025).

According to the Corporate Sustainability Reporting Directive (CSRD), large companies must include sustainability information in their management report. A company is classified as large if it exceeds at least two out of the following three criteria: €25 million total assets, €50 million in turnover and at least 250 employees (Directive 2013/34/EU, Arts. 19a & 3(4)). Companies that fall under the CSRD rules are required to report their sustainability information using the European Sustainability Reporting Standards (ESRS) (United Nations Environment Programme Finance Initiative, n.d.). Under ESRS Disclosure Requirement E1-6, undertakings are required to disclose their gross Scope 1, 2 and 3 GHG emissions and total GHG emissions where climate change is defined as a material sustainability matter in accordance with the double materiality principle (European Commission, 2023).

According to the GHG Protocol Corporate Standard (2004), Scope 1 emissions refer to direct GHG emissions generated from sources that the reporting company owns or controls. These emissions arise from on-site activities such as generation of electricity heat or steam, physical or chemical processing, transportation of materials, products, waste and employees, and fugitive emissions. Scope 2 emissions refer to the indirect GHG emissions from the generation of purchased electricity consumed by the reporting company in its operations. Technically, these emissions are created by the electricity provider but accounted for by the consumer company. Whereas Scope 1 and 2 emissions arise from sources owned or controlled by the company, Scope 3 emissions originate from activities outside of its operational control, such as the production and transportation of purchased materials, and the usage and disposal of sold products (WRI & WBCSD, 2004). In order to manage GHG related risks and opportunities, companies must account for emissions along the entire value chain (WRI & WBCSD, 2011).

2.1.2 Scope 3 Emissions in Upstream Supply Chains

In the thesis, upstream supply chain refers to activities occurring prior to the receipt of purchased goods and services by the OEM or Tier-1 supplier. Upstream Scope 3 emissions are defined as indirect GHG emissions associated with purchased or acquired goods and services (WRI & WBCSD, 2011). Accounting for Scope 3 upstream emissions involve describing the value chain, determining which Scope 3 categories are relevant to include, identifying partners along the value chain that contribute significantly to GHG emissions along the chain, and quantifying the emissions. It is acceptable to estimate emissions if there is transparency regarding the approach used for the estimations, and that the data used for the analysis are sufficient to support the objectives of the inventory. The process of verifying Scope 3 data is often difficult and depends on the availability of sufficiently reliable data (WRI & WBCSD, 2004).

Scope 3 emissions can account for the biggest part of emissions for companies (WRI & WBCSD, 2011). A study of the scope of carbon footprint and emissions in US industries show that only 26% of emissions are captured in Scope 1 and Scope 2 (Lee, 2011). Calculating carbon footprint while excluding Scope 3 emissions in the analysis will therefore cause significant underestimations of life cycle GHG emissions (Huang et al., 2009-a), even if accounting for Scope 3 emissions represents the greatest challenges (Bodendorf et al., 2022). Supply chains of the electronic manufacturing industries are complex due to a vast number of components and material required to produce electronic products. Considering this complexity, a very large part of their total carbon footprint is generated in their indirect supply chain (Huang et al., 2009-a). The Corporate Value Chain (Scope 3) Accounting and Reporting Standards by WRI & WBCSD (2011) provide both requirements and guidance for companies on how to prepare and report a GHG inventory that includes indirect emissions from activities in the value chain and can be used by companies of all shapes and sizes.

2.1.3 Product Carbon Footprint

As a consequence of facing increased pressure on automotive companies regarding decarbonization, carbon footprint has evolved as an indicator of the environmental sustainability of a product. PCF is typically measured in CO_2 equivalents and refers to the total amount of GHG emissions related to a product. The emission levels are obtained from a life cycle assessment (LCA). By some, PCF is viewed as an LCA with a limited scope focusing only on climate change. The PCF provides a quantifiable and clear measure of the environmental parameter and easy comparability (Gutwald et al., 2024).

Conducting a PCF study requires defining the scope including functional unit, system boundaries and inventory scope. The functional unit is a defined reference of a product to which all data in a PCF is linked. The system boundary is decided in accordance with the objective of the study and determines which unit process should be included in the analysis and how detailed they should be reviewed (Gutwald et al., 2024).

One critical issue with PCF is the absence of mandatory standards. Although several guidelines exist, none of them are enforced by law. A consistent standardization of methodologies will only be possible through the adoption of internationally accepted standards and norms. The most used PCF standards are PAS 2050, GHG Product Standard, and ISO 14067 (Gutwald et al., 2024).

In LCA based PCF calculations, reliable information is often only available to the company performing the respective process and the knowledge of upstream processes is limited. However, it is often the external processes that contribute the most to PCF, making it hard for companies acting as isolated entities to generate accurate PCFs. A lot of LCAs and PCFs are currently based on assumptions and generic data, rather than specific details of the supply chain (Jaeger et al., 2022).

2.1.4 Supplier Data Collection and Scope 3 Accounting

Data collection

Collecting relevant data on emissions is a resource-intensive task. Digital tools can facilitate the collection of process data by linking different data sources. Integrating Enterprise Resource Planning software with Environmental Management System will enable real-time recording of energy and material flows, as well as their allocation of the PCF product (Gutwald et al., 2024).

In order to collect Scope 3 emissions data, the reporting company has to engage with several parties, both within the organization and also with suppliers and partners outside. The focus should be on collecting data in the areas where emissions have the greatest impact. The process for collecting and evaluating data is divided into four steps; 1) prioritizing data collection efforts, 2) select data, 3) collect data and fill gaps, 4) improve data quality over time (WRI & WBCSD, 2011).

Primary activity data may be collected from tier suppliers through for example meter readings, utility bills, purchase records, engineering models, mass balance, or direct monitoring. To get a comprehensive picture of their impact, companies should seek to obtain data from all their Tier-1 suppliers. Secondary data should be used to calculate emissions when supplier specific data is incomplete or not collected. Companies should encourage their suppliers to develop GHG inventories to enable exchange of primary data in the future (WRI & WBCSD, 2011). If primary data is not available, companies can use LCA databases to fill the data gaps (Gutwald et al., 2024).

When collecting data, companies should use standardized formats on a consistent basis to allow for comparability between years and in order to reduce errors. Companies collecting emission data from suppliers may receive information that is confidential and proprietary, meaning it can only be used for a specific agreed purpose. To enable this, they enter confidential or non-disclosure agreements (Greenhouse Gas Protocol, n.d.)

Calculating Scope 3 emissions

When calculating Scope 3 emissions, companies may use either primary or secondary data. Primary data is derived from specific activities within the company's value chain, for example data provided by suppliers of the reporting company. Secondary data is not derived from specific activities within the company's value chain, but rather based on industry averages or other generic data. The quality of the Scope 3 accounting depends directly on the quality of the data used for the calculations. If the main goal of the reporting company is to reduce GHG emissions, track performance within their value chain or engage suppliers, they should select primary data. If the company would like to understand the magnitude of different Scope 3 activities and identify hotspots, they can select secondary data (WRI & WBCSD, 2011).

2.1.5 Key Challenges in Scope 3 Emission Accounting

General difficulties with emission accounting

Current voluntary disclosures do not present a consistent way or method for measuring and reporting information. Many firms publish vague and irrelevant data, making it complicated for asset managers to calculate carbon footprint. As a result, many companies have failed to report their emissions comprehensively, and the metrics published by different companies sometimes overlap, resulting in double counting. Two examples of accounting systems that consider the whole supply chain are life cycle pricing and product carbon tagging. However, due to technological limitations they are not yet relevant or applicable in reality (Sial et al., 2024).

Firms prioritize financial objectives over environmental concerns, limiting the amount of resources that goes into lowering emissions and reporting the results (Sial et al., 2024). Research indicates that 80% of chief procurement officers in large European firms reported that they do not prioritize sustainability when choosing suppliers. The reasons for this are mainly lack of necessary tools and data, but also lack of expertise and failure in identifying where Scope 3 emissions are generated in the value chain (Bodendorf et al., 2022).

Difficulties with emission accounting in automotive industry

Corporate carbon emissions are not reported consistently across company disclosures, which directly limits the accessibility and comparability of data. Consequently, the pace of industry decarbonization is difficult to predict and it remains unclear which decarbonization pathway the automotive sector is on and which GHG budget can be met (Fugger et al., 2025).

A study by Fugger et al. (2025) on decarbonization within the automotive industry shows that there is a need for more effective and faster measures to reduce emissions. Sustainability reporting varies across companies, with regional differences influencing targets and strategic priorities. Some car manufacturers have announced climate neutrality targets, but it is not possible to properly evaluate them because the OEMs do not provide enough information. More transparent data and standardized reporting methods are needed to better assess their progress (Fugger et al., 2025). An industry wide implementation of GHG Protocol could increase data transparency and comparability of GHG inventories across companies.

Difficulties with Scope 3 emission accounting

Collecting Scope 3 emissions is a challenging task since supply chains are usually complex and often involve hundreds, or even thousands of actors (Huang et al., 2009-a). Due to the complexity, companies are finding the process of collecting and reporting Scope 3 emissions overwhelming and time intensive (Buchenau et al., 2025). One reason as to why Scope 3 data is often insufficient and based on literature values rather than actual data is because the information on emissions is lost along the supply chain. Differences in Scope 3 reporting practices across industries and companies indicate a need for guidelines and standardized reporting frameworks (Buchenau et al., 2025)

Vieira et al. (2024) points out that companies have limited knowledge of their supply chain. Many firms still struggle to map and assess the environmental impact of their first tier suppliers, and show that only 15% of companies are in contact with more distant tiers (Vieira et al., 2024). A key challenge in measuring indirect carbon emissions is the lack of clear value chain boundaries. Because the conceptualization of value chains is somewhat fluid, companies often make arbitrary decisions regarding which Scope 3 emission categories to include. In addition, the data quality on emissions is poor since companies' Scope 3 inventories for the most part are based on estimations rather than primary data, which lowers the credibility of the results. Lack of primary data makes it difficult for companies to measure progress and reach their target levels (Vieria et al., 2024).

Since Scope 3 emissions arise from activities occurring outside the company's control, there are additional challenges related to the collection of such data and ensuring its quality. The challenges include reliance of partners in the value chain to provide data, low level of influence over data collection and management practices, less knowledge about data types, sources and quality, and a large need for secondary data which in turn lead to a bigger need for assumptions and modeling. These challenges contribute to uncertainty within Scope 3 accounting (WRI & WBCSD, 2011).

Difficulties with calculating and exchanging PCF data

According to Gutwald et al. (2024) one major criticism of the PCF is the absence of a mandatory standard, as existing guidelines are not legally binding. Besides gaps between PCF data within companies and in LCA databases, there is also missing knowledge and experience on how to exchange this data (Jaeger et al., 2022).

2.1.6 Supplier Engagement for Scope 3 Emissions Management

There are many different ways to engage suppliers in GHG data collection. One is through a supplier engagement program, including several steps on how to work with suppliers to collect data. The different steps include announcing the program to the suppliers in the supply chain before sending out any surveys, provide training or information on the methodology on how to collect data, check-in with the suppliers regarding their progress, establish consequences for suppliers that choose not to participate, and finally review the submitted data, clarify any issues and thanking the participants (Greenhouse Gas Protocol, n.d.).

In order to receive higher quality data for quantifying Scope 3 emissions, companies need to actively engage with their suppliers. To raise awareness and to address the issue with inconsistent data, companies can organize collaborative training sessions or workshops where firms get a fictive but realistic case scenario and calculate a PCF together. During the session, the participants develop an understanding and gain insight into the complexity of creating a PCF (Fritsch et al., 2024).

2.2 Circularity in Upstream Automotive Electronic Supply Chains

This section introduces relevant theory on circularity and introduces the concept circular economy, both on a more general level as well as closer related to the automotive industry.

2.2.1 Circularity Strategies and Principles

There are three interconnected categories separating the global material flows: “circular”, “linear”, and “potentially circular, potentially linear”. Over the last decades, resource extraction and consumption have increased drastically due to urbanization, growing GDPs and wealth levels (Circle Economy, 2025). Consequently, the linear overconsumption following the take-make-dispose logic, has caused resources becoming scarcer and thereby posing risks connected to dependency and disruptions in supply (Circle Economy, 2025; Pérez et al., 2025). The linear flow of material and resource consumption cannot be maintained. Instead closed-loop systems should be established, where materials and components are circulated back into the supply chain reducing both raw material consumption as well as carbon footprint (Montemayor & Chanada, 2023; Primadasa et al., 2025).

CE has been widely discussed as a method to decouple economic growth from resource demand and consumption, thereby preserving resources and reducing waste (Pérez et al., 2025; Mügge et al., 2023). CE is operationalized through a range of circular practices, which are often structured using frameworks such as the 9R framework proposed by Potting et al. (2017). This particular framework distinguishes the circularity strategies refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover, that being R0 to R9. The R-strategies are ordered based on their level of circularity - from high to low - indicating efficiency of the resource retention, keeping the material loop closed (Mügge et al., 2023; Potting et al., 2017).

A central condition for the implementation of the higher level R-strategies is that products are designed for multiple life cycles already in the product development phase (Pérez et al., 2025). Strategies for improving EoL practices can be broadly divided into two categories: curative and preventive. Curative approaches focus on improving recovery processes such as disassembly and recycling, whereas preventive approaches enhance recoverability already at the product development stage (Fontana et al., 2024). This is because design for remanufacturing and other “design-for” approaches, such as design for disassembly can facilitate core recovery, reduce recovery costs, and improve the product life cycle performance (Pérez et al., 2025). This way, reuse and remanufacturing can be integrated in production and assembly systems whereas recycling is reserved for the EoL management when components no longer can retain sufficient functional value. However, although the R-strategies are attractive in theory, their practical application by OEMs in the automotive industry today remains very limited. Reuse, refurbish, and repair are for example rarely applied strategies today as they are too inefficient; they are difficult to scale and will not generate meaningful sustainability impact over time (Montemayor & Chanada, 2023).

Firms ultimate aim is to generate value, and therefore circularity practices and investments must be economically justified and be supported by a positive business case in order for them to be applied (Pérez et al., 2025). However, according to the Circularity Gap Report of 2025, organizations have much to gain from adopting circular practices sooner rather than later since it contributes to a competitive edge and a stronger brand (Circle Economy, 2025). By adopting circular practices and mitigating resource risks related to supply chain disruptions and price volatility, it can even benefit the organization in terms of customer engagement and customer loyalty (Montemayor & Chanada, 2023). Furthermore, Viskin et al. (2025) argues that introducing circularity practices in manufacturing may strengthen the competitive advantage by cutting costs and improving operational efficiency.

The adoption of circular practices could become a virtuous circle. As Machur et al. (2021) explains it: “/…/ circularity can be achieved through innovation, competition, and better collaboration and coordination.”. But at the same time, the adoption of circular practices is a driver of change, and if the opportunity is seized organizations could become innovative industry leaders (Circle Economy, 2025). Yet, collaboration is key and if practices and progress are shared amongst actors it could contribute to industry-wide adoption and value generated through circular economies of scale (Circle Economy, 2025).

2.2.2 Circularity in Automotive Supply Chains Today

In 2025, new rules aiming to support the transition to a circular economy by regulating design and EoL management were adopted (European Parliament, 2025). The new rules demand that vehicle design should simplify dismantling in order to enable higher levels of reuse, recycling, repair, and remanufacturing of vehicle components. Furthermore, better dismantling practices also simplify compliance of the rules concerning EoL management, stating that vehicle producers will have a greater responsibility and are expected to cover a substantial part of the costs related to EoL treatment. It is also expected that manufacturers ensure incorporation of recycled material into parts manufacturing, starting with plastics and if successfully implemented, this should later extend to steel and aluminum, further supporting circularity principles (European Parliament, 2025).

Increased requirements have also been established on a supply chain level through legislations, such as the Supply Chain Act, to ensure human rights and environmental protection across global value chains (Brechtel, 2025). The automotive industry is particularly affected by these overarching sustainability requirements due to its complex and global supplier networks. In order to comply with the act, companies must introduce systems and technologies enabling traceability of materials and components, such as the digital circularity vehicle passports (Mügge et al., 2025). A digital passport is assigned to a newly constructed vehicle when it enters the market and remains in use until its EoL, enabling the OEM itself, along with other third parties, to update the vehicle’s circularity status throughout its lifetime. Mügge et al. (2025) later proceeds to explain how the industry is still restrained by lack of data and insufficient collaboration and digitization and along the supply chain.

There are great opportunities in terms of resource efficiency and sustainability that can be achieved in both the BoL stages, through for example design for recyclability and design for disassembly, as well as the EoL stages (Sesana et al., 2024). In fact, more than 80% of a vehicle's environmental impact is determined during the design phase at the BoL (Fontana et al., 2024). Positively, most car materials today are recyclable, and more cars are built to be repaired (Machur et al, 2021). Machur et al (2021) also argue that a common language should be established between actors in the automotive supply chain because the supply chain still require significant changes to minimize lifetime carbon emissions and resource consumption.

What makes it particularly challenging to operationalize circularity solutions is that BoL processes and EoL processes are intertwined. Product design influences EoL efficiency, and in order to reduce environmental impact and achieve the necessary business value, multiple solutions must be implemented across the value chain (Machur et al., 2021; Sesana et al., 2024). It is a lengthy process to design on behalf of circularity. Processes such as mapping product composition, identifying products with high environmental impact, and identifying bottlenecks require coordination among actors throughout the automotive value chain (Viskin et al., 2025).

Automobiles are complex products that sometimes comprise around 30 000 products, and for a vehicle to be regarded as circular, every component would have to be recovered or remade from previous vehicles, and no components should have to be removed from the system at EoL management (Viskin et al., 2025). Multiple of the big automotive OEMs have set ambitious circularity goals and are investing heavily in closing material loops (Viskin et al., 2025; Machur et al., 2021; Sesana et al., 2024). Some automotive OEMs have made substantial efforts and progress in terms of becoming more circular (Montemayor & Chanada, 2023), but generally, there is still only a limited number of components that are remanufactured and reused compared to the volume of newly produced parts and vehicles (Pérez et al., 2025).

According to Viskin et al. (2025), circularity efforts in the automotive industry in both size and scope have been limited so far. Insufficient collaboration between value chain actors is one of the multiple barriers hindering the adoption of circularity practices in the automotive value chain (Sesana et al., 2024). Sesana et al. (2024) proceeds to explain that an information sharing system is required to bridge between the actors in the BoL and the EoL processes, the OEMs and the recyclers likewise. Information critical for effective recycling and material reuse is today lost in the gap between the BoL actors and EoL actors (Sesana et al., 2024). What further compounds the complexity of CE assessment and EoL strategy evaluation are products' and components' short life cycles compared to the longer life span of a vehicle (Mügge et al., 2023). Problematically, practices changed in relation to the product design will not be evident or traceable in the EoL until ten years after its implementation (Pérez et al., 2025).

Furthermore, Sesana et al. (2024) points out lacking technology and poor infrastructure to cause poor material recovery, as well as insufficient economic incentives and the diversity of regulatory frameworks to halt circularity utilization. Regarding the latter, the trend of implementing CE practices is supported by the European Commission through multiple initiatives and regulations: general sustainability targets, more specific sustainability targets focusing on eco-design of products, and sustainability reporting requirements (Sesana et al., 2024).

When a car arrives at a dismantling facility that is certified according to the EoL Vehicle Directive, and receives a certificate of destruction, it is officially classified as EoL

(Mügge et. al., 2025). Then the vehicle is either classified as a *material vehicle* suitable for material recycling, or *parts carrier* if it contains valuable, reusable parts. The vehicle is then drained from all fluids and gases, dismantled and all of the pyrotechnic units neutralized, before the remains are compressed to prepare for transport to a recycler (Mügge et. al., 2025).

2.2.3 Circularity Challenges and Opportunities for Automotive ECUs

What are ECUs and why do they matter?

ECUs are electronic systems in vehicles that control and manage specific functions such as the drivetrain, infotainment, and advanced driver-assistance systems. Thereby they contribute to vehicle performance, safety and overall user experience. The automotive electronic control unit market's value in 2023 was estimated to be USD 104,34 Billion and it is projected to grow into a USD 156 billion market by 2030. The growth is driven by vehicles becoming increasingly heavy equipped with built-in features and software, both with the purpose of vehicle functionality and safety, but also partly in order to reduce fuel consumption and emissions (Grand View Research, n.d.).

In 2011, a medium-sized car contained 15 electronic systems on average while more luxurious cars could contain up to 50 electronic systems including microcomputers (Rosa & Terzi, 2023). Rosa and Terzi (2023) proceed to explain how these electric systems can account for 30% to 50% of the total vehicle cost depending on its luxury levels, and is one of the main sources for valuable and often hard accessible raw materials. Despite their value, the automotive sector significantly underperforms in recovering these components and the raw materials from EoL vehicles. Given the projected ECU market growth, continuing this high dependence on newly extracted critical raw materials represent a significant strategic risk.

Why are ECUs complicated in the context of circularity practices?

The end of life vehicle (ELV) recycling of steel and aluminum today does inevitably result in materials partly being sent to lower value applications, either inside the automotive sector or to be used in other industries. This is due to technical inadequacies causing alloys to form and thereby a degradation in materials purity and quality. The increased usage of electric systems in vehicles is expected to further exacerbate this operational inefficiency. This is particularly true because critical materials, such as the scarce metals contained in many of these components, can generate a substantial environmental impact during primary supply, despite only accounting for a small proportion of the vehicle's total mass (Rosa & Terzi, 2023).

The total life cycle impacts of a vehicle's ECUs are estimated to be 22,7 GJ of embodied energy and 654 kgCO_2eq GHG emissions (Rosa & Terzi, 2023). Assuming 50 ECUs per vehicle, these components embody around 5% of the total vehicle manufacturing energy. As the number of ECUs integrated into a vehicle increases, the embodied energy also increases substantially, without any significant change in vehicle total weight. Rosa and Terzi (2023) proceed to explain how this is problematic because the ELV directive's recycling targets are defined by total mass of recycled material. Thus, the recycling of ECUs and their critical materials is economically unattractive. Fontana et al. (2024) further confirms that industry decision-makers currently prioritize the recovery of key components and specific materials, such as metals and plastics, mainly in pursuit of economic benefits and regulatory compliance, while often overlooking critical raw materials (CRM). However, the willingness of industry actors to adopt more ambitious practices is evidently not dependent only on economic conditions. For example, Pérez et al. (2025) explains how cost lowerings between 40% and 65% can be achieved by remanufacturing vehicle parts and components compared to relying entirely on new production.

Circularity opportunities for ECUs

The European Commission is increasingly focusing on CRM recovery from the automotives' electronics (Fontana et al., 2024), and evidently it has given results. Particularly in relation to the curative EoL management of electronics, new technologies and methods have been developed to improve the sorting of the electronics' materials, separating metals from non-metals (Fontana et al., 2024). This can help with preventing the aforementioned issue of material degradation after EoL treatment and also retain the CRMs. Fontana et al. (2024) further explain how these technologies can even identify suitable R-strategies for specific EoL electronic components, identifying whether they should be reused, refurbished, or recycled.

Progress has also been made in the field of preventive approaches towards EoL electronics management. Tools for Sustainability Conscious Design (SCD) and Recovery Conscious Design (RCD) can quantitatively or qualitatively provide insight valuable when developing products in relation to CE. For example, LCA is considered an SCD tool. The scopes of SCD tools and RCD tools differ in the way that SCD tools evaluate components based on sustainability over their entire product lifecycle, whereas RCD tools aim to maximize product recoverability (Fontana et al., 2024).

Furthermore, literature supports the idea of using thermodynamic rarity as an indicator to measure the downcycling and degradation of materials (Rosa & Terzi, 2023), as well as decide the environmental criticality of specific materials (Fontana et al., 2024). If a material has a higher value of thermodynamic rarity, it is more important to be recovered since it is scarcer in nature and requires more energy to be extracted and refined. In order to apply thermodynamic rarity, the material composition of the components must be obtained (Fontana et al., 2024), and this can be achieved either through primary data delivered by manufacturers' technical sheets or Bill of Materials (BOMs), or in the form of secondary data from an automotive database like the International Material Data System (IMDS).

Supplier collaboration and data sharing in relation to ECUs

ECUs are high value, materially complex, difficult to assemble and recover, vital for vehicle function, and strongly dependent on information availability across supply chains as well as product life cycles. OEMs and suppliers have a hard time improving their design practices making cars easier to disassemble and recycle, on one hand because of the BoL and EoL processes being unconnected from an information sharing perspective, and on the other hand due to ELV actors' unavailability to collaborate with aforementioned parties (Rosa & Terzi, 2023).

Rosa and Terzi (2023) explain that there is vehicle material composition data available, but that it is spread out across databases with restricted accessibility. IMDS is one of these databases where information is more easily accessible to OEMs but not necessarily all actors in the automotive industry. The International Dismantling Information System is another example of a database used in the automotive industry, which contains practical information on pre-treatment and dismantling as well as information on potentially recyclable parts to promote the environmental treatment of ELV (Fontana et al., 2024; International Dismantling Information System, n.d.).

