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Empowering End-of-Life Vehicle Decision Making with Cross-Company Data Exchange and Data Sovereignty via Catena-X

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Abstract: The mobility sector is the world's second-largest producer of energy-related CO_2 emissions, and it is facing a global resource shortage. The demand for circular products, the use of secondary materials in future vehicles, and the need for sustainable business models in the mobility sector is increasing. However, a transparent and end-to-end data exchange throughout the entire value network is missing, which is hindering an efficient circular economy. Relevant information on the vehicle, its components, and materials at the end of the product life cycle are often missing. In this context, this paper presents a decision support system based on Digital Twin data for a circular economy solution as a software application. It was developed within the German research project Catena-X following an integrated approach of user-centered design, the V-model, and within the Scaled Agile Framework. By combining these methodological approaches, customer-oriented solutions were developed and continuously improved at each stage of development to shorten the time-to-market. Catena-X is based on Gaia-X principles. In Gaia-X, necessary core services are developed, and contraction negotiation for data exchange and usage policies is enabled and implemented. The decision support system provides important information about the exact composition and condition of the vehicle, its components, and its materials. Thus, it helps to improve efficiency, sustainability, and the implementation of the circular economy. The decision support system was tested and validated with a use case that provided Digital Twin data on the end-of-life vehicle.

Keywords: digital twin; circular economy; digitization; sustainable development; product life cycle; supply chain; cross-company data exchange; Catena-X

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1. Introduction

In recent years, the amount of globally generated waste has been on the rise. It is projected to reach 3.4 billion tons by 2050 [1]. With limited resources and increasing waste, it is essential to implement measures for reusing, as well as recycling strategies. The Circular Economy (CE) presents solutions that can boost economic growth while promoting sustainability through the efficient use of resources and waste reduction. It aims at separating economic growth from wasteful resource consumption by preventing the depletion of natural resources and the disposal of waste and recyclable materials [2]. Instead, resources are kept in circulation for as long as possible. To achieve this, End-of-Life (EoL) strategies are implemented to prolong the life of products and create new value by preserving the resources used to create them [3].

As an example of a complex end product with a convoluted supply chain, the automotive industry suffers from a lack of transparency and accessibility to end-to-end data throughout its entire value network. At the end of a product's lifecycle, important information about the vehicle, its parts, and materials is frequently unavailable. This makes it difficult to make well-informed and comprehensive decisions about EoL strategies. Without this data, it is hard to assess and mitigate environmental impact and economic feasibility based on the selected EoL strategy. The consequence is inefficiencies within the CE.

The decision-making process for an optimal EoL strategy in the automotive industry is highly complex. This is due to a large number of globally distributed suppliers along the value chain, varying environmental impacts during the vehicle's use phase, and the contrast between short product life cycles and the long lifespan of a vehicle. The latter pertains to the ongoing changes in vehicle design, thereby making it challenging to pinpoint the exact configuration of a vehicle at its EoL. The lack of accessible information on the history and condition of a vehicle significantly hinders the ability to identify the best EoL strategy in order to make evidence-based decisions and ultimately enable a CE. Given the complexity and interconnectedness inherent in the automotive value chain, user-oriented, context-specific data provisioning can be an effective tool for facilitating understanding and decision making by stakeholders within the value chain.

Hence, this paper outlines a decision support system for End-of-Life Vehicles (ELV) based on cross-company data exchange as part of the German research project Catena-X. The paper addresses the following research questions (RQ):

- RQ 1: How can stakeholders at the end of a vehicle's life be supported with appropriate data and information to allow better decision making that enables a CE?
- RQ 2: Which data needs to be provided and in what manner to make a decision for ELV?