2.3 Data Sharing, Digital Data Spaces, and Ecosystems

This section contains theory on data sharing, digital data space, and data ecosystems.

2.3.1 Data Exchange and Standardization in Supply Chains

The growing adoption of the model of Industry 4.0 has led to the digitization of data sharing across the supply chains. It has been shown that information sharing optimizes supply chains in several areas, such as planning and resilience (Khan & Abonyi, 2022).

To achieve sustainability objectives, organizations must set long-term goals and ensure transparency in their information reporting. The adoption of transparency entails both vertical and horizontal coordination across supply chains, alongside the establishment of shared sustainability standards and enhanced information exchange. There are several effects of supply chain transparency in regard to information sharing. Some examples include increased resilience against disruptions, increased trust in organizational partnership and reduced perceived risks. Data integration with supply chains has become essential for achieving sustainability (Khan & Abonyi, 2022).

In the literature, the concept of data-centered transparency between organization is commonly described as interoperability. Interoperability refers to an organization's ability to interact to achieve mutually beneficial goals, and involves sharing of knowledge and information between the organizations, using information technology (IT) systems to exchange data. Interoperability is one of the needs and benefits for data standardization.

There are different layers of interoperability, for example technical interoperability and semantic interoperability. Technical interoperability refers to the ability of different IT systems to exchange and receive data automatically without requiring manual intervention. It ensures that systems can connect and transfer data directly using compatible technologies and infrastructure. Semantic interoperability refers to the ability to exchange the data with a shared meaning, and ensures that the receiving system can interpret the data correctly. A high level of interoperability between technical and semantic standards makes the IT network more manageable (Khan & Abonyi, 2022).

The need for standardization of shared information exists both within and between organizations. Having a standardized data sharing capability creates opportunities for a sustainable digital ecosystem governed by external agencies (Khan & Abonyi, 2022)

There are various barriers of data integration in supply chains. Some examples are lack of knowledge, poor communication, technological incompatibility, lack of IT standards and ineffective data interoperability between various areas in the supply chains. The barriers can be characterized in three groups. Firstly, challenges include data evaluation, inconsistent data formats, reporting noise, and the legal issue with data sharing in supply chains. Secondly, there is a lack of trust between entities, as organizations are hesitant to share certain types of data publicly. Thirdly, organizations are often reluctant to allocate the human and financial resources required to maintain data repositories that enable sharing (Khan & Abonyi, 2022).

Three of the main objectives of data integration in supply chains are supply chain sustainability, supply chain performance and supply chain resilience. Integration can lead to greater visibility, improved performance and more effective material management. It can also enhance service quality, deliveries, decrease bullwhip effect and improve customer satisfaction and support innovation. Increased visibility and traceability provide decision-makers in the circular economy with valuable tools to develop and implement sustainable policies and procedures in supply chain management. Integrating and analyzing data across supply chains not only gives organizations a competitive advantage, but also makes them more resilient and agile. Through data sharing and analysis, companies can monitor energy consumption, emissions and compliance with legal and technical requirements (Khan & Abonyi, 2022).

2.3.2 Digital Data Space

In recent years, digital data spaces (DDSs) have gained importance for enabling data sharing, collection of data and the process of data exchange in a more secure manner. Digital technologies facilitate the complexity of processing relevant data through data collection, integration and analysis. One important aspect in regard to the availability of the data is the cross-organizational connectivity between actors through the entire supply chain. Having a common digital platform across the supply chain enables the information to flow smoothly from end-to-end (Steiner & Münch, 2024). There are four design principles that are the basis for which data spaces are built upon. The principles are data sovereignty, equality, decentralization and governance (Brechtel, 2025).

Sharing platforms often cause concerns regarding data security, since the data is stored centrally (Steiner & Münch, 2024). As a reaction, DDSs such as Catena-X, have emerged in order to address the security threat on common, centralized platforms. Data space solutions involve data integration where the data does not need to be stored centrally in one single location, but rather kept among the actors stored with the owner (Steiner & Münch, 2024; Brechtel, 2025). The design of data spaces supports the development of data ecosystems by enabling secure data exchange (Möller et. al., 2024). DDSs are what make it technically possible for a deliberate operation of a data ecosystem (Brechtel, 2025).

2.3.3 Data Ecosystems

Data ecosystems are advanced data based networks designed to address contemporary challenges, such as new legislation, by leveraging the potential of data sharing between different companies (Brechtel, 2025). According to Oliveira et al. (2019, p. 590), a digital ecosystem is defined as "/…/complex socio-technical network[s] that enable collaboration between autonomous actors in order to explore data". In a paper on industrial data ecosystems within the automotive industry, Brechtel (2025) defines data ecosystems based on a definition by Oliveira et al. (2018) as "a set of networks composed by autonomous actors that directly or indirectly consume, produce or provide data and other related resources (e.g., software, services and infrastructure)". A successful data ecosystem considers all components that make up a sociotechnical system including actors, technology, data, infrastructure, social elements and contextual factors (Oliveira et al., 2018).

2.3.4 Catena-X

Catena-X automotive network was the very first data ecosystem brought to the market for the automotive industry (Brechtel, 2025). More specifically, the digital data ecosystem enables data exchange through a DDS (Steiner & Münch, 2024). The initiative of creating Catena-X is led by actors within the automotive industry in the purpose of creating a more collaborative, open and secure way of sharing data in a sustainability context, especially in regard to the circular economy (Steiner & Münch, 2024). With a focus on traceability and interoperability, the initiative intends to achieve standardized PCF data exchange (Eltohamy et al., 2025). Catena-X is an implementation of the broader GAIA-X project (Wider & Werner, 2025).

According to an analysis by Brechtel (2025), some examples of what could motivate Tier-n suppliers to join Catena-X is because they see a possibility for reducing the complexity of their processes and IT landscape, or they see an opportunity to reduce the number of customer interaction channels. Another important requirement that must be met for companies to choose Catena-X is that the implementation must be smooth and efficient, and the technical documentation forms the basis for the implementation must be easy to read and interpret (Brechtel, 2025).

A major driver for Tier-2 suppliers to participate in the Ecosystem is legal compliance and an increased comparability of PCFs between firms. For Tier-1s, Catena-X seems attractive because they hold inspiring use cases. For OEMs, it is more about stabilizing uncertainties in the supply chains and making them more resilient. Triggering events for joining Catena-X are COVID and the semiconductor crisis (Brechtel, 2025).

3. Research Methodology

The methodology chapter describes the approach taken to answer the purpose and research questions of the thesis. It aims to give the reader a better understanding of how the study was conducted.

3.1 Research Design Overview

A qualitative case study approach was applied to explore the application of the Catena-X ecosystem in an upstream automotive supply chain (Bryman & Bell, 2022). The thesis is based on a case study of an automotive OEM and a Tier-1 supplier, and selected upstream actors connected to the ECU supply chain. The study is supported by a literature review on circularity and Scope 3 emissions in upstream supply chains to establish the contextual understanding of the research area. In addition, publicly available documentation from Catena-X was analyzed to understand the ecosystem's framework, standards and KITs, which are described in section 4.2.3. The empirical data was primarily collected through semi-structured interviews with respondents from the connected actors, aiming to identify perceived challenges and opportunities regarding Catena-X, circularity and emission reduction.

The research process was inspired by iterative principles similar to the ones described by Dubois and Gadde (2002), where theory, empirical insights and case understanding were developed in parallel. As seen in Figure 1, the research process was divided into three main steps. The first step involved conducting exploratory, unstructured interviews and establishing research questions in order to understand the case context and identify relevant themes for the thesis related to Scope 3 emissions, circularity and data exchange. The second step involved conducting the literature review alongside the empirical data collection through semi-structured interviews. As the empirical data collection method progressed, new insights from the interviews influenced and shaped the focus on upcoming interviews. The analysis of Catena-X documentation also contributed to a deeper understanding of the ecosystem, which also guided the researchers in their work. The final step consisted of data analysis and the development of conclusions and insights (Bryman & Bell, 2022).

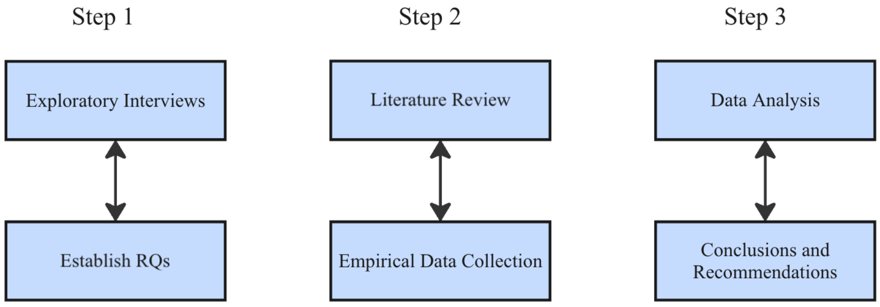


Figure 1: Illustration of the thesis research design

The qualitative research design allowed the researchers to continuously refine the research focus throughout the thesis progression as new insights and relevant themes emerged (Taylor et al., 2016).

3.2 Case Study

The thesis applies a qualitative case study approach to examine the application of the Catena-X ecosystem in upstream automotive electronic supply chains. According to Yin (2018), a case study is suitable when investigating a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and its context are not clearly evident. The implementation of Catena-X is very dependent on contextual factors such as the relationship and collaboration between actors, structure of the supply chain and data exchange practices. Therefore, Catena-X must be studied within the specific supply chain context where it is supposed to be applied.

Since Catena-X represents an emerging phenomenon with limited prior academic research, the study has an exploratory character, as the purpose is to explore the challenges and opportunities related to Scope 3 emissions, circularity and Catena-X applicability within upstream electronic supply chains.

3.3 Data Collection

The thesis combines a case study through interviews (primary data) with a literature review (secondary data). This enables a more thorough analysis, where the data collection methods complement each other, and improve the likelihood of answering the research questions.

The research process followed an iterative approach. This was based on Miles et al. (2014), who argue that an iterative work process can enhance data collection methods and data quality which in turn also makes the analysis process less overwhelming. An iterative process could even act as a healthy corrective improving data trustworthiness and reducing researcher bias. Insights from earlier interviews could lead to possible refinement of interview questions to better suit the respondent or better address data gaps. The interviews may become progressively more focused and remain analytically relevant.

3.3.1 Primary Data

The thesis is primarily based on primary data collected through direct communication via 15 interviews with 14 different respondents, as seen in Table 2. Most of the interviews were semi-structured, meaning that they combined a structured interview process where the questions are strictly predetermined, with an unstructured interview process where the interviewer can ask follow-up questions and adapt the direction of the interview (Kothari, 2004). A more detailed overview on which interviews were unstructured and semi-structured respectively are presented in Table 2 below. The interviews conducted during the thesis followed a structured yet adaptable approach. This way, the discussion could be tailored to each interviewee in order to better understand and capture their specific perspectives.

The interview respondents were selected from the companies involved in the case study based on their involvement in sustainability, supply chain operations, and their knowledge of, or prior engagement with, the Catena-X ecosystem. The selected respondents represented many areas of expertise, enabling the inclusion of multiple perspectives as can be seen in the range of roles in Table 2. To further protect the quality of the interview data, the interviews were recorded when the interviewee agreed (Bryman & Bell, 2022). One of the interviews was conducted on-site, while the others were held digitally. Specific details regarding each interview can be found in Table 2 below.

To complement the perspectives of the OEM and T1, additional interviews were conducted with external actors, including a Tier-2 and Tier-n supplier, a Research Institute and an Industry Association as presented in Table 1. This selection was made to reflect different positions within the supply chain and to capture how actors at various tiers perceive Catena-X. By including stakeholders across multiple levels of the supply chain, the thesis aimed to provide a more holistic understanding of the ecosystem, rather than focusing solely on OEM and Tier-1 perspectives.

Table 1: Description of interviewed organizations

Organization/ Anonymization	**Organization Description**
Catena-X (CX)	Automotive data ecosystem enabling secure data sharing across the value chain
OEM	Global Automotive manufacturer
T1	Global contract manufacturer of electronic equipment, Tier-1 supplier to the OEM
T2	Global semiconductor manufacturer, Tier-2 supplier to the OEM
TN	Global fastener manufacturer for the automotive industry, Tier-n supplier within the automotive industry
Research Institute (RI)	Research institute supporting innovation and sustainable growth
Industry Association (IA)	Industry association representing companies in the automotive sector

Table 2: Table of interviews, respondents and their roles

Interview	Type of interview	Length (min)	Anonymization	Role	Company
1	Unstructured, online	30	R1	Director of Sustainability in the automotive division at T1. Internationalization Committee Lead of Catena-X	T1 CX
2	Unstructured, online	30	R2	Supplier Account Manager - Semiconductors	OEM
3	Unstructured, online	30	R3	Researcher (LCA)	RI
4	Semi-structured, online	60	R4	Head of Circular Economy	T1
5	Semi-structured, online	25	R5	Researcher (LCA)	RI
6	Semi-structured, online	60	R1	Director of Sustainability in the automotive division at T1. Internationalization Committee Lead of Catena-X	T1 CX
7	Semi-structured, on site	60	R2	Supplier Account Manager - Semiconductors	OEM
8	Semi-structured, online	50	R6	Global Sustainability Compliance Manager	T1
9	Semi-structured, online	40	R7	Business Domain Manager - Sustainability	CX
10	Semi-structured, online	30	R1	Director of Sustainability in the automotive division at T1. Internationalization Committee Lead of Catena-X	T1 CX
11	Semi-structured, online	40	R8	ESG Team Manager of PCF Model	T2
			R9	Director of Automotive Team in the Nordic Area	T2
			R2	Supplier Account Manager - Semiconductors	OEM
12	Semi-structured, online	70	R10	Head of Value Chain Digitalization	IA
			R11	Environmental Manager	IA
13	Unstructured, online	25	R12	Vice President of Environment, Health and Safety	TN
14	Semi-structured, online	60	R13	Sustainability Manager for Supply Chain	OEM
15	Unstructured, online	30	R1	Internationalization Committee Lead of Catena-X	CX
			R14	International Transfer Manager	CX

Interview guides

To address the different aspects of the thesis, two interview guides were developed for the semi-structured interviews, each designed to support the research questions (see Appendix A). Both interview guides were designed to generate insights relevant to both RQ1 and RQ2. However, they were tailored to different target groups in order to capture varying perspectives. The interviewees received the interview guides prior to the interview, enabling adequate preparations and a more effective interview (Kothari, 2004).

The purpose of Interview Guide 1 was to examine the current state of sustainability-related practices within the supply chain of the case companies, with a particular emphasis on circularity and PCF. It explored aspects such as data availability, visibility and data-sharing practices between upstream and downstream partners. It also explored current challenges related to Scope 3 emissions and circularity implementation. In addition, the first interview guide included questions on the companies' readiness and perceived challenges related to the implementation of Catena-X.

Interview Guide 2 was designed to further explore Catena-X from a technical and ecosystem perspective, focusing on its applicability in practice. It aimed to capture insights from actors with more specialized knowledge of Catena-X, enabling a deeper understanding of the system's functionality, limitations and potential within the studied context.

Data template

In addition to the interviews, an Excel-based data template containing the required Catena-X PCF data points was distributed to the two focal case companies. The purpose was to evaluate data availability and usability between the Tier-1 supplier and the OEM. A detailed description of how the data template was designed can be found in Appendix B.

3.3.2 Secondary Data

As mentioned above, a literature review was conducted to provide a deeper understanding of the studied problems and their background. The review is based on secondary data, meaning data that has been collected and analyzed by others (Kothari, 2004), and serves to establish the contextual foundation of the case study and subsequent discussion of the identified challenges and benefits.

The secondary data used in the thesis was collected from both published and unpublished sources, including academic literature and documentation from the Catena-X association respectively (Kothari, 2004). Given the relatively recent emergence of the Catena-X ecosystem, the availability of peer-reviewed articles is still limited. Therefore, publicly available documentation from the Catena-X initiative itself was used to complement published sources. The collected material from the Catena-X webpage provides direct insight into the design, functionality and use cases of the ecosystem, which is essential for understanding its practical application and relevance within the context of this study. Furthermore, Kothari (2004) proceeds to explain how the secondary data should be reliable, suitable, and adequate, which is why the literature data was compiled from published sources issued by credible publishers.

3.4 Data Analysis

The interviews were audio recorded when respondents had provided their consent. According to Miles et al. (2014), the first step of qualitative data analysis involves processing and preparing the collected data into a suitable format for analysis. In line with this approach, the recorded interviews were transcribed using the transcription tool provided through the Chalmers AI portal. Following the automatic transcription process, the transcripts were manually reviewed to correct any mistakes and improve the readability, including removing irrelevant words and adjusting the formatting. Through this process, the raw interview recordings were transformed into structured material suitable for coding.

After the transcripts were cleaned, the interview material was organized in an excel document to facilitate the coding process. Each interviewed organization was assigned a separate worksheet containing selected quotations considered relevant to the RQs and purpose of the study.

The analysis began with a first-cycle coding process inspired by Miles et al. (2014), where individual quotations and text segments were assigned with descriptive keywords representing the main content of the statement. Some examples of first-cycle codes are “data exchange”, “collaboration”, “visibility”, “primary data”, “data sovereignty”, and “Catena-X development”. The aim of this stage was to structure and categorize the empirical material from the interviews in order to identify recurring patterns across the interviews.

The first-cycle coded material was then further analyzed and subsequently grouped through second-cycle coding into broader analytical themes (Miles et al., 2014). These included Sustainability and data challenges within the studied SC such as Circularity implementation; Data availability, quality and transparency; Organizational readiness, incentives, and capabilities; Standardization and methodology; and Supply chain complexity and multi-tier coordination. Five Catena-X-related challenge areas were also distinguished: Adoption and engagement; Data visibility; Ecosystem maturity; Governance and implementation; and Methodology and applicability. Finally, the same second-cycle coding resulted in some broader analytical benefit areas related to the implementation of Catena-X: Improved data, transparency, and visibility; Improved standardization and methodology; Ecosystem benefits and synergies; and DPP functionality.

3.5 Trustworthiness of Data

To ensure trustworthiness of the collected data and to strengthen the quality of the conclusions, the thesis followed the standards presented by Miles et al. (2014). In line with these standards, method triangulation was applied through the use of multiple data collection methods and data sources - semi-structured interviews, literature and Catena-X documentation. Miles et al. (2014) present five main issues for evaluating trustworthiness in qualitative research:

1. Confirmability
2. Dependability
3. Credibility
4. Transferability
5. Application

To ensure confirmability and minimize potential researcher bias, transparency was maintained throughout the research process by explaining the methods and theories pursued and the reasoning behind them (Miles et al., 2014). Furthermore, interviews were recorded when possible to ensure objectivity and to make potential claims supported.

Dependability addresses the topic of method quality over time and over all process steps (Miles et al., 2014). Transparency is key, therefore dependability was achieved through structured processes and clear communication, both between authors, but also from author to reader. Claims are supported by data, interviews followed the explained semi-structured format with interviewees being informed beforehand.

In the thesis, credibility was addressed through triangulation by method, where multiple data collection methods were used to support recurring findings across different data sources, in line with Miles et al. (2014).

Transferability is about whether the results of a case study are applicable and useful beyond the context in which they were discovered (Miles et al., 2014). The thesis provides readers with the relevant theoretical frame of reference applied when asserting the identified problems such as Catena-X functionalities, and circularity and carbon footprint calculation. As aforementioned, Catena-X implementation is dependent on company relationships and the supply chain context, and therefore the results may be of limited use beyond the investigated case relationships.

The results of the thesis are intended to be directly useful for the participating companies in the case study, which aligns with Miles et al., (2014) who describe applicability as the practical impact of the research on its participants and consumers.

3.5.1 Use of AI

In line with Gatrell et al. (2024), the use of artificial intelligence (AI) tools such as Chat GPT is permitted when used in a supportive role and transparently disclosed. During this thesis, AI has been used as a support tool for improving language and translations. The tool has not generated any content, and the authors take full responsibility for the accuracy and reliability of the content and output.

In addition, the transcription tool provided through the Chalmers AI Portal was used to support the transcription of recorded interviews. The automatically generated transcripts were manually reviewed and corrected by the authors to ensure accuracy and reliability.

3.6 Societal, Ethical and Ecological Aspects

Ethics revolve around the researcher's responsibilities towards all the participants, audience, society and academic community (Mirza et al., 2023). When collecting and analyzing data within this thesis, ethical aspects such as informed consent, confidentiality, and data handling were in accordance with GDPR and ethical guidelines presented by Mirza et al. (2023).

The thesis also considered societal and ecological aspects by adopting a social-ecologic system perspective, which enabled the analysis of interaction between social and environmental factors (Guerrero, 2018). A social-ecologic system perspective views society and the environment as an interconnected system, where human activities and ecological processes influence each other. This authors of thesis took this into consideration throughout the entire work when analyzing the supply chain of the case companies.

4. Case Background

The case examined in the thesis focuses on an upstream electronic supply chain connected to the production of a lighting component supplied by a Tier-1 supplier to an automotive OEM. More specifically, the study investigates the ECUs associated with the component and the related challenges connected to data exchange on emissions and circularity practices.

As illustrated in Figure 2, the focal case primarily concerns the relationship between the OEM and the Tier-1 supplier. Additional interviews were also conducted with external actors, including a Tier-2 semiconductor supplier, a Tier-n supplier, a Research Institute, an Industry Association and Catena-X. However, these actors are not directly connected to the lighting component supply chain. They were included to provide broader perspectives on upstream supply chains, the Catena-X implementation, circularity practices and Scope 3 emission management.

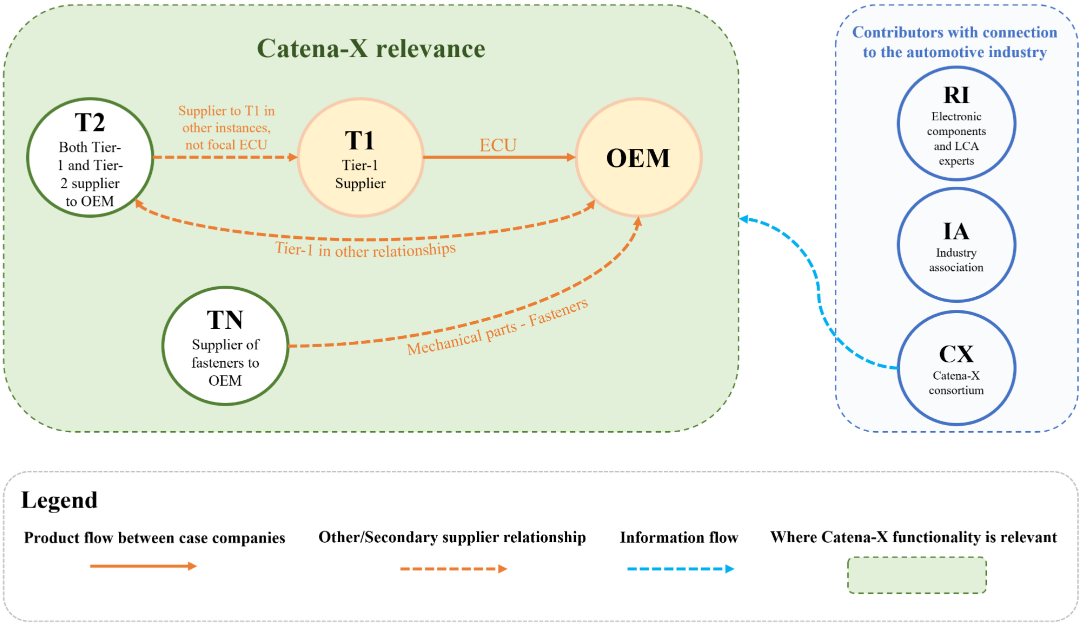


Figure 2: The relationship between the interviewed organizations in this thesis

The Tier-2 supplier represents an upstream semiconductor actor within the automotive industry. However, it is not a direct supplier to the Tier-1 supplier in the studied case. The Tier-n supplier is also not directly connected to the investigated ECU flow. Figure 2 should not be interpreted as a linear supply chain, but rather as an illustration of the relationships between the interviewed organizations included in the study. Chapter 4 further describe the case companies and their current practices, as well as the Catena-X ecosystem based on publicly available information from the organization itself.

4.1 Company Descriptions and Current Practices

4.1.1 OEM

The OEM is a global automotive manufacturer. Today, most of the OEM's ECU-related business is still structured around Tier-1 suppliers. This means that the Tier-1 suppliers primarily engage directly with Tier-2 suppliers, which are the actual semiconductor manufacturers, while Tier-1 suppliers integrate the components.

The supply chain is complex, involving a large number of Tier-2 and Tier-3 suppliers. This complexity is also reflected in the number of components required for different types of ECUs. Smaller ECUs, such as lighting-related units, may include approximately 50 - 80 incoming components, while more complex ECUs can involve substantially higher component counts. One BOM example indicates that an ECU may comprise as many as 4500 components. Overall, the number of components can therefore range from as few as five to several thousand, depending on the complexity of the ECU.

Representatives of the OEM describe the supplier relationships as rather traditional. The aim is to establish and maintain strategic relationships in which suppliers are regarded as partners, although discussions can sometimes be difficult and demanding. In relation to broader industry initiatives for data sharing and collaboration, the OEM is also a member of Catena-X. However, rather than having implemented concrete activities, the OEM is described as being in a "follow and learn" mode.

In terms of supply chain visibility, the OEM appears to have relatively good control over Tier-1 suppliers, while visibility decreases further upstream in the supply chain. The representatives express a need for increased transparency, particularly beyond the first tier. The level of visibility is also not uniform across all areas, which is reflected in the varying availability of primary data. For some topics, such as risk assessments and incident reporting, the OEM may request suppliers to provide primary data from further upstream, in some cases all the way back to the CRM extraction. This suggests that the OEM can achieve relatively detailed supply chain insight when required, but that such visibility is topic specific rather than comprehensive across the full supply chain.

Current sustainability-related practices also reflect this selective approach to data collection. The OEM requests suppliers to provide primary data during procurement processes, for example regarding environmental performance, as well as during ongoing business relationships. However, the extent to which primary data is available varies depending on context. In addition, one respondent noted that design for repairability for ECUs has decreased, suggesting that the repairability may receive less attention than in the past.

4.1.2 T1

T1 is a global electronics manufacturing company, where automotive is one of the company's six verticals. In the automotive context, T1 acts as a Tier-1 supplier to the OEM, and the relationship between the two has been ongoing for many years. T1 primarily operates as a contract manufacturer, meaning products are often manufactured based on customer-owned designs rather than designs owned by T1 itself. In the case studied, T1 receives the BOM and component design from the OEM and manufactures the ECU as build-to-print. Since the OEM especially in the case of the ECUs manufactured for the OEM.

The component provided by T1 in this context is a lighting PCBA, meaning a printed circuit board assembly consisting of an ECU in a lighting component. Since the component is a design owned by the OEM, it was not originally designed for reuse, remanufacturing, or recyclability. However, the OEM has increased its sustainability requirements during recent years, and the component should now be designed for easier disassembly.

In general, many components are dictated by the OEM. For example, the OEM can decide whether T1 must use a particular component in its product. Usually, the sourcing situation is described as 80% controlled by T1 and 20% controlled by the OEM, meaning that T1 is free to source around 80% of the sub-components while the design is still given by the OEM. In projects where T1 owns the component design, the company has greater opportunities to incorporate sustainability considerations into the product. According to T1, this enables the company to propose more sustainable design alternatives adapted to customer requirements.

Furthermore, T1 has launched initiatives related to design-for-sustainability and is working to develop products with greater efficiency, longevity, and lower impact. According to R1, this approach takes the full products life cycle into account, including sourcing, operations, use, and EoL. According to T1, these initiatives are applied across the company rather than being limited to specific components. Furthermore, T1 has also expanded its operations towards post-market services, including refurbishment, remanufacturing and similar activities. Depending on the customer and product, T1 may therefore act both as a manufacturer and as a post-market service provider, working closely with brands, suppliers and recyclers.

For PCF calculations, T1’s approach depends on customer requirements. If secondary data can be used, T1 uses the latest version of Ecoinvent and collects internal information such as the BOM, material description, and weight. If customers request primary data, T1 must engage with suppliers to obtain the required data and then create the LCA. T1 has some information from Tier-2, Tier-3 and Tier-4 suppliers, but the extent of information depends on the supplier. There is no supplier code or obligation requiring Tier-n suppliers to share data with Tier-1, but the willingness to share information is instead based on the relationship.

The component is an old product that is approaching EoL, and there is no strong request for Tier-n suppliers to start reporting PCF data for this component. T1 therefore uses Ecoinvent to calculate the emissions that will be provided to the OEM. Calculating with primary data requires substantial effort, and until the OEM states that it will pay for this effort for the specific component, T1 will continue to rely on industry averages.

T1 is currently examining multiple Catena-X use cases. T1 is also working to establish a Catena-X-related program directed towards its suppliers, asking them to begin making relevant information available. This development is described as part of both a broader digitalization trend and a sustainability trend.

The Catena-X methodology is still new, and T1 is conducting pilots where suppliers are invited to examine Catena-X before it becomes mandatory, since OEMs are beginning to mandate it. T1 does not exchange data directly with Tier-4 or Tier-5 suppliers. Instead, T1 asks its suppliers to request that their own suppliers join Catena-X so that they can share primary data. T1's first request is for suppliers to conduct PCF calculations according to the Catena-X rulebook and then try to have the value certified.

Catena-X is still evolving, although the PCF part and its processes are more mature. Respondents hope that T1 will be able to go into production live sometime this year. Some of T1's other OEM customers are already including requirements in their RFQs that Tier-1 suppliers should follow Catena-X. Over time, Tier-1 suppliers may begin placing similar requirements in RFQs towards Tier-2 suppliers and beyond.

Customer requirements are an important driver of T1's sustainability work and are increasingly asking T1 to provide PCF data, use renewable energy, and reduce emissions related to materials and circular economy. Therefore, T1 now has an internal LCA team for PCF calculations and another respondent explained that T1 has internal processes and tools for measuring transportation impact, potential CO2 reductions, and design-for-sustainability capabilities.

Since T1 is a contract manufacturer, the requirements can be very different. Furthermore, regulations and directives are more aimed towards the OEM and other companies owning and selling products rather than T1. According to T1, the OEM is responsible for the products' EoL, and that T1 currently does not receive any product returns, except for when defective parts are returned for fault analysis.

T1's need for upstream supply chain visibility has increased due to semiconductor shortages, critical components, and critical materials. Upstream visibility is improving, sometimes reaching as far back as to mining level. This visibility is relevant for PCF calculations. T1 conducts hotspot analysis to identify the top five largest contributors to the PCF. T1 is requesting these five companies' primary data, but they are not quite there yet. Primary data from these major emitters is important because PCF results differ depending on whether primary or secondary data is used.

For DPP implementation, T1 identified three main enablers: a flexible IT organization, engagement with the supplier base, and discipline processes to ensure that the correct information is captured throughout each stage of the manufacturing process, maintenance activities, and EoL stage. At the same time, T1 does not yet have all the answers regarding information ownership, accuracy, and completeness. If suppliers are unwilling to provide the required information, T1 may turn alternative suppliers where possible. On the other hand, some of T1's customers are global actors pressuring for the DPP, and T1 should comply.

4.1.3 T2

T2 is foremost a Tier-2 supplier to the OEM, although it also has some engagement on a Tier-1 level. T2 manufactures ICs, which constitute the inside of an ECU. The ICs are then sent to a Tier-1 supplier, which mounts them and builds the ECU. The relationship between T2 and the OEM has been ongoing for many years and is described as highly collaborative. T2 is also progressive in working directly with the OEM on sustainability topics and expresses a strong ambition to improve the industry.

In terms of supply chain visibility, T2 has relatively good visibility into its supplier base. When performing emissions reporting, T2 receives data from suppliers, which also gives the company strong visibility regarding emissions. However, T2 is not in contact with raw material extractors directly but instead maintains contact with suppliers a few steps upstream in the supply chain.

T2 does currently not align with the Catena-X model for PCF calculations and data exchange. Instead, the company has developed their own methodology for calculating PCFs. The model is still in a pilot phase and has not yet been fully automated. T2 decided to build an internal PCF model because third party databases were considered insufficiently accurate for chips, due to the specificity of semiconductor manufacturing. Since no industry standard was available, T2 developed their own internal methodology which can also be shared with key customers under NDAs.

T2 uses the Carbon Disclosure Project (CDP). Suppliers report their emissions through a large survey type format, which T2 then submits to CDP. T2 also uses a system that pulls directly from CDP in order to obtain supplier specific emissions data for its own emissions calculations. When suppliers report to CDP and the data passes T2's quality check, T2 uses supplier-specific primary data. But if suppliers do not report to CDP, T2 instead relies on industry averages. Currently, the amount of primary data that T2 receives is around 30 - 50 % on average, the rest is secondary. T2 only uses CDP for data that passes their quality check, since you can't just trust everything that a supplier is putting into the system. T2 does their own quality check as well. They are working actively with their biggest suppliers in order to obtain primary data. T2 states that *"Our goal year over year is to increase our primary data percentage that we have in our footprint"*.

Some of the suppliers to T2 report all of their emissions, including Scope 3 categories, while some don't report anything yet. The procurement organization is focused on getting all suppliers to start reporting their emissions. The only way T2 can reduce their emissions is if they get their suppliers on primary data and then they start reducing their emissions, which is biggest focus of the company right now.

T2 gets requests on a daily basis from their customers to report their emissions. The emissions of T2 are reported publicly in their ESG report. Regarding PCFs, they have provided a fair amount of PCFs to their customers, typically to some of their bigger customers. Since there is no standard in the industry right now for PCF, T2 points everybody to their ESG report where they have their Scope 1- 3 emissions.

In contrast to its ongoing work with emissions reporting and PCFs, T2 does not currently work with circularity for electronic components in their lifecycle to the same extent. When asked how the company currently works with circularity in this area, the answer was: *"We don't."*.

4.1.4 TN

TN is a manufacturer of fasteners within the automotive industry. The company is currently developing a draft tool for calculating PCF and is verifying whether the tool is compliant with relevant standards. TN is currently working towards compliance with the Catena-X standards because this is being requested by its customers.

TN has primary data for its raw materials, which make up for the largest part of the company's PCF, as well as primary data for its own processes. Secondary data is only used for inputs such as surface treatments and chemicals, which are separate from the primary raw materials used in the fastener. These inputs together account for less than 1% of the product weight. According to TN, this very low use of secondary data is not expected to have a major impact on PCF values.

In terms of circularity, TN's current work focuses on the raw materials used in its products. Since the company cannot guarantee that product quality remains the same after use, their focus instead lies on increasing the amount of secondary material used in the products.

4.2 Catena-X Ecosystem

Section 4.2 introduces Catena-X ecosystem, how it is structured, a subset of its KITs, and previous case examples of Catena-X implementation. The chapter is solely based on what is presented on the Catena-X webpages. Figure 3 illustrates a fictive example of where Catena-X comes in the supply chain. It shows how the Catena-X ecosystem functions as a digital layer enabling peer-to-peer exchange of PCF and circularity-related data across actors within the automotive supply chain. While the physical flow of components follows the traditional upstream supply chain structure, Catena-X enables decentralized and sovereign information exchange between connected actors through standards, connectors, documentation and KITs.

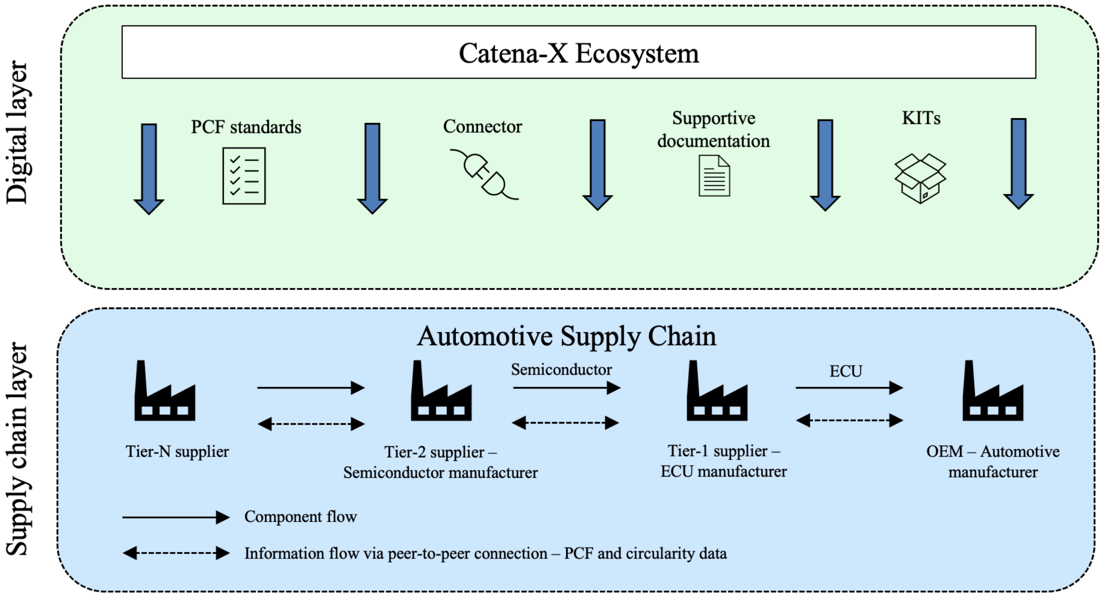


Figure 3: Simplified illustration of how Catena-X enables peer-to-peer data exchange across the entire supply chain

4.2.1 Ecosystem and Onboarding

Catena-X is an open and standardized data ecosystem built through collaboration between companies in the automotive industry, for the industry (Catena-X, 2026-a). Many companies struggle with measuring sustainability due to limited access to primary data and lack of standardized methods for collecting and comparing such data across the supply chain. Even though a reliable data foundation is critical for meeting regulatory demands, organizations lack a cohesive strategy for sustainability data (Catena-X, 2026-k). The objective of Catena-X is to support data-driven use cases that contribute to addressing the current challenges of quality, resilience and sustainability (Eclipse Tractus-X, 2026-d). Key focus areas of the initiative are a standardized way of calculating PCF and promoting circular economy through digital solutions, such as tracking (Catena-X, 2026-k).

The business areas within the ecosystem contain practical solutions to core challenges within in automotive industry, including sustainability, traceability, quality management, and demand and capacity planning. All the business areas are based on a shared technological infrastructure of standardized data modes, digital twins, interoperable interfaces and data exchange that is both sovereign and secure (Catena-X, 2026-j). The ecosystem enables sovereign data exchange and creates business value for all partners within the automotive value chain (Catena-X, 2026-a).

Entering the Catena-X network entails initial investment in terms of integration (Catena-X, n.d.-j). There are three essential steps of onboarding where the first step is to define the company’s business value and to determine how the organization will benefit from Catena-X. Catena-X offers several solutions that address current challenges in the automotive industry, such as resilient supply chains through improved transparency in order to prevent disruption, seamless integration of PCF calculations and reporting tools, and effective quality management. The second step is to register and verify your organization, which requires submission of basic company information, VAT ID and an address that has to be validated in order to become a member. The last step is to connect and exchange data (Catena-X, 2026-b).

4.2.2 Governance and Members

The Catena-X Automotive Network e. V. is responsible for certification, standardization and governance of the Catena-X ecosystem. Members of the ecosystem can actively contribute to shaping the data space through committees, working groups and expert groups. The Catena-X Association publishes standards for all the participants in the ecosystem with the goal of enabling data sovereignty, interoperability and security for the members, who must comply with the published standards by the association in order to work with the data space. By certifying the participants of the ecosystem and software components, the Catena-X Association ensures both trust and transparency within the ecosystem (Catena-X Automotive Network e.V., 2026-a). Furthermore, the Catena-X certification ensures that all solutions provided by the ecosystem are secure and use the same standardized components (Catena-X, 2026-d).

Catena-X provides modular contract components for data exchange. Having standardized contractual modules means that companies do not have to spend time developing their own from scratch, but rather modify to suit them. The goal is to make agreements across the system more clear, consistent and better aligned from a technical and legal perspective. The contracts are voluntary, and the users define who and what conditions they want to be included and for which purpose data should be shared. The Catena-X framework for contracts is designed in order to be compatible with already established supply agreements and relationships (Catena-X, 2026-e).

Within the ecosystem, the different actors have clearly defined roles to clarify what each individual actor's strengths are and how they are expected to contribute. One example of a role is Data Provider and Consumer (DOC), which provides and processes data to effectively collaborate with others in the data space to solve challenges and create value. Another example is the Business Application Provider (BAP), which develops tailored software solutions that can be integrated into already existing IT landscapes to facilitate data exchange (Catena-X, 2026-c)

There are several principles that guide the Catena-X members. Trust for example, is built by having clear rules for data exchange and contracts between all partners in the value chain. It is also built through data sovereignty and data security. Governance within the Catena-X ecosystem is based on principles of mutual collaboration across the automotive industry value chain. It promotes equality between partners and includes the involvement of external stakeholders and the scientific community (Eclipse Tractus-X, 2026-b).

4.2.3 Architecture and KITs

To support adoption and collaboration, the Catena-X data space is developed based on open source principles within the Eclipse Foundation. Eclipse Tractus-X is the official open-source project that provides the foundational components required to implement Catena-X ecosystem (Catena-X, 2026-m). To structure and guide open source development, Catena-X established organizational elements such as committees and working groups and a project in Eclipse Tractus-X (Catena-X Automotive Network e.V., 2026-a).

Figure 4 provides an overview of the Catena-X architecture and illustrates how the Catena-X Association coordinates standards and supportive documentation, while Tractus-X provides the open-source implementation components and ready-to-use solutions. A central part of the ecosystem is the KITs, which translate the Catena-X standards and frameworks into solutions for specific business cases. In the context of this thesis, the PCF KIT and Circularity KIT are particularly relevant, as they support data exchange and traceability related to Scope 3 emissions and circularity practices across supply chains. Table 3 further presents the explored KITs within the study.

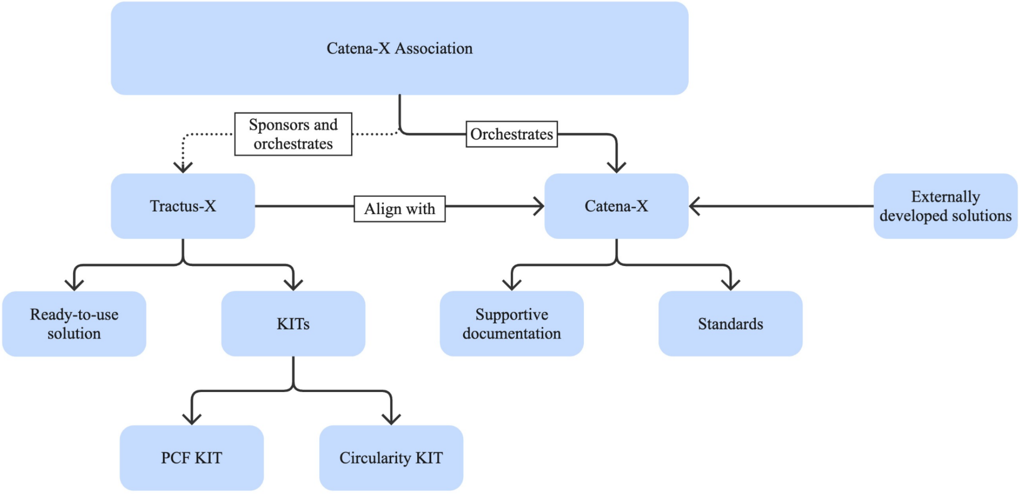


Figure 4: Adapted illustration of the Catena-X ecosystem

Catena-X has a decentralized architecture, meaning the data remains within the originating companies and is only shared with authorized parties when necessary (Eclipse Tractus-X, 2026-b). To enable this, the Catena-X architecture is supported by several core components and associated implementation guides - so called KITs.

The Industry Core KIT enables a sovereign exchange of data where information is linked to specific parts and supports the realization of multi-tier data chains. It facilitates the implementations of Catena-X use cases related to specific parts, such as circular economy, traceability and PCF (Eclipse Tractus-X, 2026-d).

The connector KIT outlines the foundational infrastructure that is used for all cross-enterprise data exchange within the Catena-X ecosystem. One prerequisite for transferring data is trust between the partners and clear definitions regarding the area of use for the data. The technologies in the connector KIT provides the framework that enables trustworthy exchange within the automotive industry. For the participants, it is important to allow integration into existing IT landscapes. A connector is a common term for the technical component that provides features that are needed to act as both data provider and data consumer within the Catena-X dataspace (Eclipse Tractus-X, 2026-e)

The KITs in the Catena-X ecosystem follow a defined lifecycle consisting of three levels: Sandbox, Incubating and Graduated. The maturity level provides an indication of the KIT's completeness and if it can produce actual business value. The incubating stage, the second maturity level, is in turn divided into three sub-stages: Draft State, In Progress State, and In Review State. The Draft State focuses on structural setup, the In Progress State involves implementation and development, and the In Review State is dedicated to validation through quality assurance performed by the community. As shown in Table 3, the Industry Core KIT, the Connector KIT, the PCF Exchange KIT, the Digital Twin KIT, and the Traceability KIT have all reached the Graduated stage, indicating mature and validated solutions with applicability in real-world scenarios. In contrast, the Circularity KIT and the EcoPass KIT remain at the incubating level. More specifically, they remain in the In Review State and are not yet considered "Production-ready with proven real-world validation" (Eclipse Tractus-X, 2026-g).

Table 3: Overview of the Catena-X KITs explored in this thesis, listed in the order in which they are presented in the report

Catena-X KIT	Maturity Level	Covered in report (section)
The Industry Core KIT	Graduated	4.2.3
The Connector KIT	Graduated	4.2.3
The PCF Exchange KIT	Graduated	4.2.4
The Circularity KIT	Incubating - In Review	4.2.5
The EcoPass KIT	Incubating - In Review	4.2.5
The Digital Twin KIT	Graduated	4.2.5

The following subsections present the primary KITs that were examined within the scope of this thesis.

4.2.4 Product Carbon Footprint Use Case

This section presents the core findings on how Catena-X supports PCF accounting.

4.2.4.1 PCF Exchange in the Supply Chain

There are three main reasons why addressing emissions in supply chains are missing reliable data about basic values, best practices and effect of reduction. The first being having to handle huge amounts of data due to the complexity of supply chains, the second being lack of trust and unwillingness to share data, and lastly lack of standardization for measuring emissions in a way that makes the results comparable. To address these issues, Catena-X is on a mission to revolutionize the automotive supply chain by providing a common platform where suppliers can share their data throughout the entire supply chain (Eclipse Tractus-X, 2026-b).

Catena-X aims at providing a unified methodology for creating, merging and sharing supplier specific data in a meaningful way. By cross-recognizing industry standards, members can adapt more quickly to the framework. This enables the determination of credible and reliable PCF values and provides the companies with a clear overview of their own carbon footprint (Catena-X Automotive Network, 2023-a). It also supports the transition from industry averages to real values (Catena-X Automotive Network, 2023-b).

In Catena-X, each tier supplier calculates the emissions from their own activities (gate to gate) and combines them with upstream emissions received from their respective tier (n+1). The resulting cradle-to-gate PCF is then reported to the next tier in line (n-1), enabling greater consistency and the aggregation of emissions across the supply chain. The cradle-to-gate PCF includes all upstream and direct emissions of producing a product, including all upstream transportation activities. The downstream emissions related to use phase and end-of-life stage are excluded from the calculations. To get the PCF from upstream activities, Tier-n should request data from tier (n+1) for upstream processes. Upstream activities that are included in the cradle-to-gate system boundaries are both emissions from production, manufacturing, transportation and transshipment of products. The boundaries of cradle-to-gate end at the outbound gate of the latest supplier (Catena-X Automotive Network, 2025).

$$PCF\ (Cradle\ to\ gate)\ = PCF\ (own\ production)\ + PCF\ (upstream)$$

The CX-PCF Rulebook (Catena-X Automotive Network, 2025) provides the methodological framework to assess the product carbon footprint. For example, it defines what GHGs that shall be accounted for, system boundaries, and what steps are included in a PCF calculation. The book also defines methodological requirements for PCF calculations, including cut-off rules requiring that at least 97% of total emissions are covered in the model. The supplementary document *Guidance product carbon* *footprint (PCF) calculation* by Catena-X Automotive Network e.V. (2024) provides specific examples and calculation formulas on how to perform PCF on a product.

The goal is that all calculations included in the final PCF should be based on primary data. As primary data will not be fully available across all actors in the supply chain during the early stages of Catena-X implementation, secondary data may be used instead. The rulebook also provides guidance rules for the use of secondary data, and which sources and databases should be prioritized in the selection of data (Catena-X Automotive Network, 2025).

As a complement to the PCF KIT (see section 4.4.4) that provides implementation steps, the technical specifications for the PCF exchange use case in Catena-X are defined in the standard CX-0136. It describes the required data models, processes and interfaces required for the exchange of data within the ecosystem. The standard is relevant for data providers, data consumers as well as business application providers. The CX-0136 standard defines technical requirements to ensure compatibility between different versions of PCF applications in the Catena-X ecosystem. However, these requirements are primarily relevant for system implementation and interoperability rather than the conceptual process of PCF data exchange (Catena-X Automotive Network e.V., 2026-b).