2. Materials and Methods

The decision support system for ELV was developed in the German research project Catena-X within the business domain CE. In total, 28 companies define the architecture of the data-driven Catena-X network, its services, and, especially, the cross-company data exchange. Also, specific software applications were developed to showcase the added value of cross-company exchange for certain domain specific topics, such as CE, from an industrial perspective. The participating partners for CE-focused topics range from application partners from the automotive industry with Original equipment manufacturers (OEMs), to suppliers and dismantling companies, to technology partners from the software industry, as well as research partners [4].

Within the research project, an agile way of working was chosen—the Scaled Agile Framework (SaFe) [5–7]—to enable fast results, close collaboration, and constant adaption to new challenges, as well as allow for the optimization of processes and organization with such a high number of partners. It was first designed by Dean Leffingwell to scale agile to large enterprises and comprises elements from SCRUM [8], Extreme Programming [9], Lean Management [10,11], and Kanban [12].

Some of the roles within the SaFe framework are responsible for the overall management, vision, and releases, such as Release Train Engineers (RTEs) for Agile Release Trains (ARTs), release management, and portfolio management teams. A Business Owner (BO) is responsible for the delivery of an added value within a specific topic, i.e., a business domain. A business domain bundles all development activities that have a common vision and are domain specific. In Catena-X, there are, e.g., the business domains of Product Lifecycle Management (PLM) and quality, resiliency, sustainability, and the CE. The definition of user-centered products and their breakdown into functional modules is done within product teams. They are responsible for core product development, its specification, and software development. There is one product owner, a development team, and a SCRUM master who is responsible for the management of the agile way of working.

The development process is broken down into timeboxes (iterations) with a specific time period, which are called Program Increments (PI). Within Catena-X, these are ten weeks each, i.e., five sprints of two weeks each. The main elements of a PI are:

1. PI Objectives: These are specific, measurable, and time-bound goals that the team aims to achieve during the PI. The objectives should align with the overall vision and strategy of the product and provide clear direction to the team.
2. Features: These are the high-level functional modules that the team plans to deliver during one PI. Exemplary features are ELV purchase decision support or DT data provisioning for the dismantling decision. Features are usually divided into smaller, more manageable chunks called stories that can be completed within a sprint.
3. User stories: These are the detailed requirements that describe the specific functionality or behavior of the system from the user's perspective. User stories are written in a user-centric language according to the following syntax: "As a [user], I want [functionality], so that [benefit]". For each user story, acceptance criteria are defined, which make it possible to check whether a user story has been successfully completed.
   - The decision support system for ELV, which is being presented, was developed by a product team consisting of representatives from research, technology provider companies, and industrial application operating within the business domain of the CE in the research project Catena-X. The collaboration of the product team was based on SCRUM principles. In a two-week period, also known as sprints, the product team worked on small tasks for specification and implementation. These tasks were described in user story format. The software JIRA was used to manage and track the progress of all user stories and dependencies with other product teams. Here, a Kanban board was used to enable management and transparency within the team and the whole project. In addition, synchronization of activities, progress, and obstacles, or impediments were discussed in a Daily Scrum meeting twice a week. Several PIs were used to specify, implement and test the presented solution with the first key users. In this context, SAP developed a project demonstrator as an implementation partner. The development scenario was the following:
   - Develop a data exchange scenario that uses cross-company-data and information to foster CE;
   - Identify a specific lifecycle phase and stakeholder for the first use case;
   - Derive the necessary data and identify the data provider;
   - Consider the scope of assets—vehicle or component—individual data versus product type data to design Digital Twins (DTs), which encompass all necessary data but are not overengineered with regard to the use case and stakeholder requirements;
   - Consider the requirements of the data provider with a specific focus on data sovereignty.

To address the special concept of DTs as an enabler for vehicle or component-specific data collection, analysis, and provision, an adapted version of the classical V-model for mechatronic products [13] for DT development [14] was utilized. The considered scenario corresponds to "extended development", which means developing a DT for an existing product without changing anything on the product, i.e., a vehicle and its components. Figure 1 illustrates the process steps in chronological order in the V-model.

Table 1 lists the detailed process steps with a short description and the relevant results for the presented decision support system within CE.