4.2.4.2 PCF Data Model, Data Set and Data Requirements

Sharing PCF results between different actors in the supply chain via interoperable ecosystems is made possible through having a common PCF data model and data exchange format (Catena-X Automotive Network & Together for Sustainability, 2025). The Catena-X data model is a standardized data model used for PCF exchange. It defines the information that firms must have when they are reporting their emissions according to the requirements of the Catena-X PCF rulebook. In addition to the PCF value itself, the Catena-X PCF dataset that is shared by suppliers also includes additional data elements (metadata) that describe the context of the PCF calculations. Examples of required data elements defined in Chapter 7 of the CX-PCF rulebook are time periods, temporal validity, geography, primary data share, and data quality-dating. The standardized structure allows companies to create comparable and consistent emissions data as well as metadata relating to the PCF (Catena-X Automotive Network, 2025)

$$Data\,set\ =\ PCF\ +\ meta\,data$$

The Catena-X ecosystem offers different semantic models to facilitate the structuring and interpretation of data. One example is the PCF Data Model presented in the PCF KIT. The model facilitates the systematic calculation and comparison of CFs, and offers a structured approach to managing data. The model enables the stakeholders to analyze their carbon footprint data both transparently and comprehensively. The KIT also provides an exemplary payload in JSON format for a requested PCF value, including all possible data properties - both mandatory and optional (Eclipse Tractus-X, 2026-b). The example file for the data requirements for PCF can also be found via Semantica-X.

4.2.4.3 PCF Verification

To ensure credibility and transparency, Catena-X and Together for Sustainability collaborated to develop a PCF verification and PCF program certification framework for verifying PCF results and datasets across automotive supply chains. The framework defines three levels of trust with underlying procedures, purposes and scopes and related review approaches (Catena-X Automotive Network & Together for Sustainability, 2025).

The first trust level is a check of the PCF data set that ensures the information in the data set complies with the required PCF data model and that all mandatory attributes are included. The verification of the structural completeness can be done either manually or by automated systems. The second trust level is PCF program verification, meaning checking that the company’s internal processes for calculating and generating PCF values are in line with the rulebook. The third level of trust is PCF dataset verification, where a specific data set is evaluated by an objective party. An independent third party as reviewer gives the highest level of trust (Catena-X Automotive Network & Together for Sustainability, 2025).

As previously mentioned in 4.4.1, the data sets will be shared from tier to tier throughout the entire supply chain, building an aggregation of values up to the final recipient, who reports the full PCF. Each PCF data set provider is responsible for applying the rulebooks, integrating the received data from their suppliers and delivering a trustworthy compilation to the tier next in line. Similarly, it is also up to each individual company to request a verification of their PCF data (Catena-X Automotive Network & Together for Sustainability, 2025).

4.2.4.4 PCF Exchange KIT

Background

To support the practical exchange of PCF data, Catena-X provides the Product Carbon Footprint Exchange Kit developed in the Eclipse Tractus-X project. The PCF KIT enables standardized exchange of PCF datasets between supply chain partners by providing the different users with the necessary methods, tools and technical guidance that should be used for a PCF data exchange. In addition, the KIT also includes guidelines for different stakeholders and a detailed description of the essential components required to exchange PCF data within the Catena-X ecosystem (Eclipse Tractus-X, 2026-b).

The overall vision is to decarbonize the value chain based on verified PCF values, while preserving data sovereignty among upstream suppliers. The purpose of the KIT is therefore to translate the rules presented in the previously mentioned PCF rulebook into practical implementation steps. While the rulebook defines how PCF should be calculated, the KIT explains how the data should be exchanged by companies that are using the Catena-X ecosystem. In Catena-X it is assumed that large enterprises, including both OEMs and Tier-1 suppliers, already have an appropriate expertise and resources to do a PCF calculation (Eclipse Tractus-X, 2026-b).

PCF calculations

Each company calculates their own PCF values with their preferred tools and systems. The PCF KIT then enables the PCF results to be shared in the same format between all downstream partners by providing the companies with standardized PCF dataset definition and JSON payload examples. When the data is sorted and converted into a standardized data set format defined by Catena-X, it is ready to be sent on to the next tier (Eclipse Tractus-X, 2026-b).

PCF Data exchange

The PCF kit defines a business process for calculating and exchanging PCF data across supply chains. The scope for this process applies to components already in series production, for which an established supply chain can be assumed. The KIT describes three customer journeys of calculating and exchanging the data (Eclipse Tractus-X, 2026-b).

The first customer journey, called PCF data exchange, is an asynchronous communication process where the customer requests information from its supplier regarding a component through a “PCF request”, and the supplier responds with data through a “PCF response”. The second customer journey, called PCF data pull, is a synchronous communication process where the customer requests existing PCF data from a supplier on a component that has a digital twin. Through this, the PCF data can be retrieved immediately since it is already calculated and available. The third customer journey occurs when PCF data for a component do not exist, called PCF calculation, where the supplier has to calculate the PCF before they can provide the requested information (Eclipse Tractus-X, 2026-b).

In the case of non-existing data, the process of exchange is initiated top-down, often at the OEM but it could start at any level of the supply chain. Then it is continued step by step throughout the entire supply chain. Through these requests being sent upstream across the entire supply tree, the result would be a PCF that is fully based on requested and reported data. Realistically, it can be assumed that there will be an information gap somewhere along the chain due to several reasons. However, it is of high importance that a reported PCF value always represents the entire supply chain behind it. The receiving company therefore aggregates upstream PCF values with its own emissions, resulting in a PCF including both scope 1, 2 and 3 emissions from all actors in the chain (Eclipse Tractus-X, 2026-b).

4.2.5 Circularity Use Case

CE is one of Catena-X's key areas in their work towards a more sustainable automotive industry (Catena-X, 2026-k). Solutions in the circularity field are mainly designed with the purpose of being able to track and document materials as well as components. Inadequate traceability and transparency, data fragmentation, and the lack of available digital product information are major issues in today's global supply chains (Eclipse Tractus-X, 2026-f). This affects risk management and compliance with regulatory standards, and product sustainability. Catena-X offers solutions to aforementioned topics through its Circularity KIT and the EcoPass KIT.

The Circularity KIT aims to help stakeholders enable data-driven decision making to improve circularity practices by providing frameworks, guidelines and best practices for sustainable materials management and resource efficiency within automotive value loops (Eclipse Tractus-X, 2026-a). Likewise, the EcoPass KIT is intended to make sustainability core consideration throughout the product lifecycle (Eclipse Tractus-X, 2026-f). By enabling up-to-date component data on material composition, as well as related lifecycle, performance, and sustainability attributes, the proposed DPP provides manufacturers with a more comprehensive basis for assessing resource efficiency and recycling processes (Eclipse Tractus-X, 2026-f).

4.2.5.1 Circularity KIT

The Circularity KIT provided by Eclipse Tractus-X (2026-a) currently covers the five topics: EoL/Dismantling Services, the Circular Economy strategy Assistant (CE Assistant), Secondary Marketplace, Material Accounting, and Secondary Material Content. Furthermore, the content focuses on improving sustainability and circularity practices within the automotive industry by addressing how to manage sustainable materials, reducing waste, and improving resource utilization. It also explains how different actors can benefit from these practices (Eclipse Tractus-X, 2026-a). The topics are presented more in detail below.

Five intended business opportunities for service providers in automotive supply chains are: Unified circular economy framework, access to new market opportunities, enhanced sustainability credentials, data-driven decision making, and collaboration and innovation.

Today, it is vital that companies move towards CE because of environmental pressures and resource scarcity. There are benefits to be gained through the implementation of R-strategies and optimized EoL processes, both from an environmental standpoint as well as from an innovative and economic perspective (Eclipse Tractus-X, 2026-a).

Some of the other R-strategies in the life extension and material recovery categories are not explicitly stated but can be regarded as indirectly supported by the Circularity KIT. However, the circular strategies relevant earlier in the product lifecycle, i.e. R0 (refuse), R1 (rethink), and R2 (reduce), relating to product design and consumption behavior in the smarter product use category are not explicitly covered. The KIT focuses on keeping materials in the loop rather than energy recovery (Eclipse Tractus-X, 2026-a).

CE Assistant

The purpose of the CE Assistant is to provide decision support on a component level when evaluating and choosing the most appropriate R-strategy from an environmental and economic perspective. The relevant R-strategies constitute a subset of the mid- and lower-level circular strategies from Potting et al's. (2017) 9R hierarchy presented in Section 2.2.1. The subset consists of reuse, remanufacture, recycle, and recover. The CE Assistant comprises standards, APIs and system architectures that help support decision making. Its selection process is highly dependent on availability and granularity of data spanning across the automotive value chain (Eclipse Tractus-X, 2026-a).

The CE assistant is connected to the Digital Twin functionality (Eclipse Tractus-X, 2026-a), which will be further described in section 4.2.5.3 below when explaining Catena-X's Digital Twin KIT. More specifically the CE assistant relies on data both from a digital twin, a virtual representation of a vehicle and its components, containing identifiers, technical data, lifecycle information, component data, and maintenance and use history of the vehicle. Advantageously, Digital Twin functionality builds on its connectivity to multiple data sources, and thereby connecting individual vehicle information with fleet-level knowledge (Eclipse Tractus-X, 2026-a). But, the CE assistant must also consider what the Circularity KIT explains as real-world insights, that could be practical data of the vehicle or component defining its current condition (Eclipse Tractus-X, 2026-a), and that could for example be mileage, quality status and inspection results of components.

R-strategy selection on a component level depends on the access to different kinds of EoL data. For the CE Assistant, this information can be grouped into three categories: process data, product-type data, and instance specific data. Process-related data comes from the executing company's operations, product-type data comes from design and production information of components, and instance specific data comes from the actual lifecycle of the individual component and is collected through digital twin technology (Eclipse Tractus-X, 2026-a).

Based on information and descriptions of the CE Assistant from Eclipse Tractus-X (2026-a), the following section outlines the CE Assistant's process and decision logic. The CE Assistant process begins when the user enters a vehicle identifier number. The system shows vehicle, component, and material information from the digital twin. The user can then choose a component for further assessment and evaluate which ones of the possible R-strategies: reuse, remanufacturing, recycling, or recovering, are appropriate. This decision logic is conducted through a series of processes. This assessment starts with technical feasibility criteria, such as reuse potential, material composition, expected remaining lifetime, and whether the component can be dismantled. If all of these criteria are fulfilled, the component is suitable for the higher level R-strategies: reuse and remanufacturing. However, if any of the aforementioned criteria are not up to standard, the component is restricted to the lower lever R-strategies recycling or recovery. After and if the component fulfills the dismantling criteria, a visual inspection is carried out, followed by a quality comparison. If quality does not live up to reuse standards, further validation can be made to investigate if remanufacturing still is an option. (Eclipse Tractus-X, 2026-a).

Secondary Marketplace

The Circularity KIT introduces the concept of a secondary marketplace in which secondary materials and components can be made visible and traded between potential buyers and sellers (Eclipse Tractus-X, 2026-a). In other words, such a marketplace increases transparency and creates an actual exchange space for interested actors, while also generating new value-adding opportunities for OEMs and dismantlers. The information required by actors depends on the intended R-strategy. For example, quality is critical for remanufacturing and reuse, whereas dismantlers and recyclers require reliable information on material composition. Therefore, buyers must have access to trustworthy and relevant information in order to make informed purchasing decisions. The generic DPP is described as a highly valuable data source for the secondary marketplace (Eclipse Tractus-X, 2026-a).

Material Accounting

Since data of recycled material is not shared in a consistent way across the automotive supply chain, it becomes difficult to determine how much recycled material is available, exchanged, and reused within the ecosystem. Companies often use their own internal methods for documenting material inputs and outputs, thus limiting the comparability with others. Therefore, the material accounting feature is intended to help actors track material flows more reliably and make them digitally verifiable (Eclipse Tractus-X, 2026-a).

Eclipse Tractus-X (2026-a) depicts the process through a figure. The figure demonstrates nine data points along a closed value loop involving OEMs, recyclers and suppliers. It begins when scrap is recorded and sent out by the OEM. This is later received by the recycler that also processes, stores and sends out this secondary material to a secondary inbound material supplier. The supplier receives the secondary material and integrates it into components that are later delivered back to the OEM. When the OEM assembles its components, information about the secondary material content is then linked to a DPP. Thus, material accounting can support transparency as well as verification of recycled material flows (Eclipse Tractus-X, 2026-a).

Secondary Material Content

The secondary material content framework presented by Catena-X aims to incorporate secondary materials into automotive value chains through seamless data exchange and standardized calculation methodologies, and thereby contributes to increased transparency.

Secondary Material Content data varies in terms of availability and quality, going from estimates to more exact and calculated data, as the focal product moves through its lifecycle. In turn, depending on the nature of the available Secondary Material Content data, two different exchange scenarios can arise. If the data is based on assumptions or prognoses, and therefore is not fixed, the SecondaryMaterialContentCalculated data model should be used. But, if the data is based on actual measured information that therefore can be verified, the SecondaryMaterialContentVerifiable data model should be used instead. The data models are used to exchange the secondary content data between actors in the supply chain.

Through the Secondary Material Content initiative Catena-X also aims to achieve standardized calculation methodologies and consistent metrics. Through the Circularity KIT a formula for calculating the Secondary Material Content (SMC) using consumer material content (cmc) and optionally Reutilization Content (RC), is presented:

$$SMC = Pre_{cmc} + Post_{cmc} + RC$$

where

$$Pre_{cmc} = \frac{weightPre_{cmc}material}{weight\ total} * 100$$

$$Post_{cmc} = \frac{weightPost_{cmc}material}{weight\ total} * 100$$

$$RC = \frac{weight\ reused\ material}{weight\ total} * 100$$

By assuming that the sum of all components in a vehicle equals the vehicle itself, the SMC can be defined on component level. Pre-consumer material content refers to material recovered or recycled from manufacturing waste before it reaches the end user and that is then integrated in products again. Post-consumer material content refers to material that has been discarded after use by end users and that is then recovered or recycled. Reutilization material content refers to by-product material from a process that can be reused within the same process. All three represent material streams that can substitute for primary material (Eclipse Tractus-X, 2026-a).

4.2.5.2 EcoPass KIT

Digital passports of three kinds have been developed to help supply chain actors navigate the difficulties by gaining a comprehensive, accurate, and updated view of their products' lifecycles. This way, digital information on physical products can be stored in a standardized format (Eclipse Tractus-X, 2026-f). The product passport only contains necessary product-related information required by stakeholders throughout the product's lifecycle (Eclipse Tractus-X, 2026-f), and intends to help with meeting regulatory obligations and enhance operational processes across the supply chain (Catena-X, 2026-k).

There are four types of passports presented in the EcoPass KIT: the Digital Product Passport (DPP), the Battery Passport, the Electric Drive Passport and the Transmission Passport (Eclipse Tractus-X, 2026-f). The DPP template captures traceability, material composition, sustainability and identification data. There is also information available for how to create a new passport that better fits new components currently not covered perfectly by the available passport types presented by Eclipse Tractus-X (2026-f).

Some potential benefits for organizations when launching DPPs using Catena-X systems and standards are that the ecosystem ensures interoperability, sovereign and secure data exchange, and its already ready-to-use infrastructure and governance. The DPPs are built on open standards and Catena-X ensures their compatibility across borders, ecosystems, and industries, as the DPPs are aligned with international frameworks (Catena-X, 2026.-l), and legislations, such as the European Union's Ecodesign Directive (Eclipse Tractus-X, 2026-f). Furthermore, Catena-X's decentralized architecture and data sovereignty principles ensure that participants are only required to share what is necessary (Catena-X, 2026-l). There is however a certain ambiguity here as the EcoPass states that the DPP contains data fields mandatory according to European legislation, however information sharing is "/…/ based on the individual decision of each provider (Eclipse Tractus-X, 2026-f). This way, by protecting sensitive business data, the companies' authority is preserved while simultaneously promoting supply chain transparency. Finally, Catena-X helps companies launch DPPs more quickly and smoothly because it already has the technology, structure, and rules needed to make them work properly (Catena-X, 2026-l).

The DPPs are structured to meet the increasing regulatory sustainability requirements shaping the product value chains (Eclipse Tractus-X, 2026-f). The transparency they provide enhances R-strategies such as recycling, reuse, and repairability. The DPPs standardization efforts help with traceability to track product's origins and ensure accountability at EoL stages (Eclipse Tractus-X, 2026-f).

4.2.5.3 Digital Twin KIT

The Digital Twin KIT enables technical interoperability between business partners by providing a standardized digital representation of physical assets along the supply chain. It helps Catena-X members create digital versions of parts and materials, which can support some of the functionalities presented in the Circularity KIT.

It enables tracing of parts and materials across the value chain and supports data-driven use cases across multiple supplier levels. In order to achieve this, the KIT provides standards, APIs and structures for the Digital Twins. Thereby, the integration of new systems and connections between actors become simpler, and it supports the development of new Catena-X use cases (Eclipse Tractus-X, 2026-c).

4.2.6 Requirements

Data Requirements

The necessary data requirements for calculating PCF in this thesis is based on the PCF Data Model document available in the Product Carbon Footprint exchange KIT (Eclipse Tractus-X, 2026-b). In general, data requirements and examples on how the files should be formatted for the different use cases, for example PCF and DPP, can be found on semantica-x.com (Semantica-X, 2026).

Technical Requirements

The technical requirements that are required to enable Catena-X are dependent on the individual use case and can be viewed on Catena-X GitHub under *Overview Standards*. In both the PCF and Circularity use cases, an EDC connector is required, along with either a digital twin or agent. Each standard in the respective use case defines which model may be used (Catena-X Automotive Network e.V., 2026-c).

However, to exchange data with partners in the ecosystem, all participants must complete the onboarding process regardless of the use case. The third step of the process is the technical integration process, which includes creation of technical users and implementation of an Eclipse Data Space Connector (EDC). The connector registry is necessary to be discoverable by others in the network, and is also known as the technical gateway (Catena-X Automotive Network e.V., 2026-d; Catena-X, 2026-b) In addition, Catena-X provides documentation on technical basics and implementation enablement services, including information regarding the connector, identity management and digital twin context (Catena-X Automotive Network e.V., 2023)

4.2.7 Case Examples of Catena-X Implementation

Previous implementations of Catena-X show how data-driven collaboration works in reality. It also demonstrates the value Catena-X can generate. Companies across the automotive value chain report comprehensive results, including increased transparency, reduced costs, faster processes, and more resilient supply chains. The shared standards enable measurable progress, and the stories show that both large and medium-sized companies can benefit from the ecosystem. Common for all success stories is that they share a foundation of trust and data sovereignty, as well as a clear objective to create a more efficient, digital and sustainable automotive industry (Catena-X, n.d.-j). This section presents case examples of how other companies have benefited from adopting Catena-X standards and Catena-X-verified solutions. Table 4 below shows an overview of implementations of Catena-X in real life scenarios, and their respective benefits.

Ford, Flex and Micron

Ford, FLEX and Micron, representing an OEM and its tier-1 and tier-2 suppliers respectively, adopted Catena-X PCF reporting standards with the aim of lowering costs and reducing emissions. By implementing certified Catena-X solutions, each actor selected the modules that best aligned with their existing IT infrastructure, seamless and secure exchange of primary PCF data between the tiers of the supply chain was enabled. This reduced the need for estimations and secondary data, improved the efficiency and accuracy of calculations, and minimized manual data management (Catena-X, 2026-f).

Table 4: Real life scenarios of Catena-X implementation and their benefits

Case scenario	**Benefits from Catena-X implementation**
Ford, Flex and Micron - PCF case	• Increased access to primary data • Reduced PCF values compared to industry averages • Multi-tier collaboration • Seamless exchange of PCF values along the value chain • Implementation of certified Catena-X solutions
BMW Group, Bosch and DENSO - Quality management case	• Secure and sovereign data exchange between partners • Increased trust between partners • Reduced resource usage • Increased collaboration data transparency
WITTE automotive - Standardizing PCF calculations	• Smooth data flow and data sharing with business partners • Cost savings • Efficient PCF calculations
Koller Kunststofftechnik - Digitization of production	• Increased production and energy transparency • Improved compliance with OEM and regulatory requirements

BMW Group, Bosch and DENSO

The lack of standardization in data exchange processes can cause analysis and operations to become inefficient, and it can be especially problematic in a supplier-OEM relationship. Slow data retrieval, combined with misleading data regarding component performance and quality, resulted in suppliers being unaware of issues and reacting late to quality problems (Catena-X, 2026-g). This is problematic because if defective parts are detected late, it may result in interruptions, rework and increased costs.

However, by adopting Catena-X standards and ensuring data sovereignty and security between partners, greater trust was established. This trust inspired a solution in which suppliers gained access to OEMs’ fleet data, allowing potential issues to be identified early before becoming too costly. The solution has been particularly valuable for the

BMW Group and its suppliers by reducing costs, reducing resource usage, reducing reaction time, and reducing implementation time by increasing collaboration and data transparency. The BMW group aims to extend the solution further by integrating more suppliers and thereby covering additional components in the near future, potentially even including tier-2 suppliers (Catena-X, 2026-g).

WITTE Automotive

Witte Automotive, an automotive supplier specializing in locking systems, tampered with the aspect of implementing standardized sustainability practices. Their PCF calculations must be standardized and communicated fittingly to various customers as well as suppliers simultaneously, requiring a certain level of supply chain transparency. Together with SAP, WITTE Automotive integrated digital solutions in compliance with the Catena-X PCF rulebook enabling smooth data flows and data sharing with business partners. The results include cost savings and more efficient PCF calculations (Catena-X, 2026-h).

Koller Kunststofftechnik

Due to an increasingly complex industry environment demanding digital proof of production processes and compliance with an increasing amount of regulatory requirements and sustainability requirements, Koller Kunststofftechnik was prompted to improve data traceability and availability along the supply chain. As a solution, a Catena-X-certified software module was integrated, giving Koller Kunststofftechnik access to the ecosystem. The improved data transparency led to multiple efficiency gains (Catena-X, 2026-i).

5. Empirical Findings from Interviews

This chapter presents the results derived from interviews conducted with the case companies, as well as with other actors in the automotive industry. The findings were categorized into three main areas. The first category, context, was presented in section 5 above and provided material on current company practices. The second category, challenges, was used to answer RQ1. The third category, benefits, provided the basis for answering RQ2.

5.1 Challenges in the Supply Chain and Challenges with Catena-X

As seen in Figure 5, the identified challenges were further divided into the two subcategories; Sustainability and data challenges within the studied SC, and Catena-X-related challenges. The former refers to challenges currently present in the automotive industry affecting the investigated companies but that are not directly linked to the adoption of the Catena-X ecosystem. The latter refers more specifically to difficulties associated with implementing Catena-X functionality and standards in practice. Figure 5 below provides an overview of the identified challenge areas and the corresponding organizations addressing each area, which will be further presented and explained in detail in the following subsections.

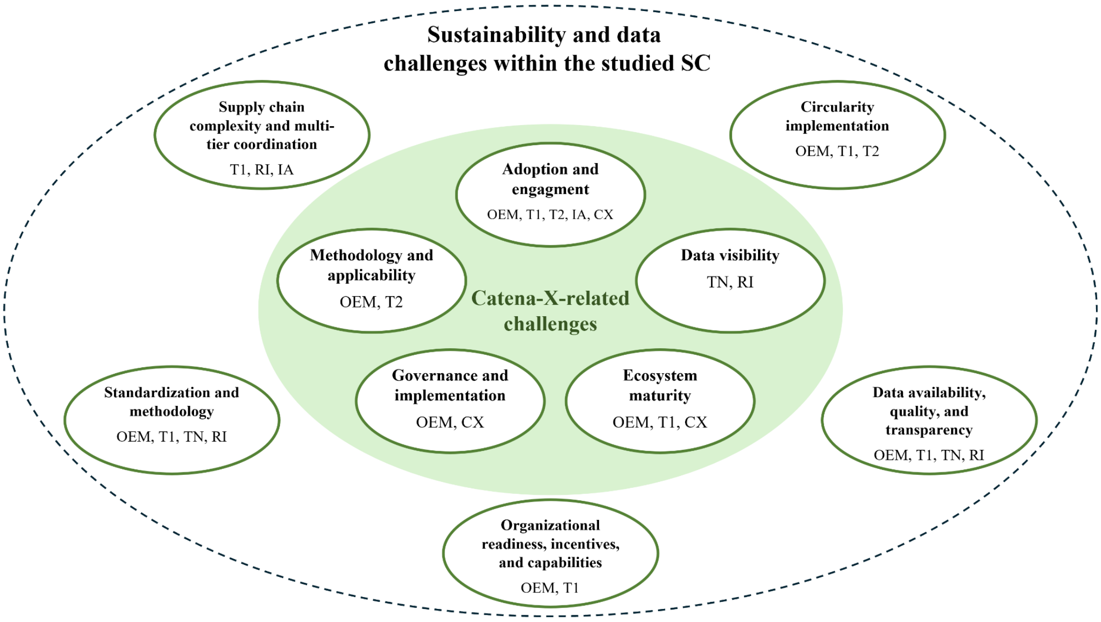


Figure 5: Overview empirically identified challenges

5.1.1 Sustainability and Data Challenges Within the Studied SC

After coding and categorization of the interview data, five sustainability and data challenges areas were identified. These challenge areas capture broader barriers currently affecting the case companies, as well as the other companies investigated in the thesis. Although these challenges were not expressed in direct relation to the Catena-X ecosystem, they were identified as potential influences on the adoption of Catena-X standards and functionality. Therefore, they were grouped in this separate subsection 5.1.1. The five challenge areas are:

1. Circularity implementation - refers to the challenges related to the limited maturity and practical implementation of circularity practices for electronic components.