The main challenges within the development process arise due to the diversity of partners, which range from small and medium enterprises to large corporations. This leads to different ways of working and roles within the participating companies as well as different states of digitalization and capacities for agile working. There is a high amount of time and effort to be calculated for the establishment and operation of agile processes, especially meetings and task management. Also, the project was started during the COVID-19 pandemic, which led to remote and globally distributed teams collaborating virtually. The project teams, as a result, established methods and processes for the onboarding of new members and constant exchange with virtual tools. There were regular reflections on the way of working and results after each PI to improve collaboration.

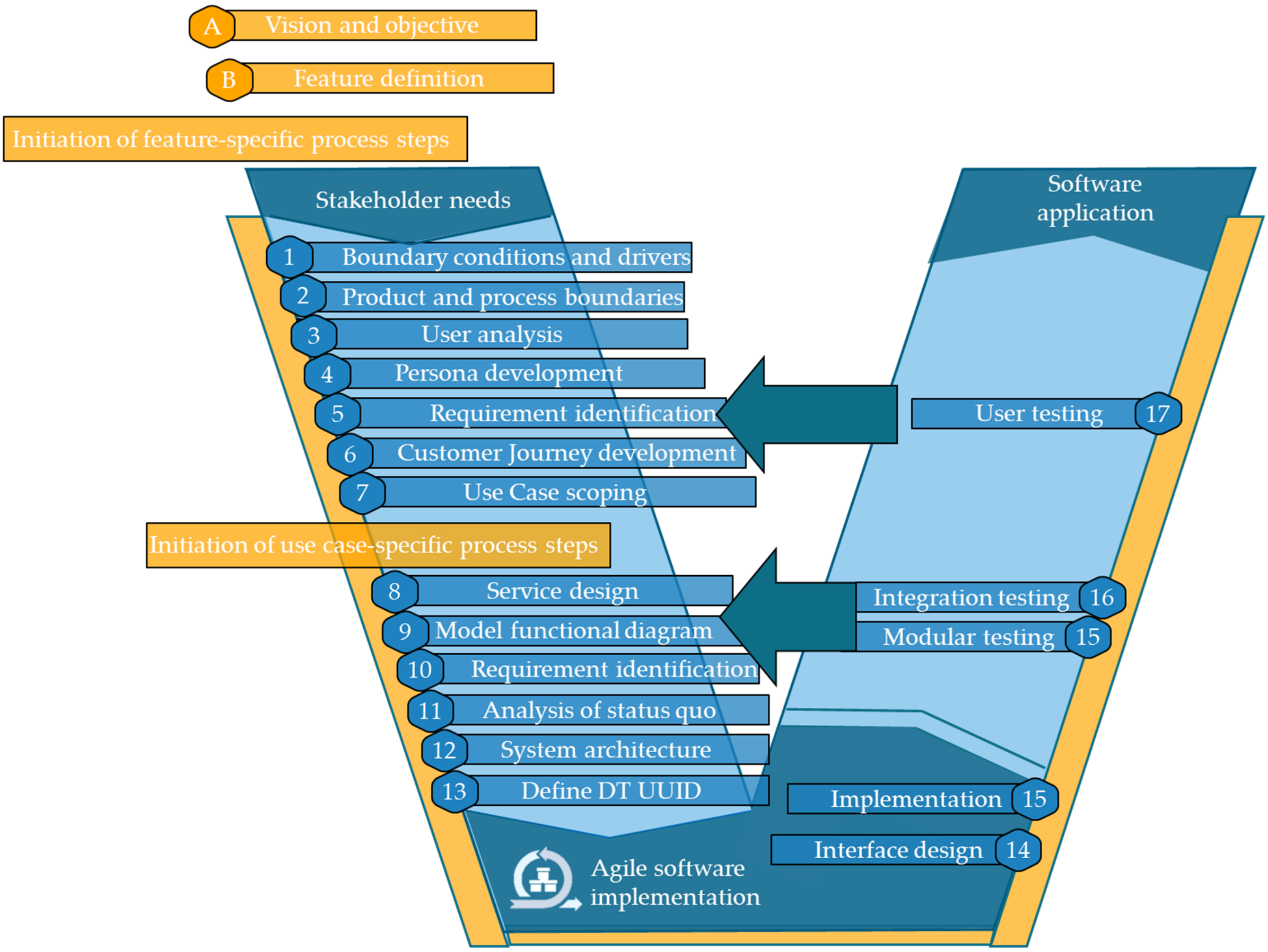

Figure 1. Methodical development of the decision support system for End-of-Life Vehicles according to the V-Model.

Table 1. Methodical development of the decision support system for End-of-Life Vehicles: detailed process steps.

No.	Step	Short Description	Results
A	Vision and objective	Analysis of the overall topic of CE and the life cycle(s) across the different stakeholders in the automotive supply chain Definition of an objective for the business domain CE and all entailed features	Overall vision and objective(s)
B	Feature definition	Definition of several topics, which include the stakeholders of the automotive value chain and consider the potential business value for CE	Defined features with an overall objective and expected business value. Within this paper, the feature "ELV decision support" is the focus.

Table 1. *Cont.*

No.	Step	Short Description	Results
		Initiation of feature-specific process steps	
1	Boundary conditions and drivers	identify the most relevant boundary conditions within the feature with regard to regulatory drivers and environmental challenges	Overview of regulatory drivers and environmental challenges Within the feature, social aspects were not the primary focus.
2	Existing product and process boundaries	Define the motivation to develop a DT and identification of the main problem that needs to be solved with the DT, boundary conditions, existing product in use, and derivation of the first requirements	First list of requirements and data needs, pre-existing DT elements. In this case, the existing product is the automotive vehicle with its components and materials with different states along its lifecycle.
3	User analysis	Refinement of the stakeholder analysis to the feature decision support system for ELV to identify the core life cycle phase and stakeholders as potential users	Stakeholder map along the lifecycle
4	Persona development and as-is process	Execution of interviews with representatives of the future users, analysis of as-is-process, identification of pain points, and development of respective generic personas	Interview documentation, as-is-process documentation, including pain points and persona description
5	Requirement identification	Derivation of first requirements from the interviews and process analysis	First requirements for data, functions, and non-functional requirements
6	Customer journey development	Development of a customer journey, which depicts the interaction of the future consumer/customer with the DT and the decision support system	Customer journey definition and user stories
7	Use case scoping	Define use cases (use case diagram), identify the most relevant use cases to be prioritized and developed within one PI (iterative for each PI)	Use case diagram
		Initiation of use-case-specific process steps (per PI)	
8	Service design	definition of DT services in close cooperation with the business model and service design team to identify the first functional building blocks (FBBs)	Functional building blocks
9	Model functional diagram	Functional diagram (generic) with first information (generic)	Functional diagram
10	Requirement refinement and identification	Define (1) functional and non-functional requirements and (2) requirements for detailed definition of data in the form of content, context, type, sensitivity, DT-relevance (instance-specific or product type)	Requirements list

Table 1. *Cont.*

No.	Step	Short Description	Results
		Initiation of use-case-specific process steps (per PI)	
11	Analysis of status quo	Analyze status quo to identify pre-existing services within Catena-X, as well as (re)usable IT systems, data, models, data bases—internally at data provider and data consumer side, as well as externally (Gaia-X, IMDS, IDIS)	Overview of prerequisites
12	System architecture definition	Define system architecture (solution neutral), including relevant interfaces	System architecture
13	Define DT Universally Unique Identifier (UUID)	DT: Define UUID and depict the system of DT and respective DT processes of registering, managing, and deleting	DT UUID and process description
14	Interface design	Develop user interface mockup/dashboard	Interface mockup
15	Implementation	Agile implementation within SCRUM and documentation according to ARC42 [15]	Implementation documentation (ARC42)
16	Modular testing	Modular testing, verification of the modules, and incremental bug fixing	Test documentation and list of identified bugs
17	Integration testing	Integration testing, verification of the integrated system, and incremental bug fixing	Test documentation and list of identified bugs
18	User testing	Validation of the decision support system, as well as the interface, and identification of improved potential or redesign ideas	Test documentation and list of improved potential