2. Data availability, quality and transparency - refers to challenges related to accessing primary data, ensuring reliable data quality across the value chain, and maintaining transparency and traceability across supply chains.

3. Organizational readiness, incentives, and capabilities - refers to challenges related to supplier maturity, technical and regulatory capabilities, trust, internal coordination, and insufficient incentives hinder the adoption of Catena-X.

4. Standardization and methodology - refers to challenges related to inconsistent standards leaving room for interpretation, methodological ambiguity and, differences in how sustainability data is calculated, structured, and compared across companies.

5. Supply chain complexity and multi tier coordination - refers to challenges related to the electronic components' complex composition with large geographically spanning supply chains, and the coordination of large amounts of data across multiple actors and tiers.

A more detailed description of the specific issues highlighted by the respondents during the interviews is provided below.

1. Circularity implementation

"To be frank, actually, electronics per se has not come to that stage where circularity is that popular /.../" - R1 (T1)

As the quote above implies, circularity appears to be limited within electronics and semiconductor components. In the case of the focal component discussed this became evident as circularity was not included as a design requirement, and therefore the component was not designed for circularity (T1).

For semiconductors specifically, circularity is described as very limited. Integrated circuits are sent to the customers to then be incorporated into highly advanced equipment, and they will not be returned to the manufacturer upon component EoL. Instead, any later implemented R-strategy on the component materials depends on the actors extracting the materials from the machine. There are global recycling companies operating in this part of the chain extracting precious metals out of the semiconductors. This is not handled by the semiconductor supplier since the process of dismantling the semiconductor, verifying what parts are functional and then reselling it would be too expensive (T2).

Another factor further limiting circularity practices within the automotive industry is risk mitigation and components being safety critical. A component that is unused but a couple of years old may not be used by OEMs, and reusing components that have already been in the market is considered a major risk (OEM).

2. Data availability, quality & transparency

RI explains that the main issue is not data availability itself, since secondary data often can be obtained from databases and used as proxies for specific processes or materials. Rather, the problem lies in actors not obtaining nor sharing primary data, which RI connects to product secrets.

The OEM addresses the use of secondary data from another perspective. Due to increased requirements for verifiable data, it is harder to rely on default figures. However, using other values is also challenging, since the OEM must be able to verify when it performs better than default figures.

T1 further builds upon the issue of data quality through the statement: “It all boils down to garbage in, garbage out”. While RI emphasizes that primary data is hard to obtain, T1 highlights that if data from suppliers is not verified, it is of limited quality.

T1 also addresses challenges in relation circular economy activities, EoL handling, and data quality. In circular economy contexts, substantial information is required to make well-informed decisions. Currently however, there is insufficient information at EoL phase and regarding material composition more generally, hindering component reuse, material separation, recycling, and recovery. This is also connected to whether product information remains accurate over time. For example, if a product is repaired and a component is replaced, but the digital product passport is not updated, it becomes uncertain whether the passport still reflects the product’s actual composition. If product data is missing, T1 may use global average assumptions, similar to what is done in environmental evaluation, since a component cannot simply be excluded due to missing information.

TN also confirms difficulties in data exchange, stating that it is challenging to obtain supplier specific data on ready-made outsourced products.

3. Organizational readiness, incentives and capabilities

Both the OEM and T1 address challenges related to collecting data from suppliers. T1 explains suppliers may not be mature enough to provide the required data, may not know how to provide it, or may not be interested in doing so. Although there have been improvements, collecting primary data remains challenging. T1 explains that some suppliers are not sharing emissions data because they do not know what PCF is, do not know how to perform the complex calculations, or do not have the necessary time. T1 states:

> *"So there is a very, very, very big bottleneck for us as a company to be able to provide data to our customers."* - R1 (T1)

The OEM connects this challenge to supplier hesitation around sharing information that may threaten their business or expose cost margins. Due to customer-supplier relationships, the OEM explains that there are always concerns regarding what data the OEM requests and how it will be used.

However, both T1 and the OEM also describe differences in supplier willingness and readiness. T1 explains that suppliers are beginning to request support on how to calculate PCF and are realizing that if they do not provide primary data, they may fall behind competitors. T1 also notes that suppliers are starting to embed sustainability and data traceability more into their daily processes. The OEM, meanwhile, explains that companies may be hesitant to share primary data when they underperform, since it could make them look bad from a competitive standpoint. These suppliers may therefore prefer to rely on secondary industry averages rather than sharing their own figures. In contrast, the OEM emphasizes that suppliers with better sustainability figures are more open to sharing their data.

T1 explains that the industry must encourage sustainability by establishing a premium to be paid for products that are more sustainable. OEMs, Tier-1 actors, and Tier-2 actors should encourage this, and once sustainability has become the standard, the premium can be removed. This would incentives more products being designed for sustainability.

In addition to data supplier collection, T1 also addresses organizational readiness in relation to the DPP. T1 explains that not all companies, regardless of size, are ready to do everything required by the DPP. This is especially challenging in the early stages, where suppliers may not know what the DPP is about, what is needed from them, and what amount of data is required. T1 explains that the implementation is clearly internally complex, since it requires involvement from several teams and departments cross-functionally across the organization, to achieve the desired visibility and traceability the DPP is said to establish. Furthermore, T1 also explains that higher-tier suppliers sometimes expect T1 to provide solutions and answers, showing the lack of readiness from their side. If the higher tiers were embedding DPP in a very early stage and understanding what the regulations was about and the complexity, they would be more ready for those conversations. The low level of awareness is challenging, especially outside of the EU, but the initiative must come from other actors as well in order to increase the awareness around for example regulations.

4. Standardization & methodology

The OEM, T1, TN and RI all highlighted challenges related to standardization and methodology. RI acknowledges that, especially regarding ISO standards, there is room for interpretation in PCF calculation methods. RI further explains that if companies rely on general LCA standards to calculate emissions, the definition of functional units and system boundaries may vary between companies. This, in turn, affects how results are interpreted. The OEM confirms that data is difficult to obtain, and that it is even more complicated to obtain it in a comparable format with relevant system boundaries.

TN also acknowledges that there is extensive legislation within the sustainability context, while also pointing to an absence of PCF standards. This is further conformed by T1:

> *"Standardization of the calculations, that is something that was missing, at least in the automotive industry."* - R1 (T1)

T1 further explains that there are many different standards depending on the industry, such as in the steel and chemical industries. However, before Catena-X, there was no unique way for actors in the automotive industry to calculate their PCF data and exchange it along the supply chain. According to T1, this is important because standardization can help prevent selective reporting and beautification of emission data, which is currently an issue when companies use their own calculation methodologies.

T1 also connects this issue to DPPs, where actors have varying interpretations and expectations from a regulatory standpoint. Today, it is not possible to know precisely which elements will be required for different products in the passport in the future, as T1 expects more legislation to come. Regarding electronics, T1 explains that the "what" and "why" of DPPs are relatively clear, but that the implementation remains complicated. Even today, some of the data required by DPPs cannot be provided by T1 alone, making compliance with DPP regulations a cross-functional effort involving other suppliers.

5. Supply chain complexity and multi-tier coordination

T1, RI and IA all address challenges related to supply chain complexity. IA explains that a modern vehicle from the OEM contains approximately 40 000 components, and that keeping these components together in one BOM is complicated. RI explains that this complexity increases when components, such as electronic components, are composed of different materials and are part of supply chains spanning different geographical locations and actors. This makes components harder to trace and complicates the collection of primary data. T1 connects this issue to the DPP, since many parts originate outside the EU, raising the question of whether the passport will be able to provide all necessary information. IA further adds that when data for approximately 40 000 components is shared and multiplied with several criteria, the amount of data rapidly becomes substantial.

5.1.2 Catena-X-related Challenges

Similar to the previous subsection, five Catena-X related challenges areas were identified through the coding and categorization of the interview data. These challenge areas capture barriers that are directly linked to the design, adoption and use of the Catena-X ecosystem.

In contrast to the Sustainability and data challenges within the studied SC presented in section 5.1.1, these challenges reflect difficulties specifically associated with the functionality, structure, and governance of Catena-X. As such, they provide insight into the current limitations of the ecosystem and factors that might hinder its effective adoption and utilization across the entire value chain. The five identified challenge areas are:

1. Adoption and Engagement - refers to challenges related to resistance, low awareness, weak incentives, supplier readiness, and passive participation among actors within the ecosystem.

2. Data Visibility - refers to challenges related to data access, scope and quality.

3. Ecosystem Maturity - refers to challenges related to the early-stage nature of the ecosystem, including underdeveloped use cases and unclear future applications

4. Governance and Implementation - refers to challenges related to governance structure and technical implementation, such as the one-up one-down principle, system integration, interfaces and IT related barriers.

5. Standardization and Methodology - refers to challenges related to disagreement with the Catena-X calculation methodology, specifically regarding data scope and auditability, and applying the standards in practice.

A more detailed description of the specific issues highlighted by the respondents during the interviews is provided below.

1. **Adoption and engagement challenges**

As this category covers a wide range of aspects, the data was structured into four subcategories for improved readability. The four categories are High Complexity SC, High Cost, Low Awareness and Low Industry Pressure.

High Complexity SC

One of the respondents from T2 explained that because they have thousands of suppliers, it would be challenging to go back in the supply chain to involve all of the suppliers in Catena-X. However, for their closest suppliers, they do not expect significant resistance to adopting Catena-X. T2 thinks that Catena-X is straightforward if you are making steel for example, but continues by stating:

> *"Since the semi is so unique, it just adds a layer of complexity to it"* - R8 (T2)

High Costs

From a CX committee perspective, many of the strategies described are very theoretical. The CX respondent proceeds to explain that from a business perspective the recycling game is about margins, and you need to somehow find a way to monetarize it and get into life. A respondent from the OEM indicated uncertainty regarding how to mandate supplier participation in Catena-X, highlighting that the associated costs act as a significant barrier to adoption.

> *"The main challenge is the cost. Who's going to take the cost?"* - R1 (CX)

From a more reflective perspective, the respondent suggested that although Catena-X has developed promising use cases, there is a need to further articulate the underlying business cases and benefits. There is always a return on investment that must be calculated; what do companies get for the money? (IA).

Low Awareness

According to R1, the first difficulty is to actually understand Catena-X. Similarly, a respondent from the OEM stated that the only thing they want for the moment in relation to Catena-X is to make sure that people understand the potential. Another respondent highlighted that their understanding of applicable use cases is still developing, which may be linked to a lower degree of involvement from their side. For Catena-X to be widely used by everyone within the automotive industry, there has to be awareness and spreading of the network (T1).

> *"After four years, I have to admit that I don't fully understand everything either."* - R10 (IA)

Another problem that one of the respondents from the OEM noted is that discussions with Catena-X have largely focused on product carbon footprint. This has led to it being perceived primarily as a sustainability initiative, and thereby overlooking its broader potential as a tool for business communication with suppliers within the supply chain. Furthermore, another respondent perceived that promising use cases within Catena-X lacked clearly defined rulebooks, which led to the impression that implementation would require starting from scratch.

During one of the interviews, it was suggested that some companies may pay the membership or monthly fee to participate in Catena-X, without actively engaging in the ecosystem.

“Fear of missing out is sometimes a bigger motivation rather than doing the right thing” - R9 (T2)

Low Industry Pressure

When asked about the best option for data sharing and data ecosystems, IA explained that the development of Catena-X is highly dependent on industry adoption and alignment. If major German OEMs do not actively implement Catena-X, it becomes difficult for other actors to establish it as a standard towards common suppliers, highlighting a strong dependence on industry-wide acceptance (IA)**.** Similarly, another company respondent highlighted that, as Catena-X is a German driven project, the involvement of German actors is considered important in showcasing its potential and relevant use cases.

When asked about what incentives must be created in order to make all actors in the automotive industry join Catena-X, an interviewee of IA responded abruptly: OEM pressure. If the OEM does not demand this from the suppliers, the suppliers will do absolutely nothing. In relation to a discussion regarding the upcoming DPP requirements, especially the battery regulation coming into force next year, CX stated that:

"All the solutions are there, but I would say they are not that frequently used because there is no need yet to report." - R7 (CX)

The lack of coordinated industry pressure is further reflected in how OEMs tend to initiate individual activities, as the topic of sustainability is perceived as complex. At the same time, increasing regulatory requirements such as ELV regulation, are adding pressure on companies to act (IA). In response to this fragmentation, Catena-X is trying to increase the alignment and collaboration across stakeholder to kickstart the material accounting use case and better understand what is needed;

“But it is a huge effort, and everyone rather goes for themselves right now, so we need to merge forces” - R7 (CX)

2. Data Visibility

During the interviews, challenges related to data handling in Catena-X were raised, particularly regarding data collection scope, data quality and the use of different data sources. A key issue concerned the difficulty in determining how far upstream in the supply chain data should be collected. Respondents also highlighted challenges in accessing data and ensuring sufficient data quality, especially when extending further into higher-tier suppliers. In addition, the primary challenge was not related to the Catena-X standards itself, but the flexibility in the choice of data sources, which may affect the consistency of the results.

3. Ecosystem maturity

From the beginning, Catena-X was established as a government-funded consortium. As described by one respondent, some of the output was published before being fully finalized, and the ecosystem is currently in a phase of further developing and operationalizing these results (CX).

"As of now, there's no strong design for sustainability elements in Catena-X" - R1 (CX)

The circularity within Catena-X is in an early stage of development. While several standards, data models and concepts have been introduced through the circularity KIT, feedback indicates that they cannot be applied very well. At present, the material accounting standards is the most useful element in the circularity KIT, being actively piloted. When asked about data requirements, Catena-X is not defining anything with respect to circularity in Catena-X, only for DPP. However, the association is working to establish a new group aimed at advancing the circularity, with ongoing efforts focused on identifying the data points needed to enable useful solutions across every process in the supply chain. As of now, Catena-X won't support, but will encourage circularity (CX).

"Design for sustainability or circularity is not there" - R1 (CX)

Participation in Catena-X is voluntary and not financially compensated, limiting the resources available for developing the use cases further. This constraint was highlighted as affecting the further development of circularity related use cases. In particular, the involvement of dismantlers with IT capabilities was identified as important, although such competencies are currently limited. It was also noted that dismantlers need to develop capabilities related to communicating requirements and contributing to the development of data models. More broadly, respondents emphasized that effective circularity, especially in EoL processes, requires coordination and collaboration among multiple stakeholder roles (CX; OEM).

4. Governance and Implementation

A respondent from CX highlighted that companies participating in Catena-X exchange aggregated data values, meaning it is not possible to identify a supplier in the far back of your supply chain that is too inefficient and emits too much. As recipient, you only see an aggregated value. Even though a more detailed breakdown would be technically possible, such as PCF breakdown and hotspot visibility, this level of granularity is not enabled through the ecosystem. One of the reasons as to why Catena-X doesn't do a breakdown of the data value, is partly because it could reveal business data. It is not possible now and it has been decided again in a discussion that it will not be followed, and Catena-X won't provide this even if it is possible. Catena-X is governed by all industry members, where everyone has equal rights and no single company can demand specific features or solutions (R7, CX).

“*As Catena-X dataspace participant, you can see one up, one down. That is the principle of Catena-X”*- R7 (CX)

Respondents describe Catena-X as complicated and difficult to implement. According to CX, there has previously been insufficient information on how the different components of the ecosystem should be integrated, contributing to a high level of implementation complexity. Although solutions are being developed by the Catena-X association and made available through the Cofinity-X marketplace, they remain difficult for companies to fully understand. Even when applications are difficult to use, companies still need to adapt their own IT infrastructure to implement the solutions effectively. A respondent from CX emphasizes this by stating that:

“If you want to use it, you need to bring effort. It's not plug and play.” - R7 (CX)

Furthermore, technical interface-related challenges are highlighted as an additional barrier. One of the respondents notes that establishing the required technical interfaces has been difficult.

In a discussion regarding whether Catena-X is applied at component level or across the entire company, R7 explained that only the companies themselves can define the problems they are facing. The Catena-X association facilitates discussion by bringing companies together in expert groups to talk about their problems, but they cannot determine how companies apply the standards in practice. As a result, the association relies on the issues that companies chose to share. One reason for this is that companies are not allowed to discuss strategies or their use of Catena-X, as such information is considered sensitive from a competitive standpoint and falls outside the pre-competitive nature of Catena-X. Furthermore, even within an expert group, companies are described as having different priorities and problems they want to solve. According to CX, bringing needs and requirements together is quite complicated.

5. Methodology and Applicability

During one of the interviews, it was highlighted that the interviewed company did not align with the Catena-X methodology. Specifically, the company questioned the approach of tracing Scope 1 and 2 emissions upstream in the supply chain, as this process was described as very challenging to do and extremely hard to audit - particularly emissions from suppliers further back in the chain. In addition, it was stated that while some suppliers are supportive of Catena-X, others are less supportive as it raises concerns regarding the auditability.

One of the respondents stated that if Scope 3 emissions have already been calculated and third-party verified, these values would be preferred over tracing Scope 1 and 2 emissions from the beginning of the supply chain. In this case, the company has already calculated supplier-related emissions and had them audited, and therefore express confidence in the accuracy of these values. The respondent further emphasized the importance of credibility and completeness, highlighting that all data should be subject to verification.

Furthermore, challenges related to the clarity and applicability of Catena-X were highlighted. According to one of the interviewees, the framework is perceived as difficult to grasp, particularly in terms of understanding how and where it can be applied in practice. In addition, Catena-X is described as having limited success in making its offers understandable for customers. At the same time, the respondent noted that the company itself has not invested sufficient effort into fully understanding the framework.

5.2 Empirically Identified Benefits of Catena-X Adoption and DPP

The identified benefits were further divided into the two subcategories Catena-X-related benefits and DPP benefits. The distinction made it possible to separate benefits linked to shared product and material data within the Catena-X framework from benefits specifically associated with use of DPPs.

5.2.1 Data, Standardization and Ecosystem Benefits with Catena-X

There were three Catena-X-related benefit areas identified:

1. Improved data, transparency, and visibility - refers to benefits related to Catena-X enabling the exchange of primary and higher-quality data, while increasing transparency and visibility between actors in the supply chain without compromising data sovereignty, due to its decentralized architecture.

2. Improved standardization and methodology - refers to benefits related to Catena-X enabling greater comparability between calculation methods, results, and thereby suppliers, while supporting smoother data exchange and facilitating regulatory requirements as a driver of change within the industry.

3. Ecosystem benefits and synergies - refers to benefits emerging from greater Catena-X adoption, including cross-customer efficiency gains, ready-to-use solutions and applications developed by the community, and shared cost reductions among developers and members.

1. **Improved data, transparency, and visibility**

A challenge for manufacturers working with LCA is obtaining reliable data, and according to TN, that is one area in which the standards of Catena-X may help. Representatives from CX explain that a major advantage of Catena-X is that it facilitates primary data exchange throughout the supply chain. This is important because:

“Only if you can measure your own primary data, can you be better than the average.” - R7 (CX)

When companies know their own primary data, operational performance and outputs become more precise (CX). The OEM also recognizes this advantage and states that if Catena-X enables a greater share of verified supplier data rather than industry averages, for example PCF data, the OEM will likely use it. The OEM further states that the core of Catena-X is ensuring that everyone provides data, owns their own data, and decides with whom to share it:

“If you don’t believe in that business, then you shall not be part of Catena-X /.../” - R13 (OEM)

A representative from CX explains the functionality and benefits of Catena-X in relation to decentralized data exchange and data sovereignty. When exchanging data, actors find each other within the data space and establish a peer-to-peer connection, meaning that the exchange is decentralized (CX). R1 explains that this is connected to sovereignty, as participants define to whom they provide data, for how long, and under what conditions. Data sharing is also governed through agreements, as participants sign data sharing agreements before joining Catena-X, and these agreements are established between participants. Furthermore, the data space checks credentials and confirms the identities of the data sender and receiver. Once credentials are confirmed, data can be transmitted, while Catena-X has no control over or visibility into what is exchanged through the funnel (R1).

CX emphasizes that Catena-X is not a database, but rather a tool built on data space technology that facilitates smooth and secure data exchange. However, an expert group is currently investigating the possibility of establishing a connection to the IMDS. Regarding secondary PCF data, Catena-X has a group working on establishing a data pool. The CX representative explains that it is not yet clearly defined how this will be accessed, but it will be possible to retrieve values from this data pool if not all data is available.

“Catena-X is not a database. It is a data space” - R1 (CX).

2. Improved Standardization and Methodology

Respondents from CX, T1, and RI highlight that one key benefit is improved comparability and interpretation of carbon footprint data. According to R1, the use of shared methodology enables companies to more easily compare and choose between suppliers, provided that calculations are performed in a consistent way. Similarly, RI emphasized that standardized guidelines for calculating PCF allow results to be compared across actors.

In addition, the importance of standardization for interpreting data is emphasized. TN explains that life cycle assessment results require a common standard in order to be meaningful, as figures alone lack context without a defined methodology. The absence of such standards has previously created uncertainty, illustrated by situations where customers were unable to specify which standards should be used for PCF data. In this context, Catena-X is described as filling an existing gap.

> *"Catena-X is not defining their own standard. What they're trying to do is they're looking at all the standards and then they're publishing a rulebook. Follow this methodology, then you are meeting all those standards"* - R1 (CX)

According to R1, Catena-X does not define a new standalone standard but instead builds on existing standards by publishing a rulebook that aligns with them. By following this methodology, companies are able to meet multiple established standards. Currently the primary focus is on PCF, where Catena-X provides a rulebook and methodology while also standardizing the exchange of information. In addition, for DPP, Catena-X is standardizing how data is transferred. what data is included and the format in which it is shared.

> *"Catena-X only facilitates your calculation, they will define the rulebook and they will provide some kind of a certified software which you can use to calculate your emissions. How you're going to reduce your emissions, that is up to you."* - R1 (CX)

In addition, CX is described as a potential solution for managing increasing data requirements in supply chains. According to one of the respondents, there is a growing need for exchanging more data with suppliers, raising questions about how such communication should be structured if not done through Catena-X. Furthermore, as regulatory requirements can be difficult for companies to comply with, Catena-X is described as providing easy-to-apply solutions that make it simpler to align with these regulations (CX). This way, regulatory pressure is described as an important driver for adoption. Upcoming regulations, such as the DPP, are expected to further increase the need for companies to declare and exchange operational data (RI). In this context, the PCF use case is described as the most advanced use case to date with existing standards, KITs, and data models, although it remains under continuous development (CX).

3. Ecosystem benefits and synergies

Respondents highlight several benefits related to collaboration and synergies within the Catena-X ecosystem. For Tier suppliers, one advantage is the ability to reuse calculated PCF values across multiple customers, as the same component may be supplied to several OEMs (R1).

In addition, the ecosystem is described as providing access to advanced ready-to-use solutions and applications through the Cofinity-X marketplace. The value of shared standards is also emphasized, as data from suppliers certified within Catena-X could be used without additional validation and thereby simplifying data exchange (CX).

Furthermore, synergies are described to increase when Catena-X is applied across multiple use cases, as the required infrastructure only needs to be established once. The ecosystem is also highlighted as enabling joint problem-solving, where industry actors can collaborate on common challenges instead of developing separate proprietary solutions (CX). This collaborative approach is reflected in the broader idea of doing things together, which is described as more efficient than individual efforts (IA).

When discussing other use cases, early involvement of suppliers is highlighted as beneficial for the implementation of Catena-X (T1).

5.2.2 Benefits of DPP functionality

Benefits related to the implementation of DPPs were mainly addressed by various representatives of T1. T1 are confident that the DPPs can make the circular economy more efficient and effective, and contribute to more informed decision-making by providing accurate information about, for example, material composition. Another respondent highlights that, through the DPP, dismantlers will be able to trace the origin of materials. If suppliers could share more information about what they are supplying, the DPP could accurately describe material composition, identify the value in components, and thereby improve safety for operators dismantling products that may be harmful due to hazardous materials or dangerous or incorrect dismantling techniques. Currently, T1 are not harvesting parts at EoL themselves to the extent they want because they do not know what they are dealing with. Easy access to a product's safety sheets when dismantling begins is therefore crucial. Hopefully, the passport can change this by improving dismantling through increased knowledge.

Regarding safety and maximizing reuse in the context of material handling during dismantling, a representative of T1 states:

> *"/.../ if there is a risk we are just not gonna do anything with it."* - R4 (T1)

The respondent of T1 proceeds to explain that if this risk could be managed or mitigated, more material could be recovered. This could potentially lead to increased reuse, greater recirculation of materials, and improved material segregation. The respondent argues that this would increase raw material recovery and improve circularity practices.

5.3 Summary Empirical Findings from Interviews

This section summarizes the empirical findings from the interviews by presenting the identified challenges and benefit areas together with the actors who raised them and supporting quotations. The purpose of the section is to provide an overview of the patterns identified across the interviews before the findings are further discussed in relation to the frame of reference in Chapter 6.

Table 5 presents the identified challenge areas across the two categories, together with the actors who raised each challenge during interviews and supportive quotations. As shown in the table, several challenges were raised across multiple actor groups, while other appeared more specific to certain organizations and positions within the supply chain. The pattern suggest that some challenges are industry-wide, whereas others are more closely connected to the operational context of the individual actors.

Within the *Sustainability and data challenges*, the two categories *Data availability, quality and transparency* and *Standardization and methodology* were raised by four actors – OEM, T1, RI and TN. *Organizational readiness, incentives and capabilities* also emerged as an important challenge area, particularly related to suppliers' ability and willingness to provide primary sustainability data.

Within *Catena-X-related challenges, Adoption and engagement* represented the broadest challenge category and was discussed by five different actors. Within the category, *High costs* and *Low awareness* regarding what Catena-X actually is were the most frequently discussed challenges across actors. At the same time, certain challenges appeared more actor specific. For example, *High Complexity SC* was raised specifically by T2 in relation to semiconductor supply chains, while concerns regarding *Data visibility* was raised by TN and RI due to challenges associated with obtaining reliable upstream supplier data.

The two challenges categories are closely intertwined. Several of the *Sustainability and data challenges* identified appear to influence the ability of organizations to adopt and operationalize Catena-X in practice. For example, limited organizational readiness and insufficient data quality were frequently connected to challenges related to supplier onboarding, data sharing and ecosystem participation.

In addition to the identified challenges, the interviews also revealed several potential benefits associated with Catena-X adoption and DPP functionality. Table 6 presents the identified benefit areas together with the actors who described them and supporting quotations. As shown in the table, several actors identified potential benefits related to standardization, transparency and collaboration across the supply chain. At the same time, some benefits appeared more closely connected to specific actor roles and use cases.

Table 5: Overview empirically identified challenges with supportive quotations

Challenges			OEM	T1	T2	TN	RI	IA	CX	Supportive quotations from interviews	
Sustainability and data challenges within the studied SC		**Circularity implementation**	X	X	X					*"To be frank, actually, electronics per se has not come to that stage where circularity is that popular /…/"* - R1, T1	*"Looking into components that are completely new but have been on the shelf for some years, the OEM is hesitant to use them in their cars. Using components again from what has already been used on the market is considered a huge risk in automotive, where components are very safety critical for the most part."* - R2 (OEM)
		Data availability, quality, and transparency	X	X		X	X			*"The challenges are always in regards to primary data, because for secondary data, you can always find something in databases to use as a proxy for a specific process or material."* - R5 (RI)	*"When you are at the very end at the EOL phase of products, you practically have the product but zero information"* - R4 (T1)
		Organizational readiness, incentives, and capabilities	X	X						*"Sometimes the suppliers are not 100% mature to provide the data, and sometimes it goes down to the suppliers simply not knowing how to provide the data, or they are not interested in doing so. So there is a very, very, very big bottleneck for us as a company to be able to provide data to our customers."* - R6 (T1)	*"Some companies may not yet be ready or comfortable sharing primary data if their performance is weak."* - R2 (OEM)
		Standardization and methodology	X	X		X	X			*"There are a lot of room for interpretation in current methods for calculating PCF, especially if you look at the ISO standards."* - R5 (RI)	*"If the suppliers use their own unique methodology, they can just play around and reduce their values with assumptions. This is one of the main challenges that is going on within the automotive industry"* - R1 (T1)
		Supply chain complexity and multi-tier coordination		X			X	X		*"Some components, such as electronic components are composed of different materials and thus present in different supply chains, different geographic allocations, and different actors. Thus, it becomes harder to trace components and obtain the primary data."* - R5 (RI)	*"A modern car from the OEM contains approximately 40 000 components. Keeping that together in one bill of material is quite complicated. Starting to share data on these components multiplied by a number of criteria , that is, to be honest, a shitload of data."* - R10 (IA)
Catena-X-related challenges	**Adoption and engagement**	High complexity SC			X					*"Since the semi is so unique, it just adds a layer of complexity to it"* - R8 (T2)	*"And also, without really knowing, I mean, how shall we let's say force our suppliers to be part of Catena-X? That has been involved in huge costs, etc, and that has been a threshold."* - R13 (OEM)
		High costs	X	X				X	X	*"The main challenge is the cost. Who's going to take the cost?"* - R1 (T1)	*"There is always a return on investment that must be calculated; what do companies get for the money?"* - R10 (IA)
		Low awareness	X	X	X			X		*"After four years, I have to admit that I don't fully understand everything either."* - R10 (IA)	*"The only thing I want for the moment in relation to Catena-X is to make sure that people understand the potential."* - R13 (OEM)
		Low industry pressure	X					X	X	*"As long as the OEM does not demand this from the suppliers, the suppliers will do absolutely nothing. From a more philosophical point of view, the problem with getting so far is that the Catena-X association has created fantastic use cases, but they have been bad at building business cases showing the benefits."* - R10 (IA)	*"Everything is based on different use cases that they have identified. Also, by looking at other industries and what is the mainstream. If for example any of the big German OEMs decide to use Catena-X, it is very difficult for the focal OEM to go to a common supplier and say, this is how we do it."* - R10 (IA)
		Data visibility				X	X			*"Another potential problem is accessing data and what kind of data quality you have, especially when you go higher up in the supply chain."* - R5 (RI)	*"The main challenge is not the Catena-X standard itself, but rather the flexibilities regarding what sources of data that must be used."* - R12 (TN)
		Ecosystem maturity	X	X					X	*"There is also a published standard, but it is currently not very applicable in practice. It was released by the first consortium, but no solutions have yet been built on that data model. Although there are data models, standards, ideas, and topics intended to address different aspects of circularity, the feedback indicates that they cannot be applied very well."* - R7 (CX)	"Design for sustainability or circularity is not there." - R1 (T1)
		Governance and implementation	X						X	*"You cannot identify a supplier in the far back of your supply chain that is too inefficient and emits too much. You only see an aggregated value. Catena-X doesn't do a breakdown of the data value, partly because it could reveal business data. /…/ As Catena-X dataspace participant, you can see one up, one down. That is the principle of Catena-X."* - R7 (CX)	*"Catena-X is quite complicated, and previously there have been insufficient information for how to build everything together. The complexity is quite high and Catena-X is therefore hard to implement."* - R7 (CX)
		Methodology and applicability	X		X					*"If T2 have calculated scope 3 emissions and gotten them third party verified by their auditors, they would want to use those values instead of going back in the supply chain and doing Scope 1 and 2 for suppliers from the beginning."* - R8 (T2)	*"But to start with, Catena-X is difficult to grasp. It hasn't been easy to really understand and see where we can apply it properly."* - R13 (OEM)

Table 6: Overview identified potential benefits with supportive quotations

	Benefits	OEM	T1	T2	TN	RI	IA	CX	Supportive quotations from interviews	
Data, Standardization and Ecosystem benefits with Catena-X	**Improved data, transparency, and visibility**	X	X		X			X	*"It's all about primary data, right? Catena-X gives you the advantage to have primary data through the whole supply chain" - R7 (CX)*	*"The data space checks your credentials and confirms your identity, i.e. is the the right T1 and the right OEM? Then, it will open up the communication channel. What data goes into the communication channel is up to you and your customer, Catena-X has no control or visibility of what goes in the funnel" - R1 (CX)*
	Improved standardization and methodology	X	X		X	X		X	*"One benefit with adopting Catena-X is that you can more easily choose between two different suppliers, provided that they have calculated their value with the same methodology" - R1 (CX)*	*"Catena-X is not defining their own standard. What they're trying to do is they're looking at all the standards and then they're publishing a rulebook. Follow this methodology, then you are meeting all those standards" - R1 (CX)*
	Ecosystem benefits and synergies		X				X	X	*"As a Tier supplier, you often supply the same part to several OEMs, meaning there are optimizations and benefits for Tiers in calculating their PCF, since they can use the same value for several customers" - R1 (CX)*	*"The philosophical idea behind Catena-X is that: let's do this together, because if we do it single-handedly we will have to pay each and everyone of us" - R10 (IA)*
DPP	**DPP fucntionality**		X						*"The product passports can really make circular economy more efficient and effective. By providing information such as material composition, better decision making can be made" - R4 (T1)*	*"We do not necessarily make the most of harvesting parts because you just do not know what you are dealing with. I am hoping that the passport will help us with that aspect as well." - R4 (T1)*

Improved standardization and methodology was the most broadly recognized benefit area, and was raised by OEM, T1, TN, R1 and CX. Several actors also highlighted *Improved data, transparency and visibility* as a key potential benefit, particularly regarding access to primary data and more structured communication across supply chain tiers.

Some benefits appeared more actor specific. *DPP functionality* was primarily emphasized by T1 in relation to circularity practices and improved decision making during EoL management. This may partly be explained by the fact that the T1 interview material included respondents with greater expertise and involvement in DPP-related topics compared to the other interviewed actors. Furthermore, DPP was not a central focus in the interview guide of the thesis, meaning that DPP-related discussion emerged more naturally in some interviews than others. *Ecosystem benefits and synergies* was discussed by T1, IA and CX.

Although Table 5 demonstrate that Catena-X adoption is associated with several challenges, Table 6 simultaneously show that many of the same actors who identified these challenges also perceive substantial potential value in the ecosystem. Together, the findings present a nuanced picture in which Catena-X is viewed both as a complex implementation challenge and as a possible enabler of improved data transparency, standardization and support for circularity and emission management within automotive supply chains.

6. Discussion

This chapter discusses the empirical findings presented in Chapter 4 and 5 in relation to the frame of reference presented in Chapter 2. The discussion aims to interpret the identified challenges and opportunities related to the application of the Catena-X ecosystem in upstream automotive supply chains, in line with the purpose of the thesis to assess the potential of Catena-X for increased circularity and emission reduction opportunities.

Although Catena-X is presented as a promising ecosystem for enabling transparency and sustainability improvements across automotive supply chains, the empirical findings show that its practical implementation is associated with several challenges. While respondents acknowledged the potential benefits of standardized data exchange, there are also uncertainties regarding data availability, willingness to share sensitive information and ecosystem maturity that remain significant barriers to adoption.

The discussion is structured around the main themes identified throughout the study: challenges and benefits related to data exchange, scope 3 emission management, circularity practices, and the practical applicability of Catena-X. The findings are analyzed in relation to prior research to identify similarities, differences, and contextual factors that influence the implementation and functionality of Catena-X in this specific case setting.

6.1 Challenges in the Supply Chain and Challenges with Catena-X

6.1.1 Sustainability and Data Challenges Within the Studied SC

Many of the identified challenges within the study are not directly related to the Catena-X ecosystem itself, instead they originate from broader structural and organizational issues already present within automotive supply chains. Challenges related to lack of standardized data exchange, difficulties obtaining primary data and organizational readiness were highlighted both in literature and throughout the interviews. With that in mind, the implementation of Catena-X should not solely be understood as a technical adoption process, but also as an attempt to address pre-existing supply chain challenges connected to Scope 3 emission accounting and circularity practices.

The findings can be understood and interpreted from two perspectives in relation to the emergence of Catena-X. From one perspective, the existing lack of transparency and interoperability strengthens the need for collaborative data ecosystems such as Catena-X. On the other hand, these same challenges may also slow down or complicate the implementation and practical utilization of the ecosystem across multi-tier supply chains.

Circularity implementation

The limited implementation of circularity strategies for electronic components is not primarily caused by a lack of sustainability awareness. It is rather caused by limited operational knowledge and experience regarding how circularity practices can be implemented and scaled within complex electronic supply chains. Although literature increasingly emphasizes the importance of circularity and closed-loop systems (Montemayor & Chanada, 2023; Primadasa et al., 2025), the empirical findings show that implementation of circularity strategies for electronic components remains limited.

The findings reveal a clear gap between theoretical circularity ambitions and current operational requirements within the studied supply chain. Although literature emphasizes that higher-level circularity strategies, such as reuse and remanufacturing, require products to be designed for multiple life cycles already during the product development phase (Pérez et al., 2025), circularity ambitions have not yet been fully integrated into upstream product development requirements. This is reflected in the findings, where T1 expressed that design for circularity is not perceived as a requirement from the OEM. As a result, the practical value of Catena-X may be limited, since increased transparency and data exchange alone are insufficient if circularity principles are not integrated already during the product development phase.

The findings demonstrate that economic feasibility remains a major barrier to the implementation of higher-level circularity strategies. T2 highlighted economic barriers connected to circularity implementation, explaining that dismantling semiconductors, verifying component functionality and reselling recovered parts would likely become too costly and resource intensive. This supports previous literature arguing that circularity practices are often difficult to justify economically unless clear business incentives exist (Pérez et al., 2025). Furthermore, it explains why higher-level circularity strategies remain limited in practice despite increasing regulatory pressure and technological developments.

Another major limitation for circularity implementation is that OEMs may continue prioritizing newly manufactured components regardless of the existing possibilities for a more circular product design. From the OEM perspective, concerns related to risk mitigation and component safety were identified as major barriers toward increased reuse of components. This aligns with Rosa and Terzi (2023), who describe ECUs as materially complex and difficult to recover, while also being critical for vehicle functionality. Previous literature further argues that circularity efforts within the automotive industry remain limited in size and scope (Viskin et al., 2025), while reuse, refurbish and repair strategies are often considered difficult to scale and too inefficient (Montemayor & Chanada, 2023). The findings therefore suggest that challenges related to circularity implementation are not only connected to technical solutions, data availability or ecosystems intended to support data exchange, but rather to broader organizational and operational uncertainties, for example quality and safety concerns. Consequently, broader adoption of reuse practices may depend on whether reused components can be verified as equally safe and reliable as newly manufactured parts.

Data availability, quality and transparency

The main challenge regarding data is the limited availability and sharing of verifiable primary data across the supply chain. Although secondary data and default values can often be obtained through databases and used as proxies, the findings show that actors remain reluctant to share supplier-specific primary data due to concerns related to product secrets. This aligns with Vieira et al. (2025), who argue that Scope 3 inventories largely rely on estimations and secondary data rather than supplier specific primary data, resulting in poor emissions data quality. This becomes particularly interesting considering that companies aiming to reduce GHG emissions are recommended to rely on primary data rather than secondary data (WRI & WBCSD, 2011).

The findings demonstrate that data transparency alone does not solve the underlying challenge of emission accounting if the shared data cannot be verified and trusted. This was emphasized by T1 through the statement "Garbage in, garbage out", highlighting that supplier-specific data becomes of limited value if its quality and reliability cannot be ensured. Similar challenges are reflected in previous literature, where WRI & WBCSD (2004) explain that the process of verifying Scope 3 emissions is often difficult and highly dependent on the availability of sufficiently reliable data.

The findings reveal a mismatch between the increasing demand for verified primary data and the limited availability of such data across the supply chain. The OEM emphasized that increasing verification requirements make it more difficult to rely on secondary data and default figures alone, reinforcing the preference for primary data whenever available. This aligns with both industry practice and previous literature arguing that Scope 3 emissions become more inaccurate if calculated using secondary data, while access to primary data remains limited. This is where initiatives such as Catena-X become relevant, as the ecosystem aims to promote standardized exchange of primary data throughout the entire automotive value chain, reducing the need for using secondary data to calculate Scope 3 emissions.

Challenges related to data quality and verification may become equally important as data availability itself within Catena-X. Since the ecosystem is built around sovereign and standardized exchange of data, ensuring that the shared information is reliable and verified becomes essential for enabling trustworthy data exchange across the value chain. This also becomes a matter of safety and trust for actors who choose to participate in Catena-X. Such challenges are reflected in the structure of Catena-X, where participating actors must comply with common standards in order to operate within the data space, while certification of both participants and software components is intended to ensure trust and transparency across the ecosystem (Catena-X Automotive Network e.V., 2026-a).

Challenges related to circularity implementation are not solely connected to the physical recovery of components and materials, but also to the availability, transparency and accuracy of information throughout the product lifecycle to facilitate circularity practices. The findings show that insufficient information regarding material composition at EoL handling may hinder activities such as reuse, recycling and recovery, which align with the literature describing how limited information sharing and insufficient transparency between BoL and EoL actors are major barriers toward effective circularity implementation within automotive supply chains (Sesana et al., 2024; Mügge et al., 2023). If product information becomes outdated due to repairs or component replacements not being updated in the system, uncertainties may arise regarding the actual material composition of the product, which further complicates EoL handling. It is therefore important to establish a common system for reporting product changes throughout the lifecycle in order to facilitate the circularity practices.

Organizational readiness, incentives and capabilities

Organizational readiness and supplier capabilities remain major challenges in relation to sustainability reporting, PCF calculations, and data sharing across the supply chain. The findings show that several suppliers lack the knowledge or resources to provide emission data, while concerns about protecting their competitive position further reduce their willingness to share information. This is particularly problematic considering that companies heavenly depend on suppliers when collecting Scope 3 data (WRI & WBCSD, 2011). The findings further align with Khan and Abonyi (2022), who identified limited trust and reluctance to allocate resources as major barriers toward data integration across supply chains.

At the same time, organizational readiness appears to be gradually improving across the supply chain. T1 describes how suppliers are increasingly requesting support regarding PCF calculations and beginning to integrate sustainability and traceability more into their daily operations. This aligns with Fritsch et al. (2024) who argue that companies actually need to actively engage suppliers and increase awareness around sustainability reporting and PCF calculations to improve data quality and participation. The findings therefore suggest that achieving sustainability requirements depend more on collaborative learning and implementation processes between companies and suppliers, rather than placing the full responsibility for achieving sustainability requirements on the suppliers alone.

Challenges related to organizational readiness and internal capabilities significantly influence the practical implementation and adoption of the Catena-X ecosystem. Although the ecosystem technically enables sovereign and standardized data exchange, its practical value ultimately depends on whether actors across the supply chain possess the knowledge, resources and willingness required to participate and share supplier-specific data. If organizations are not sufficiently prepared to calculate, manage or exchange PCFs and sustainability data, the potential benefits of a collaborative ecosystem such as Catena-X may remain difficult to fully realize in practice for now.

Standardization and methodology

Methodological inconsistencies and lack of standardization remain major challenges within PCF calculation and sustainability reporting. The empirical findings demonstrate that varying interpretations of ISO and LCA methodologies may result in differences regarding functional units, system boundaries, and data comparability across organizations. RI described how methodological interpretations may differ between actors, while the OEM emphasized difficulties in obtaining data in comparable formats with relevant system boundaries. Similar challenges are discussed by Gutwald et al. (2024) who argue that the absence of mandatory and internationally accepted PCF standards limits the consistency of method between different organizations. Although previous literature emphasizes that PCF studies should be based on clearly defined functional units, system boundaries and inventory scopes in order to ensure consistency and comparability of results (Gutwald et al., 2024), the empirical findings suggest that companies still experience significant practical difficulties related to these methodological definitions and interpretations.

Lack of standardization negatively affects the comparability, credibility, and transparency of sustainability data across the automotive supply chain. The findings show that companies use different methodologies for PCF calculations, including internally developed approaches. When different actors apply different calculation methods, reported emission data becomes more difficult to compare and verify. This, in turn, creates room for selective reporting and beautification of emission data. These findings align with previous literature, which states that standardized methodologies and reporting formats improve comparability and transparency between organizations (WRI & WBCSD, 2004).

The findings highlight why ecosystems such as Catena-X will become increasingly relevant within the automotive industry, particularly due to the previous absence of common PCF methodologies and standardized approaches for exchanging sustainability data. By developing common standards and interoperable frameworks, Catena-X may help reduce methodological inconsistencies and improve the comparability of data between actors (Catena-X Automotive Network e.V., 2026-a).

However, full standardization remains difficult to achieve in practice. PCF methodologies, DPP requirements, and future legislation are still evolving, and they are interpreted differently by different actors and industries. The findings show that interoperable data exchange alone does not guarantee comparable or consistent results if actors rely on different assumptions, system boundaries and interpretations of reporting requirements. This may become problematic for ecosystems like Catena-X.

Supply chain complexity and multi-tier coordination

The complexity of automotive electronic supply chains makes the collection and coordination of Scope 3 sustainability data highly challenging in practice. A newly produced vehicle from the OEM contains up to 40 000 components, which is also confirmed in the literature by Viskin et al. (2025). Literature further states that supply chains of electronics are particularly complex due to the large number of sub-components, materials and actors (Huang et al., 2009-a). Therefore, companies experience the process of data collection time consuming and overwhelming (Buchenau et al., 2025). The empirical findings reinforce this complexity, as even coordinating communication and discussion sessions across organizations proved highly time consuming. It is difficult to engage thousands of suppliers in collecting and sharing sustainability data across the supply chains.

The complexity and global structure of automotive supply chains make it difficult to ensure complete and transparent sustainability data exchange across all supply chain tiers. Components often originate outside of the EU and span multiple geographical regions, raising concerns regarding whether initiatives such as DPP can provide all necessary product information through the value chain. This aligns with Vieira et al (2024) who argue that companies have limited knowledge of their supply chain and have very limited contact with Tier-2 and higher-tier suppliers. Such complexity becomes particularly problematic when suppliers operate under different regulations and reporting requirements. In this context, Steiner & Münch (2024) emphasize the importance of cross-organizational connectivity throughout the entire supply chain. The findings therefore highlight why ecosystems such as Catena-X are becoming increasingly relevant, as traditional coordination approaches alone appear insufficient for managing sustainability-related data exchange across highly complex automotive supply chains.

6.1.2 Catena-X-related Challenges

As indicated by the results in Table 5, several Catena-X-related challenges were identified across the investigated organizations. Catena-X is relevant due to the automotive supply chains struggling with fragmented data, inconsistent PCF methodologies, and limited transparency. However, the results also show that Catena-X does not eliminate these challenges. Rather, the implementation of Catena-X appears to shift some of the challenges from the need for data sharing itself to the practical conditions required for data sharing to occur. In other words, while Catena-X is presented as a potential solution for enabling standardized and secure data exchange in the automotive industry, its effectiveness is highly dependent on whether companies are willing and able to adopt the ecosystem in practice.

The barriers to adoption are diverse. Some companies lack awareness of Catena-X, some may not yet have the technical maturity required to participate in the data ecosystem, and others do not perceive a sufficiently clear business case for adopting

Catena-X's practices. This indicates that challenges are also organizational and strategic, not only technical. Catena-X may provide the infrastructure for data exchange, but the value of the ecosystem depends on companies' ability and willingness to integrate functionality into their existing processes, systems, and relationships.

Table 5 presents the five identified challenge areas related to Catena-X: Adoption and Engagement, Data Visibility, Ecosystem Maturity, Governance and Implementation, and Standardization and Methodology. However, the table should not be interpreted as a ranking of challenge area severity. Although Adoption and engagement is the category mentioned by the highest number of organizations, this does not necessarily mean that this is the most severe challenge area for every actor. The relevance and severity of each challenge area are case specific and depend on factors such as the organization's role in the supply chain, internal capabilities, size, structure, and its strategic priorities. Therefore, the following discussion does not treat the challenge areas as equally important for all actors, but instead examines how they affect the case companies in relation to their specific positions in the supply chain.

Adoption and engagement

To improve readability, the challenge area Adoption and engagement was divided into the four subcategories: High complexity SC, High costs, Low awareness, and Low industry pressure. This also increased the granularity of the results, providing a more detailed view.

T2 was the only company that addressed issues related to supply chain complexity. T2 explained that this is because semiconductors are complex products, and that involving all of its thousands suppliers in Catena-X would be challenging. This finding aligns with Huang et al., (2009-a), who state that electronics manufacturing supply chains are complex due to the large number of components and materials involved. It also supports T2's claim that Catena-X adoption may be more difficult in semiconductor supply chains than in simpler material flows, such as steel. This is also reflected in the results, as the only challenge area addressed by TN was Data visibility, including difficulties accessing specific data and the existence of flexibility in data sources. Together, these findings demonstrate that Catena-X-related challenges are case specific.

Interestingly, the theory presents two contrasting perspectives on this issue. Huang et al.'s (2009-a) broader point is that complex supply chains of hundreds or thousands of actors hinder Scope 3 data collection. At the same time, WRI & WBCSD (2011) argue that data should be obtained from all Tier-1 suppliers to achieve a comprehensive picture of emissions. WRI & WBCSD (2004) also note the benefits of converging to a common standard, including reduced costs, enhanced transparency, and more comparable data. However, companies often find it overwhelming and time intensive to collect and report Scope 3 emissions. It is therefore not surprising that Buchenau et al. (2025) explain that emissions information is lost along the supply chain, and that this results in a greater use of secondary industry data values rather than primary data. Furthermore, if the supply chain is more complex with many tiers and innumerable suppliers, a significant amount of the data will be lost. This supports T2's concern that supply chain complexity can make Catena-X adoption more challenging.