3. State-of-the-Art Analysis

The first steps (A, B, 1 and partly 2) of the previous described methodical approach can be addressed within a state-of-the-art analysis. For the process steps A and B but also the analysis of boundary conditions and main drivers, the following chapters give an overview of the state-of-the-art updates in the CE, DTs, DTs for the CE, and existing databases.

3.1. Circular Economy

The CE can be defined as an economic model that pursues the goal of efficient resource use. For this purpose, this includes the minimization of waste, the reduction of primary raw materials, and the long-term preservation of value by extending the life of products and returning components and materials to the cycle at the end of their useful life [16–18]. The principle of the CE is applied considering the environmental protection and sociological benefits at all times [16,17].

The potential of the CE covers the decoupling of economic development from resource consumption, which leads to sustainable product development [16,17]. The CE enables future resources to be secured, thus preventing supply bottlenecks and resource shortages in the supply chain. At the same time, the resilience of the supply chain is increased [19]. In practice, this means that discarded products are reused or recycled, thereby minimizing waste and requiring fewer natural resources to produce new products [16].

The CE is implemented through various CE strategies, also known as the so-called R-Strategies, which can be located throughout different phases of the product life cycle and are measured according to their degree of circularity. A higher degree of circularity means that materials stay in the loop longer, and fewer resources are needed to retain materials in the loop [20]. The number of published R-Strategies varies depending on sources, between 2–10 [2,16,17,19–35]. One of the most well-known approaches is that of Potting et al., which considers nine R-Strategies in order of their circularity: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover [20].

Furthermore, the implementation of the CE includes not only the rethinking of the use of resources, but also the development and establishment of new business models, which can take place in combination with new digital technologies such as the Internet of Things, Big Data tools, or DTs [19,36–38].

Circular business models aim to preserve the added value of products for as long as possible. In doing so, circular business models often occur in three phases of the value chain [39]:

- Before use (mining, production, distribution): In this phase, the value of products increases;
- Use phase of a product: In this phase the value of products is the highest;
- After use: Here, the value of the product decreases. The value is recovered by returning the complete product or its components to the previous use phases.

Four categories of circular business models can be differentiated [19,39]: Circular design models belong to the circular business models, which are located in the product's pre-use, design, development, and production phase. They focus on the development of existing or new products and processes. For example, products are designed for longer life, easier repair, remanufacturing, or recycling. This category also includes developing new materials that can be bio-based, more resource efficient, or recycled.

- Optimal use models belong to the use phase of products. This business model aims to improve value during the product's life by providing services or add-ons that extend its lifetime. Furthermore, possibilities for more intensive or efficient product use pertain to this category. For example, product service models provide products to users, as in the case of least vehicles, whereby the manufacturer remains as the owner.
- Value recovery models are circular business models that can be found in the after-use phase. Here, the focus is on the maximum recovery and recycling of products and materials, thereby capturing the value of used products. In addition, the logistics of return from the point of consumption to the point of production are also part of this purpose.
- Circular support models refer to the coordination of management and the coordination of CE networks to form a fourth overarching category. Additionally, the management and coordination of resource flows and the optimization of incentives for stakeholders and other supporting activities in a circular network are included.

The mentioned business model categories are not dependent on each other but can also be applied together [39].

Figure 2 shows an overview of options for implementing the CE. When implementing the CE, CE models, R-Strategies, and digital technologies as drivers should be considered [36].