However, the OEM and T1 also work with thousands of suppliers, yet Table 5 does not identify High complexity SC as a challenge area for these two actors. This is because the table reflects what was expressed as a challenge specifically in the Catena-X adoption context. The OEM and T1 may definitely have complex supplier networks, but they did not frame this complexity as a Catena-X adoption and engagement issue in the same way as T2. T2 explicitly connected supplier volume and product complexity to the challenge of involving suppliers in Catena-X. For T1 and the OEM however, this complexity may be indirectly present but coded differently, as respondents discussed the topic through other barriers falling under other challenge areas.

High costs were also raised as an issue by the two focal companies, as well as by IA and CX. The cost aspect is particularly relevant in the circularity context. Representatives from both T1 and CX highlighted this issue, explaining that recycling depends on margins and must somehow be monetized, while also raising the broader question of who in the value chain should bear the cost. This is supported by Pérez et al. (2025), who explain that circularity practices must be economically justified and supported by a positive business case to be applied. Sial et al. (2024) further confirms this by explaining that firms prioritize financial objectives over environmental concerns.

Theory also presents some cost-related opportunities. As mentioned earlier, WRI and WBCSD (2004) state that costs can be reduced through standardization. Likewise, Viskin et al (2025) argue that circularity practices in manufacturing can reduce costs, improve operational efficiency, and strengthen competitiveness. However, as Pérez et al. (2025) state, firms' ultimate aim is to generate value. This raises the question of how value is understood, and whether companies struggle to connect Catena-X and circularity initiatives to a clear return on investment.

IA explains that Catena-X has developed promising use cases, some of which are operational today, while others are still under development. However, IA also emphasizes the need to further articulate the underlying business cases and benefits. The results in other identified Catena-X-related challenge areas indicate that companies find the ecosystem difficult to understand and implement, which is a reason for companies not seeing potential business value. However, theory also explains that organizations are often reluctant to allocate personnel, competence, and financial resources, to maintain data repositories and enable data sharing (Khan & Abonyi, 2022). When companies avoid these investments, they hinder data integration and Catena-X implementation by not wanting enough to invest in and understand the data ecosystem. There are a lot of legislations and regulations around sustainability, and compliance has proven demanding for actors in the automotive industry. Referring to R7's quote in Section 5.1.2, ambiguity and uncertainty about best course of action cause companies to develop their own solutions, which are likely both expensive and time-consuming. Therefore, Catena-X-related costs and implementation efforts should not be understood only as burdens for individual firms, but as challenges requiring coordinated industry action. Catena-X was developed by the industry, for the industry, and the organizations should not have to pay for sustainability transition individually when it can be addressed by the automotive industry as a whole.

Low awareness is the following challenge area identified under Adoption and engagement issues. As mentioned above, the ecosystem is complex, which has made actors hesitant to commit to Catena-X adoption.

Another issue is that companies have gotten the wrong expectations or understanding of the network. They perceive value elsewhere in the functionality of Catena-X, such as the OEM that in most contexts has gotten the ecosystem promoted as a sustainability initiative. Consequently, its functionality as a tool for business communication has fallen away or been overlooked.

As stated in theory above, Brechtel's (2025) analysis suggests that factors motivating Tier-n suppliers to join Catena-X are the possibility for companies to reduce complexity of processes, IT landscape, and customer interaction channels. However, the thesis' empirical findings indicate a weaker form of adoption, where firms may join more defensively and without understanding the benefits of the ecosystem. Low awareness includes both lack of knowledge and poor communication, both of which act as barriers to Catena-X adoption and may result in passive memberships. Khan and Abonyi (2022) raises the lack of knowledge, poor communication, technological incompatibility, lack of IT standards, and ineffective operability as some of the key barriers to data integration. This aligns with the empirical findings showing that organizations along the automotive supply chains join or consider Catena-X without fully understanding purpose, requirements, and potential value. Catena-X participation should not be understood as a binary question of membership or non-membership. As can be seen in Section 5.2.1, highlighting the Catena-X-related benefits, and more specifically the Ecosystem benefits and synergies, the ecosystem becomes more valuable as the community becomes stronger. However, a stronger community does not only mean a larger number of participating organizations. It also requires active members that contribute data, knowledge, resources, and practical engagement to the ecosystem. As by the theory above, effective Catena-X adoption also requires organizations to have internal knowledge, technical capability, and the proper resource allocation. Otherwise, firms are formally participating in the ecosystem, yet remain passive in practice, thereby also limiting the true value the ecosystem can generate across the supply chain.

Therefore, Catena-X adoption is more than technical access and formal membership. Oliveira et al. (2018) explain that a successful data ecosystem considers the system surrounding it, not only the technology. They suggest that it makes up for a bigger sociotechnical system, with a surrounding infrastructure, a context, social factors, and different stakeholders, and if companies main driving force for joining Catena-X is the fear of missing out, as the quote in empirical findings implies, the ecosystem will fail to maximize value. This way, passive participation indicates that social and organizational dimensions of Catena-X may be just as important as the technical infrastructure. To engage suppliers in GHG data collection, the Greenhouse Gas Protocol (n.d.) suggests supplier engagement programs as a solution. This could potentially be a solution for increasing member engagement for Catena-X as well and it aligns well with the empirical findings in Section 5.2, indicating that T1 is establishing such a Catena-X-related program directed towards its suppliers.

Finally, the empirical findings identify Low industry pressure as the last challenge area under Adoption and engagement challenges. Theory suggests that OEMs are pursuing carbon emissions reductions due to customer and stakeholder demands (Fugger at al., 2025), and thus the PCF has been established as a comparable parameter since it is quantifiable and comparable (Gutwald et al., 2024). The increased comparability of PCF and legal compliance is a driver for Tier-2 suppliers to participate in the ecosystem (Brechtel, 2025). This aligns with empirical findings suggesting sustainability regulations, such as the ELV regulation, pressures companies to act.

However, an empirical finding that differs from the theoretical frame of reference is that OEM pressure is addressed as a solution to increase adoption and implementation of Catena-X. Brechtel (2025) explains how the bigger actors and OEMs of the automotive industry can influence smaller firms and distributors (see Section 1.1.2). Empirical findings demonstrate that this must happen more so that the Catena-X community can grow stronger. Companies in the supply chains are waiting for the German OEMs to take the lead and adopt Catena-X standards before doing the same. Brechtel (2025) further explains that influential Tier-1 actors can coordinate upstream supplier development, such as T1 is demonstrating through their supplier involvement and introduction of Catena-X, but an industry-wide acceptance could accelerate Catena-X adoption.

T1 expresses in Section 5.2 that regulations and directives are often aimed primarily at OEMs and companies that own and sell products. As a contract manufacturer, T1 is therefore not exposed to the same level of regulatory pressure. It is reasonable to assume that sustainability regulations may drive OEMs to further develop their sustainability processes. This could in turn increase OEM pressure on Tier-1 and Tier-2 suppliers, leading to greater exchange of primary data and the implementation of circular practices, such as design-for-sustainability, across the supply chain.

Data visibility

The empirical findings indicate that the Catena-X-related challenge area Data visibility mainly concerns issues related to data collection scope, data quality, and the use of different data sources. Respondents highlight that it can be difficult to determine how far upstream primary data should be collected. This difficulty is connected to the relationship between data collection scope and data quality, since extending data collection further into higher-tier suppliers may reduce the availability and reliability of data. Theory suggests that companies must account for emissions along the entire value chain in order to manage GHG related risks and opportunities (WRI & WBCSD, 2011). At the same time, it is reasonable that data quality decreases as the collection scope extends further upstream since Jaeger et al. (2022) explain that in LCA based PCF calculations, reliable information is often only available to the company performing the respective process, while knowledge of upstream processes is limited.

Theory further suggests that primary data should be used when tracking performance in the supply chain or when engaging suppliers, and secondary data can be used to identify hotspots (WRI & WBCSD, 2011). Interestingly, the empirical findings and the Catena-X approach do not fully align with this theoretical distinction. Through Catena-X, each supplier calculates its own gate-to-gate emissions and combines these with upstream emissions received from its suppliers. The resulting cradle-to-gate PCF is then passed downstream to the next supplier. As explained in section 4.2.4, each company is responsible for calculating its own PCF values using preferred tools and methodologies, if they conform with the Catena-X PCF rulebook. This is further supported by the empirical findings, where a respondent from Catena-X explains that the recipient only sees an aggregated value, and that the PCF breakdown and hotspot visibility is not enabled through the ecosystem.

Another issue within the Data visibility challenge area is the flexibility in the choice of data sources, which may negatively affect result consistency. Catena-X can be considered flexible regarding the internal tools, systems, and data sources companies use to calculate PCF, as described above. However, this flexibility is limited by the requirement that the resulting data must be structured and exchanged according to the standardized Catena-X PCF data model and dataset format. The semantic models, such as Semantica-X's PCF Version 7, make it relatively clear what data can be exchanged between actors in the supply chain. The Excel template designed for this thesis and sent out to the focal case companies was also based on this model, as shown in Appendix B.

Catena-X improves the exchangeability and standardization of PCF data, but it does not automatically solve the visibility problem if recipients only receive aggregated values. One could also argue that data quality is not guaranteed to be improved since, as mentioned in Section 4.4.1, Catena-X aims to move from industry averages to real values but does still allow secondary data to be used when primary data is absent.

Ecosystem maturity

Chapter 4 describes Catena-X as a data ecosystem built around sovereign data exchange, interoperability, standardized data models, digital twins, and shared infrastructure. However, the empirical findings show that having this architecture is not the same as having mature and applicable circularity solutions. Connecting to the Oliveira et al. 's (2018) description of a data ecosystem as a bigger sociotechnical system, one could argue that Catena-X as an ecosystem is not fully mature. The technical and conceptual foundations exist, but the sociotechnical surroundings are still under development, because circularity practices require an ecosystem in which actors all along the supply chain understand their roles, contribute with data, and participate in shared use cases.

The circularity KIT presents mainly four solutions for improving circularity. The way the concepts are presented, in other words the CE Assistant, the Secondary Marketplace, Material Accounting, and Secondary Material Content, it is very difficult as a reader to identify which of them are currently implementable. Empirical findings, however, explain that Material Accounting currently is the most developed solution. One could argue that this is because Material accounting can be understood as a more foundational concept than the others, since its primary aim is to increase visibility in circular material flows and make them digitally verifiable across the value chain. This represents a comparatively natural step in a supply chain and for an ecosystem that is not sociotechnically fully mature and under development. Before some of the more advanced applications presented in the Circularity KIT, such as the CE Assistant which is intended to support decision making regarding R-strategy implementation, the ecosystem first needs sufficient visibility and competence among stakeholders, so that circular practices can be developed gradually. Material accounting can therefore be seen as somewhat of an enabling function by establishing data management and transparency required for the other circularity applications.

There is an information sharing gap between BoL actors and EoL in automotive supply chains acknowledged by Sesana et al. (2024), and this lacking data exchange prevents efficient EoL vehicle management and design-for-recycling (Sesana et al., 2024). This absence of design-for-circularity is also evident in the empirical findings. This is not too surprising since design-for-circularity is complex and demands substantial process and product knowledge, along with coordination between actors throughout the value chain (Viskin et al., 2025), which may not be there at the moment.

However, the absence of design-for-circularity is problematic since the concepts presented in the Circularity KIT require a full product life cycle perspective in order to operate and support the R-strategies as intended. Especially the higher-level R-strategies are harder to achieve because they require components to keep functional value rather than only a material value. Therefore, parts become more dependent on product design, disassembly capacity, remaining lifetime, maintenance history, material composition, and thereby the coordination between BoL and EoL actors. Mügge et al. (2023) confirms that if component and material data is unavailable at the vehicle’s EoL phase, this hinders well-informed decision making about EoL strategies. This is something that does speak against the CE Assistant. Also unfortunately, empirical findings indicate that dismantlers, and presumably other EoL actors, need more IT capabilities, and must be better at communicating requirements and contribute to development of data models. This connects to the theory explaining BoL and EoL are not collaborating and the information gap.

Governance and implementation

The governance structure of Catena-X limits the level of supply chain transparency that can be achieved through the ecosystem. Since participants receive aggregated PCF values rather than detailed supplier-level information, the possibility of identifying specific emission hotspots and insufficient upstream actors though Catena-X is restricted. This creates a trade-off between supply chain transparency and protection of sensitive business information. While previous literature highlights that carbon footprint reporting is used as a strategic business tool for identifying inefficiencies and reducing emissions (Lee, 2011), the governance principle of Catena-X restricts how much visibility a participating actor can obtain regarding their upstream supply chains. The ecosystem therefore supports accuracy of PCFs, while limiting detailed transparency in order to protect competitive and confidential business information.

Trust and willingness to share information remain fundamental conditions for successful ecosystem collaboration. Although Catena-X is designed to support transparency and sustainability-related data exchange, the practical value of the ecosystem ultimately depends on whether participating actors are willing to share sufficiently reliable and relevant information. Khan and Abonyi (2022) argue that increased transparency and information sharing strengthen organizational trust, improve resilience and reduce perceived risks across supply chains. Reluctance to share data and limited willingness to allocate resources for maintaining data repositories are barriers toward data integration in supply chains. This is particularly relevant in terms of Catena-X, where concerns related to confidentiality and competitive positioning may limit the level of transparency that can be achieved across the ecosystem. As a result, insufficient willingness to share sustainability data reduces the overall effectiveness of supply chain-wide sustainability initiatives.

Implementation complexity remains a challenge for the practical use of Catena-X. The findings suggest that implementation requires significant organizational effort, technical knowledge and system integration capabilities from participating companies. This aligns with Jaeger et al. (2022) who argue that organizations still lack knowledge and experience regarding sustainability-related data exchange. Khan and Abonyi (2022) further identify technological incompatibility, lack of IT standards and ineffective interoperability as barriers toward supply chain data integration. Since automotive supply chains are consisting of global actors operating in various different systems, achieving a smooth technical interoperability remains difficult despite the existence of common standards.

Methodology and applicability
The findings demonstrate that methodological alignment is a challenge for the applicability of Catena-X, and partly explain why some companies choose not to participate in the ecosystem. One of the interviewed companies in the study preferred their own existing internal calculations methods and already verified emission data over implementing a new approach. This becomes relevant in the catena-X methodology of tracing Scope 1 and 2 emissions upstream in the supply chain, which was described as difficult to audit and verify across multiple supplier tiers. If companies already trust internally established and verified methodologies, achieving broader methodological alignment across the automotive supply chain will be difficult. The practical applicability therefore depends on whether participating actors perceive the methodology and verification processes as sufficiently credible.

The findings further demonstrate that the clarity regarding how Catenena-X can be applied in practice influences the breadth of the adoption. The framework is described as difficult to fully understand and apply in practice, which is a challenge since companies are expected to adapt the Catena-X methodology to align with the ecosystem. On the other hand, the findings also indicated that some actors have not fully engaged with the ecosystem and its functionalities. This aligns well with Brechtel (2025) who argue that implementation process and technical documentation must be smooth, efficient and easy to interpret in order for companies to adopt Catena-X. Broader ecosystem implementation depend on whether companies actually understand how the framework can be integrated within their own operations.

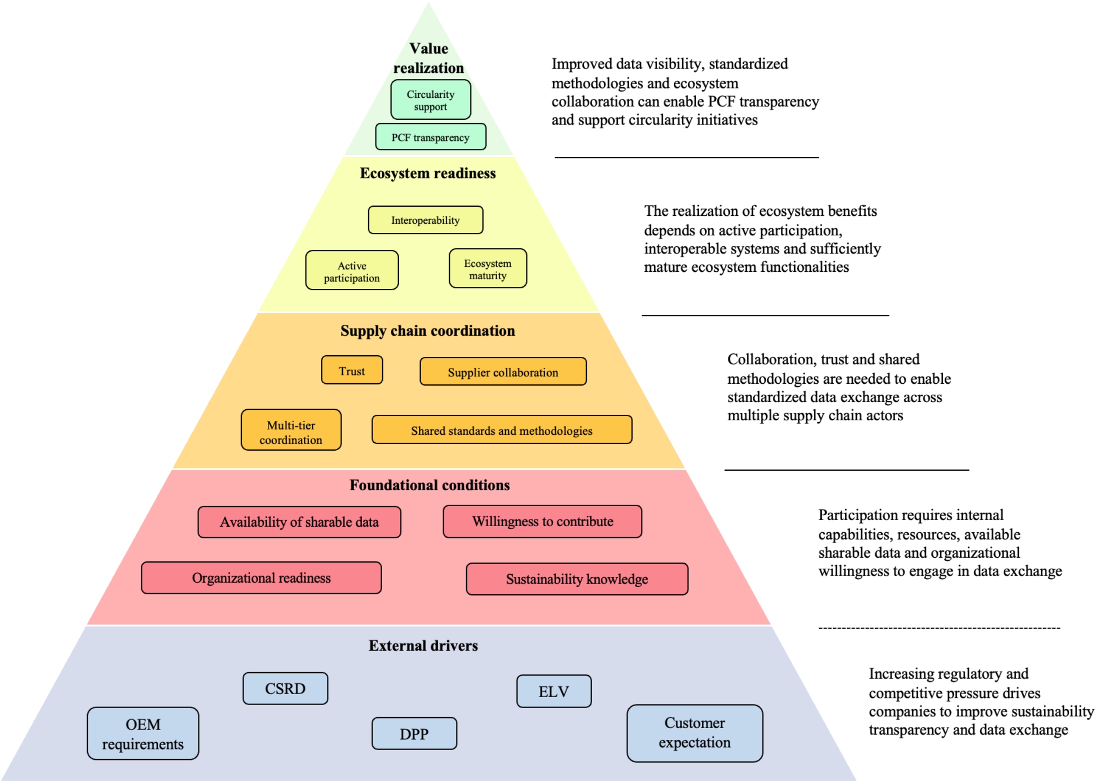
6.1.3 Reflections on Organizational Readiness and Ecosystem Maturity

Despite the identified challenges, the findings should also be interpreted in relation to the broader sustainability transition currently taking place within the automotive industry. A large part of the interview design was oriented towards identifying perceived challenges related to sustainability reporting, PCF calculations, circularity practices and the implementation of Catena-X. As a consequence, the findings naturally emphasize operational difficulties, uncertainties and implementation-related challenges experienced by the respondents.

Several of the identified challenges are not only connected to Catena-X itself, but also to the increasing complexity of sustainability reporting, PCF calculations and circularity implementation in upstream supply chains in general. The findings show that several actors still experience uncertainty regarding PCF methodologies, reporting requirements and how ecosystems such as Catena-X should be integrated into existing operations in practice. Since Catena-X remains under development and represents an emerging phenomenon within the automotive industry, varying interpretations and different levels of awareness among the supply chain actors are not unexpected.

However, even though the ecosystem currently faces several implementation challenges, the findings suggest that Catena-X contributes to increased discussion regarding PCF calculations and sustainability reporting across the supply chain. In addition, the ecosystem appears to encourage greater collaboration between actors regarding sustainability-related data exchange, methodological alignment and standardization. Although Catena-X is still under development, the ecosystem already contributes to increased awareness regarding sustainability reporting and data exchange across the automotive supply chain. The value of Catena-X may therefore not only lie in the ecosystem and its technological aspects, but also in the ongoing process of improving collaboration and alignment between actors.

Based on the discussion above, Figure 6 presents a conceptual interpretation of different conditions and challenges the companies should consider when implementing Catena-X throughout upstream automotive supply chains. The figure illustrates how external sustainability pressure, foundational conditions, supply chain coordination and ecosystem readiness together influence the ability of the studied companies to realize benefits related to PCF transparency and circularity support. The model should be understood progressively from the bottom an upward, where lower levels need to be addressed before companies can move upwards in the pyramid.



Improved data visibility, standardized methodologies and ecosystem collaboration can enable PCF transparency and support circularity initiatives

The realization of ecosystem benefits depends on active participation, interoperable systems and sufficiently mature ecosystem functionalities

Collaboration, trust and shared methodologies are needed to enable standardized data exchange across multiple supply chain actors

Participation requires internal capabilities, resources, available sharable data and organizational willingness to engage in data exchange

Increasing regulatory and competitive pressure drives companies to improve sustainability transparency and data exchange

Figure 6: Illustration of conditions and challenges influencing Catena-X implementation

At the bottom of the triangle in figure 6, external drivers such as CSRD, DPP requirements, ELC regulations and OEM requirements create increasing pressure for companies to improve their sustainability work. The next level (red area) show that companies require several foundational conditions, such as organizational readiness, willingness to contribute and the availability of sharable data before meaningful participation in the ecosystem becomes relevant and possible. The orange layer focus on supply chain coordination, where collaboration, trust, supplier engagement and shared standards and methodologies become important as next step toward value realization. The next layer, ecosystem readiness, depends on active participation, interoperability between systems and sufficiently mature ecosystem functionalities. This was especially relevant regarding circularity-related functionalities, where several respondents described the ecosystem as still relatively immature and under development. Finally, at the top of the pyramid, companies may begin to realize value if and when the foundational conditions are met and overcome.

6.2 Benefits of Catena-X Adoption and DPP

Section 6.2 discusses the benefits related to Catena-X presented in the empirical findings and relates them to the case examples of previous Catena-X implementations described more in detail in Section 4.2.7. The benefits discussion is structured around the two benefits subcategories established in Section 5.2: Data, Standardization and Ecosystem Benefits with Catena-X including its corresponding identified benefit areas, and DPP benefits.

In contrast to the discussion in Section 6.1, the analysis in this section is not only based on the empirical interview results and the publicly available information on Catena-X, but also on the Catena-X case examples introduced in section 4.2.7. Based on this comparison, the relationships between the case examples and the benefit areas are categorized as either direct or indirect connections. Figure 7 below presents the four case examples from Section 4.2.7 and its corresponding identified benefits, and their connections to identified benefit areas presented in Section 5.2. The case examples are color coded to increase the visibility of these connections.

A direct connection in Figure 7 indicates that the case explicitly demonstrates a benefit area, thereby strengthening the validity of that benefit area and illustrating concrete opportunities related to implementing the data ecosystem. An indirect connection means that the case does not primarily address the benefit area, but includes enabling conditions or related outcomes that may support it. For example, this could mean that the case presents relevant benefits that are not strictly related to a PCF or circularity context, or that the case includes material that could be addressed through DPP functionality, thereby supporting the benefit area even though DPP is not explicitly mentioned.

This structure makes it possible to discuss the empirical benefit areas not only as expected or perceived advantages, but also in relation to practical examples of Catena-X implementation. This is important because several respondents described Catena-X as promising but still difficult to evaluate in practice, which may be related to the data ecosystem's limited maturity and the lack of awareness discussed in Section 6.1.

On the left side of Figure 7 that is presented below are the four case examples from earlier Catena-X implementations. Below each case, the identified benefits and achievements are listed. These listed benefits, together with the more detailed case descriptions in Section 4.2.7, were compared with the empirically identified benefit areas. Overall, the direct and indirect connections indicate that the earlier case implementations support several of the identified benefit areas.

The strongest support is found for increased transparency and standardization, demonstrated by the four direct connections, see Figure 7. This also aligns with Table 6, where this benefit area is shown to be the most broadly recognized among respondents. Furthermore, it is notable that the Ford, Flex, and Micron case has three direct connections. Since this case also concerns PCF exchange, and is therefore highly similar to the case investigated in this thesis, it further increases the credibility of the identified benefit areas.

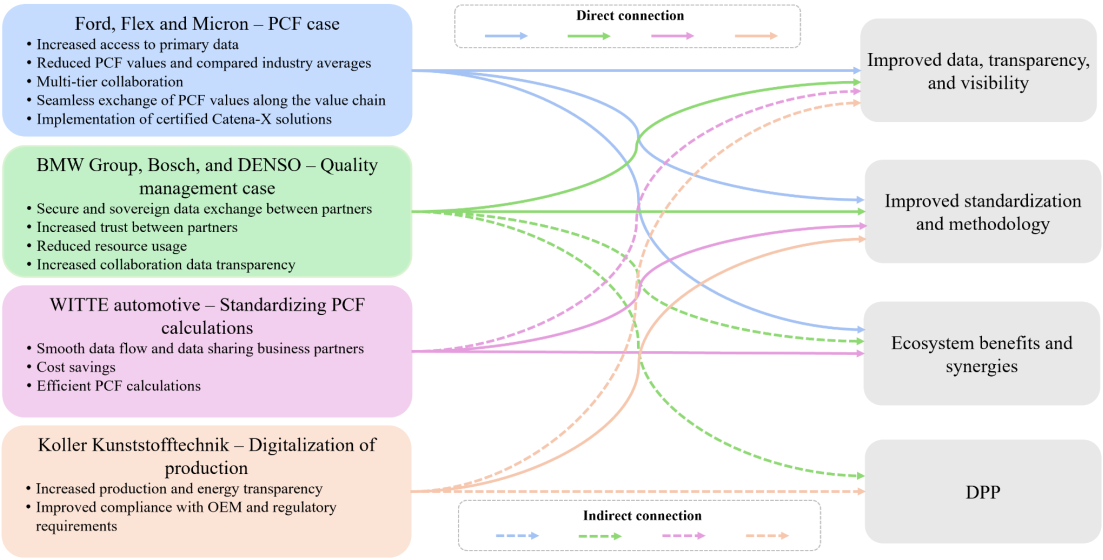


Figure 7: Connections between Catena-X case examples and empirically identified benefit areas

6.2.1 Data, Standardization and Ecosystem Benefits with Catena-X

Improved data, transparency, and visibility

Although the two focal case companies addressed several challenges in relation to data availability, quality, and transparency, the empirical findings also show that they are aware of the potential benefits that Catena-X adoption and standards provide. Based on the empirical findings and the connections depicted in Figure 7, there are several case examples supporting the idea that Catena-X offers solutions to help improve transparency, visibility, and data exchange along the supply chain.