Digital technologies can play an important role in successfully implementing the CE [36,38,40,41]. They support data-driven material and product tracking, whereby the collected data can be used to provide decision support for the optimal reuse of products, components, and materials from an environmental and economic perspective. Furthermore, digital technologies can provide component monitoring and are capable of quality assessment. They are also a basis for the exchange of data and information in real time. In this way, they enable increased transparency of the value chain for all involved stakeholders and can thus close the often-missing information gap throughout the value chain [36].

To implement the CE successfully, it is necessary to involve all stakeholders in the value chain. The implementation of a new, circular business model is also associated with dynamic changes within an industry. For this purpose, traditional roles of the stakeholders in the value chain may change, and additional roles may be required. Therefore, it is very important within a circular business model to ensure that all stakeholders are established in a value-creating way [16,36].

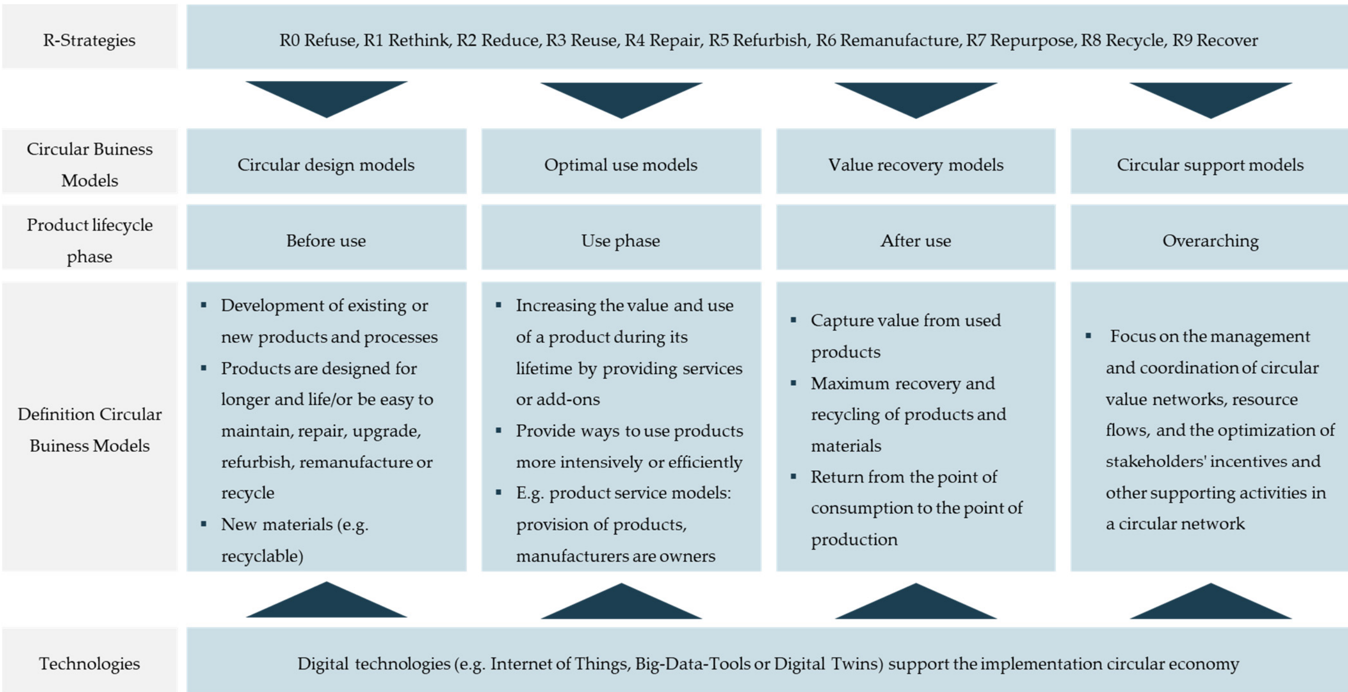

Figure 2. Framework for the implementation of data-based Circular Economy (figure based on Refs. [19,20,36,39]).