The frame of reference states that a central issue within LCA based PCF calculations is that reliable information is often only available to the company performing the specific process, and knowledge of upstream processes remains limited (Jaeger et al., 2022). At the same time, external processes contribute significantly to the PCF, and therefore companies cannot rely solely on internal data to calculate accurate PCF values. In the empirical findings, CX confirms this by stating that when companies know their own primary data, operational performance and outputs become more precise. This is also evident in all cases from Section 4.2.7.

As seen in Figure 7, the Ford, Flex, and Micron case provides a clear direct connection to the benefit area of improved data, transparency, and visibility. It is claimed in the case that the Catena-X implementation has enabled a greater flow of primary data and less reliance on industry averages, aligning well with frame of reference, where primary data is described as essential to improve quality of scope 3 emissions accounting (WRI & WBCSD, 2011). The seamless exchange of PCF values along the supply chain, together with claimed multi-tier collaboration, also indicates increased transparency and visibility between supply chain actors. However, another interesting aspect is that when primary data replaces industry averages, PCF calculations become more case specific.

The BMW Group case also motivates a direct connection to this benefit area, since improved data access and data transparency can be linked to circularity. Although the Catena-X implementation focused on quality management, suppliers gained access to OEM fleet data, which enabled earlier identification and mitigation of component failures. This consequently led to reduced resource usage, and therefore shows how improved visibility between BMW and its suppliers can support circular practices and keeping the material loop closed. This motivates the relevance of the case for the thesis, even though the case is not primarily focused on PCF or circularity.

The Koller Kunststofftechnik case connects indirectly to this benefit area. In this case, regulatory requirements and higher demands in terms of data availability and traceability led to the implementation of Catena-X. The results highlight improved traceability as well as secure and standardized data exchange. However, it is not strictly related to PCF or circularity, but rather in relation to energy consumption.

As can be seen in Figure 7, the WITTE automotive case has an indirect connection to improved data, transparency, and visibility. Smooth PCF data sharing requires some level of transparency between customers and suppliers, but the main focus of this case is not visibility nor data access. Instead, the case primarily concerns the standardization of sustainability practices and PCF calculations. However, the frame of reference does help explain how standardization can still support visibility. Khan and Abonyi (2022) describe interoperability as dependent on data sharing and the standardization of data sharing. Khan and Abonyi (2022) further explain the two concepts technical interoperability and semantic interoperability. Technical interoperability refers to systems being able to exchange data automatically, while semantic operability refers to systems being able to understand what the data means. When both the technical and meaning aspects are standardized, interoperability becomes higher and data exchange systems become easier to maintain and use. The WITTE case therefore demonstrates that transparency also depends on standardization, since a data flow is not valuable if actors cannot interpret the data in the same way.

The responding companies recognize the potential benefits of Catena-X for data exchange, quality, traceability, and visibility. The OEM for example states that it is likely to use Catena-X and its data sharing rather than industry averages if it enables access to a higher level of verifiable data. At the same time, the OEM also emphasizes that the automotive industry actors believe in the network in order to be part of it. This points to an important tension in the findings: actors can see the potential value of Catena-X yet remain hesitant to implement its standards. This can further be connected to topics discussed in Section 6.1.2 above, regarding how to prevent companies from joining without meaningful engagement, while simultaneously avoiding excessive barriers for participation. The curiosity and companies joining is apparently important to attract other companies, meanwhile, the ecosystem loses credibility, value, and efficiency if “slackers” join.

Once again, the discussion leads back to the question of what must be done in order to strengthen the community. Catena-X can improve the flow of primary and operational data, but that visibility still remains partial, conditional, and dependent on what actors are willing and able to share. This issue will however remain as it is partly a by-product of the sovereignty Catena-X aims to achieve. Since actors to great extent decide the conditions and agreements for data exchange with partners, and since Catena-X has no visibility into or control over what is exchanged through the funnels, this conditional and partial visibility is likely to remain. Stronger relationships may therefore provide more visibility than weaker ones, which also connects to the aforementioned point that Catena-X implementation is case specific.

Finally, the sovereignty and decentralized structure also address the issue of data security, which is a common concern in other data sharing platforms where data is stored centrally (Steiner & Münch, 2024). Catena-X does not solve transparency by forcing everyone to reveal everything, since there is still this conditional visibility with actors exchanging data under agreed conditions, but instead creates a controlled form of transparency. In this sense, sacrificing some visibility and transparency may be worth it if the data space technology can improve transparency and still manage data sensitivity.

Improved standardization and methodology

The main value identified of Improved standardization and methodology is not that Catena-X provides another calculation method for the PCF, but rather that it creates a shared methodological and technical language for PCF data exchange across supply chains where actors currently calculate, interpret, and report sustainability data in different ways. This is evident in Figure 7, showing that all four of the Catena-X implementation cases pose direct connections to the identified benefit area.

Furthermore, empirical findings suggest that comparability and interpretation of PCF data improves due to the implementation of Catena-X, which in turn enables for more thorough supplier comparison. PCF values do not say anything unless they are all calculated consistently with the same methodology. One respondent even stated that LCA results require a common standard in order to be meaningful. This is true to some extent, but the empirical findings also show that it is very important that the data and calculation method is verifiable. Even in this study, a company was encountered that does not want to apply Catena-X standards because they argue that they already receive certified and audible data through their own calculation method. Given that this thesis collected empirical material from only a handful of actors out of the numerous thousands active in the automotive industry, it is fair to assume that overcoming this barrier of convincing OEMs and suppliers in the industry to switch from established calculation methods to the Catena-X PCF rulebook's methods, to be a challenge for widespread Catena-X adoption. This poses a disadvantage for the community of Catena-X, since the ecosystem is the strongest the larger number of engaged and contributing members there are. The responding company will likely only change its method of choice as a result of heavy OEM pressure, Catena-X proposing a massive business case, or stricter regulations removing the room for interpretation or even the alternatives of other calculation methods.

Gutwald et al. (2024) and CX in the empirical findings further confirms this by explaining that internationally accepted standards and norms will drive standardization and uniformly applied methodologies. Currently, there is an absence of mandatory PCF standards enforced by law (Gutwald et al., 2024). A question that arises is, what decides that Catena-X is the best method? This question does not currently have one absolute answer, however what can be said is that, the empirical findings as well as the four direct connections in Figure 7 indicate that Catena-X is not automatically the "best" solution, but it may become valuable because it creates alignment in an area where no mandatory standard currently dominates and it is a well-developed initiative with already some big and influential actors investigating its practicability.

Standardized PCF exchange and calculations are central in the Ford, Flex, and Micron case, as well as the WITTE case, thereby resulting in the direct connections for Figure 7. Direct connections were also assigned between the benefit area and the BMW Group, Bosch, and DENSO case, and the Koller Kunststofftechnik case, despite not having PCF connections. The former explicitly stated the resolution of lacking standardization in data exchange processes halted field data reporting of component performance, and can be therefore be connected to reduced resource usage and circularity, whereas the latter explains describes how a higher regulatory compliance was achieved through the implementation of Catena-X certified solutions, hence the standardization.

Figure 7 and empirical findings point to standardization and methodology being one of the most important benefits of the ecosystem. However, the benefit is conditional and also exposes a vulnerability for Catena-X. Catena-X may reduce friction by giving actors a shared methodological language, but Catena-X evidently does not provide the only possible method. Therefore, its value is highly dependent on whether industry actors and regulators pick Catena-X as the shared network.

Ecosystem benefits and synergies

The benefit area Ecosystem benefits and synergies refers to benefits that arise from the ecosystem as a wider network. Some examples from the empirical findings are reusing PCF values across multiple customers, shared and easy-to-use solutions available through the community and Cofinity-X, and synergies across multiple use cases - once the Catena-X infrastructure is installed for one solution, it is easier and cheaper to build upon it. The Koller Kunststofftechnik case however shows no connection to this benefit area, as demonstrated in Figure 7. This is because the case mainly demonstrates standardization and regulatory compliance, as well as energy transparency and internal operational improvements rather than ecosystem level synergies such as joint problem solving or shared cost reductions.

Figure 7 shows two direct connections, between the Ford, Flex, and Micron case, and the WITTE automotive case. It also shows one indirect connection with the BMW Group, Bosch, and DENSO case, and finally no connection to the Koller Kunststofftechnik case.

Ecosystem benefits emerge because sustainability problems cannot be solved by single companies alone. Catena-X coordinates actors vertically and horizontally. CX mentioned it, companies are developing solutions individually to cope with increasing sustainability regulations. Instead, by merging forces and working as a greater collective and adapting to the same standards, the automotive industry can pay for the sustainability transition cost together, instead of every organization paying individually.

7. Conclusion

This chapter summarize the key findings and provide answers to the research questions, and also provide recommendations for future research.

7.1 Key Findings

***RQ1**: What challenges exist for the adoption of the Catena-X framework for emission data transparency and increased circularity within the supply chain for companies in the automotive industry among the case companies?*

The findings show that the adoption challenges for Catena-X can be understood through two related categories. The first category concerns underlying supply chain challenges that already exist regardless of Catena-X, whereas the second category concerns Catena-X specific adoption challenges. Both categories hold five identified challenge areas each, into which the identified issues addressed by the case companies have been divided. Through this two-sided categorization it is apparent that the adoption of Catena-X is constrained both by structural challenges already present in the company supply chains, and in particular to the context of electronics. But it is also constrained by factors such as maturity, implementation, and perceived value of the ecosystem itself.

The five broader challenge areas provide the context for why Catena-X is needed, but also why it is difficult to implement. The findings show that circularity for automotive electronic components remains at an early stage of practical implementation. Although circularity is increasingly emphasized conceptually, and Catena-X provides the structure for circularity related data exchange, the empirical findings indicate that circularity has yet to be translated into concrete product design requirements during product development, supplier expectations and economically viable business cases. This is particularly difficult for complex and safety critical components such as ECUs, which are not currently designed for circularity, and reuse of the components remains limited due to quality and safety risks pressuring the OEMs. Therefore, Catena-X cannot create circularity on its own, but can support it.

Another challenge concerns the availability, quality, and reliability of primary data across the supply chain. Companies often rely on industry averages because they are easier to obtain than primary data. Primary data can also be sensitive to share, or unavailable due to limited supplier maturity. In some cases, suppliers lack the knowledge or capabilities to calculate and provide PCF data, while in other cases they avoid sharing primary data if it reveals poor performance. Even when data is shared, its value is limited if it cannot be verified. Unverified data equals worse quality of the data and weakens the credibility of emissions accounting and circularity assessment. These issues are further amplified by inconsistencies in methodology for PCF calculations. Standards and regulations still leave some room for interpretation regarding functional units and system boundaries. For complex, globally distributed ECU supply chains involving many components and actors, it is difficult to trace materials, obtain reliable primary data, and achieve the necessary product lifecycle transparency needed to support emissions reduction and circularity.

The adoption of Catena-X is also limited by factors related to the ecosystem itself. Among the identified challenges are for example low awareness, unclarity regarding perceived business value from organizations point of view, implementation costs and the uncertainty regarding who should carry the costs, reduces companies' willingness to adopt the Catena-X standards and participate more actively in the ecosystem and its development. It is an issue that companies become members but wait for others before committing to strengthening the community. Furthermore, Catena-X's decentralized structure and focus on data governance protects sensitive data but also limits full upstream visibility.

As illustrated in Figure 6, the identified challenge areas can also be understood and depicted as a layered progression. Derived from the empirical findings, the pyramid shows how external drivers incentivize adoption among the organizations. Some examples of drivers are regulations, OEM requirements, and customer expectations. Furthermore, the challenge areas are in Figure 6 broken down into the internal, interorganizational, and ecosystem-related conditions that must be met before Catena-X can be implemented successfully. Evidently, the challenges are not isolated. Some challenges become relevant once only the more fundamental conditions are in place. Companies must have sufficient organizational readiness, sustainability knowledge, access to shareable data, and be willing to contribute to the data ecosystem, in other words fulfill the basic prerequisites, before the ecosystem maturity becomes an issue.

To conclude, Catena-X adoption is not primarily limited by the absence of technical standards, but by the readiness of the surrounding supply chain system. Catena-X is part of a bigger sociotechnical system meaning that its functionality is dependent on the ecosystem's technological and regulatory readiness, the surrounding infrastructure, the using actors' competence, maturity, and awareness, but also the wider industry's and society's direction and goals. Catena-X can support standardized and sovereign data exchange, but its practical value is highly dependent on whether actors across the supply chain are willing and able to adapt to the standards and follow the guidelines.

RQ2*: How does shared product and material data, as defined by Catena-X, support reduction of Scope 3 emissions and strategies for increased circularity, such as reuse, remanufacturing and recycling, for the investigated case companies in upstream electronic supply chains?*

Catena-X primarily supports reduction of Scope 3 emissions for the investigated case companies by enabling standardized and interoperable exchange of sustainability related data across the automotive supply chain. Rather than directly reducing emissions itself, the ecosystem focuses on enabling sovereign data exchange of supplier-specific primary data between actors. As a result, participating companies gain access to more accurate and credible emission data compared to relying on secondary data and estimations. Following the methodology and rulebooks of Catena-X provides the participants with aggregated emission values. The ecosystem does not enable hotspot analysis. This means that the responsibility for identifying and reducing actual emissions remains with the participating companies themselves. In this particular case, access to aggregated emissions data across different components and supply chains may still support the investigated companies in identifying areas where sustainability improvements are needed. Reduction of Scope 3 emissions therefore becomes an indirect effect of improved data exchange and increased emissions visibility across the supply chain.

Catena-X currently provides limited practical support for circularity strategies such as reuse, remanufacturing and recycling within upstream automotive electronic supply chains. Although the ecosystem introduces concepts related to circularity and lifecycle-related data exchange in the Circularity and EcoPass KITs, these functionalities remain under development and have not yet been fully integrated into practical operations. The findings showed that design for circularity is absent within the ecosystem, limiting the practical applicability of higher level R-strategies in the investigated supply chains. In this particular case, continued prioritization of newly manufactured components by the OEM further limits the practical implementation of circularity strategies such as reuse and remanufacturing within the supply chain.

Catena-X contributes to increased awareness and discussion regarding circularity related information sharing across the automotive supply industry. The ecosystem encourages development of standardized approaches for exchanging information related to material composition, product changes and life cycle related data throughout the supply chain. This may improve future conditions for EoL activities such as dismantling and recovery of electronic components. However, the findings show that circularity implementation remains heavily constrained by economic feasibility, organizational priorities and limited integration of circularity principles during the product development phase.

7.2 Future Research

This thesis aimed to examine the potential of the Catena-X ecosystem for increased circularity and emission reduction opportunities within upstream automotive electronic supply chains. The findings of this thesis have provided a foundation that can be further developed through future research. Therefore, suggestions for future research will be presented in this section.

First of all, it would be valuable for the case companies to conduct a pilot implementation of Catena-X between the OEM and T1 in order to examine how data exchange works in practice. Since PCF exchange is currently one of the most developed use cases within Catena-X, the pilot should focus on PCF data exchange. A pilot implementation could contribute to a better understanding of the practical applicability of Catena-X, while also enabling the companies to evaluate whether larger-scale implementation across the supply chain would justify the required investments in terms of time, resources and costs.

Another area for future research is to investigate the DPP and EcoPass KIT in greater detail. The empirical findings showed that the circularity-related aspects of Catena-X are currently less mature than the PCF-related functionalities. However, the EcoPass KIT was identified as one of the more developed circularity-related solutions within the ecosystem. Therefore, future research could examine how DPP-related solutions may support material traceability, EoL management and circularity practices within automotive electronic supply chains.

Furthermore, future research should include interviews with companies that currently have limited or no awareness of Catena-X. The respondents in this thesis were all connected to or already familiar with the ecosystem, which may have influenced their perspectives presented throughout the thesis. Including organizations with lower awareness could contribute with additional perspectives regarding barriers to adoption, perceived value and organizational readiness within the broader automotive industry.

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Appendix A

Presented below are the two interview guides used in this study to collect empirical data. The questions in the templates provided guidance during the semi-structured interviews.

Each interview began with a brief introduction to the study and the purpose of the project. The participants were then asked for their consent to participate and to have the interview recorded.

The first interview guide aimed at understanding the operations of the OEM and its Tier-n suppliers, while the second interview guide was aimed at experts within the topic of Catena-X in order to better understand the possibilities and benefits of implementing the ecosystem.

Interview Guide 1 - OEM and Tier-n suppliers

Background

1. Can you briefly describe your role and main area of responsibility in the company?
2. How are sustainability topics, more specifically emissions and circularity, connected to your role and everyday work?
3. Can you describe/show the specific case components in more detail?

Visibility and data sharing

4. How would you describe your relationship and collaboration with your upstream suppliers/ downstream customers?
5. How far upstream in the components' supply chains do you currently have visibility?
6. How frequently do you exchange sustainability data with your supply chain partners, and in what format?
    - Is the data shared proactively or only on request? Is it structured (spreadsheets, EDIs) or unstructured (PDFs)?
7. Do you currently have access to primary data from your suppliers regarding sustainability - circularity data and/or emissions
8. What information from upstream suppliers is difficult to obtain in regards to sustainability and circularity?

Circularity

9. How does your company currently work with circularity regarding the electronic components across their lifecycle?
10. To what extent are the components currently designed for circularity; for example for reuse, remanufacture, or recyclability?
11. Who is responsible for the components end-of-life?

Product Carbon Footprint

12. How does your organization currently calculate and manage the PCF of the components?
    - Who is responsible for the calculation and how are the results used within your organization?
13. What emission data do you currently receive from your suppliers, and in what format?
14. Where are the biggest data gaps or uncertainties in your current Scope 3 emissions accounting for these components?

Catena-X

15. Are you or your organization familiar with or have any previous experience of working with Catena-X or other data ecosystems?
16. What are the key obstacles or difficulties you see with implementing Catena-X for this specific supply chain?
17. How well does your current IT infrastructure support integration with systems as Catena-X connectors (e.g., Eclipse Dataspace Connector)?
    - If unfamiliar with EDC → do you have APIs or data integration capabilities that could connect to an external data ecosystem?
18. If your company were required to share PCF and circularity data across the supply chain, would you be prepared and willing to do so, and what would be the biggest challenges?
19. Which requirements and conditions would need to be met by other parties for your company to adopt Catena-X?
20. If your suppliers were required to share standardized sustainability and circularity data through a unified data standard protocol (defined by Catena-X), what challenges do you think they would face?

Final comments

21. Is there anything you would like to add?

Interview Guide 2 - Catena-X

General information

1. What is your title and area of expertise?
2. How is your role connected to sustainability topics such as emissions and circularity?

Catena-X

3. What key technical components and data requirements are needed to apply the Catena-X standards?
4. What are the biggest challenges companies face when adapting Catena-X standards?
5. Does Catena-X have, use or support any databases?
6. What role do EDC connectors play in the Catena-X ecosystem?

Product Carbon Footprint

7. How does Catena-X support the exchange of PCF data and reduction of Scope 3 emissions across supply chains?
8. Is it possible to identify "hot spots" (where the majority of emissions are occurring) in the supply chain with the help of Catena-X?

Circularity

9. To what extent does Catena-X currently support circularity in automotive supply chains?
10. What circularity related data are companies expected to share within Catena-X?
    - Does it vary depending on chosen R-strategy (reuse, remanufacture, recycle)?
11. How does Catena-X support tracking functions for materials and components across supply chains aimed at circularity?

Catena-X in the future

12. How do you see the development and adoption of Catena-X in the up-coming years?
13. From your experience, what needs to happen for Catena-X to become widely used by all parties in the automotive industry value chains?

Final comments

14. We are primarily investigating the PCF and circularity KIT. Which other KITs would you recommend for this case?
15. Is there anything you would like to add?

Appendix B

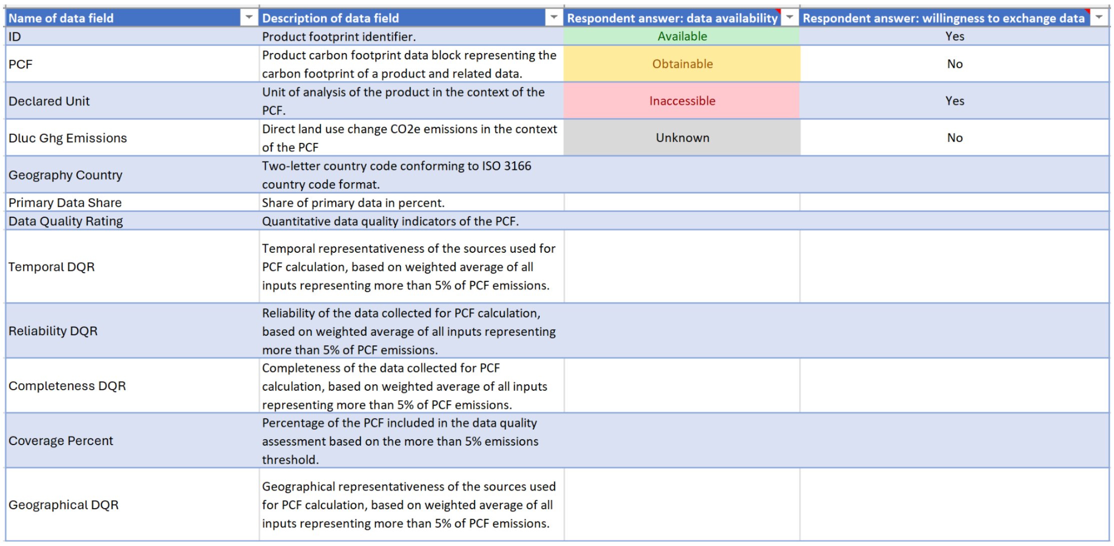
An excerpt of the PCF data file sent to the two case companies can be seen in *Appendix B*. The file was shared in Excel format to allow respondents to easily complete the required data fields for the study. The file is based on the Semantica-X blueprint for PCF formatting version 7, which is available as open source (Semantica-X, 2026).

As seen in the excerpt below, the data file contains four columns: Name of data field, which refers to the name of the fields in Semantica-X's version; Description of data field, which explains what type of data should be entered in the field; Respondent answer: data availability; and Respondent answer: willingness to share data.

In the column Respondent answer: data availability, the respondent can use drop-down menus in the cells to select one of the following alternatives: Available, Obtainable, Inaccessible, and Unknown. These options indicate whether the responding company has access to the data, does not currently have the data but could obtain it if needed, does not have access to the data, or is uncertain either about what the requested data refers to or whether it can be obtained.

In the column Respondent answer: willingness to share data, the respondents use drop-down menus to indicate whether the data is considered sensitive to share within the supply chain by choosing from the alternatives: yes or no.

The purpose of the data file was not to collect the specific data itself, but rather to compile an overview of data availability among the two cases to see if the case companies have the necessary data to apply the PCF use case. However, due to the ongoing priorities and limited available resources within the participating organizations during the thesis period, the requested material could not be fully completed or prioritized by the companies.



Name of data field	Description of data field	Respondent answer: data availability	Respondent answer: willingness to exchange data
ID	Product footprint identifier.	Available	Yes
PCF	Product carbon footprint data block representing the carbon footprint of a product and related data.	Obtainable	No
Declared Unit	Unit of analysis of the product in the context of the PCF.	Inaccessible	Yes
Dluc Ghg Emissions	Direct land use change CO2e emissions in the context of the PCF	Unknown	No
Geography Country	Two-letter country code conforming to ISO 3166 country code format.		
Primary Data Share	Share of primary data in percent.		
Data Quality Rating	Quantitative data quality indicators of the PCF.		
Temporal DQR	Temporal representativeness of the sources used for PCF calculation, based on weighted average of all inputs representing more than 5% of PCF emissions.		
Reliability DQR	Reliability of the data collected for PCF calculation, based on weighted average of all inputs representing more than 5% of PCF emissions.		
Completeness DQR	Completeness of the data collected for PCF calculation, based on weighted average of all inputs representing more than 5% of PCF emissions.		
Coverage Percent	Percentage of the PCF included in the data quality assessment based on the more than 5% emissions threshold.		
Geographical DQR	Geographical representativeness of the sources used for PCF calculation, based on weighted average of all inputs representing more than 5% of PCF emissions.		

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