3.2. Digital Twins

The term DT originated from the aerospace industry, was first introduced in 2002 at the University of Michigan (Ann Arbor, MI, USA) by Michael Grieves, and was linked to the term Product Lifecycle Management [42,43]. Since then, many different definitions and application areas of a DT have come to exist [44,45]. In general, a DT describes "a digital representation of an active unique product [...] or unique product-service system", which can be described by models, information, and data within one or more lifecycle phases and includes certain characteristics, properties, conditions, and behaviors. The data and information through the product lifecycle are linked and analyzed accordingly [44].

In the German research project Catena-X, the cross-company data exchange within the automotive industry's value chain is implemented with the help of DTs. DTs have established themselves as an essential element for structuring data and were used as enablers of the Catena-X network. In this context, the definition of the DT is based on the definition of the Industrial Digital Twin Association and the Asset Administration Shell. The DT is defined as a virtual representation of assets, which has several properties [46,47]:

- The DT has at least one Catena-X-wide unique ID;
- DTs are organized by a set of aspects, which can be extended over the lifetime;
- A single aspect can be connected to different heterogenous data sources;
- The DT can represent asset types (e.g., virtual prototype of a vehicle) and asset instances (e.g., real vehicle);
- A DT can cover the whole asset lifecycle;
- A DT can provide individual asset and fleet-related knowledge.

In the automotive industry, DTs are used in a variety of ways and throughout the entire product life cycle of a vehicle. During product development, for example, DTs support by collecting vehicle behavior information and providing valuable information to product developers. Furthermore, DTs can simulate the use of different components and systems and provide valuable information about suitability, interoperability, and performance. They also enable optimization during use by collecting and predicting real-time data of the vehicle and components [48]. The collected data helps in maintenance, repair, reuse, and recycling. It can also be used to improve future product generations (feedback to design) [48–50].

3.3. Digital Twins for Circular Economy

Digital technologies include the DT support the implementation of the CE [36,37]. DTs help to continuously collect, evaluate, and analyze data and information throughout the product life cycle. In this way, they provide transparency across the entire supply chain and enable the traceability of individual products, components, and materials [51–57]. In addition, DTs help to provide the right information to the right stakeholders at the right time in a decentralized manner [51].

In the design, development, and production phases, DTs support the evaluation and simulation of a product. They evaluate current and future product conformity to enable the consideration of future reuse and recycling at the beginning of the product life cycle. This allows the elimination of non-recyclable and dangerous materials and the development of durable and repairable products [51,58]. Moreover, DTs contribute to an increase in the resource efficiency of production [45,58].

Through continuous data collection, evaluation, and analysis of the product, this instance-based DT information can be implemented in the usage phase to make decisions regarding maintenance, repair, and overhaul [45].

In the EoL phase, instance-based DT data support the decision-making process for the reuse and recycling of components [55–57]. They provide essential information about the material and component composition of the product. This is relevant for the sustainability and further use of the product [53,59]. In the future, regulatory requirements such as the obligatory use of recycled content in polymers and other materials will be included [59]. This information can be used to determine the remaining useful life of components [55]. Thus, DTs underpin questions relating to the reuse of individual components, as well as if and when these components should be handed over for recycling [55–57,60]. Furthermore, DTs can help to reduce the complexity and improve the efficiency of the EoL disassembly processes by providing the necessary information, e.g., an indication of compulsory disassembly or the location of parts to be disassembled. In addition, DTs can perform the virtual disassembly and reassembly of products [57].

3.4. Existing Databases: IMDS, IDIS, Schwacke

In the automotive industry, several databases have been established over the past decades for the exchange of product and material data of vehicles. In contrast to the instance-specific data provided by DTs, these databases contain generic or product-type information. The most relevant databases in the German automotive industry constitute the following:

- The International Material Data System (IMDS), which is a globally standardized exchange and management system for material data in the automotive industry;
- The International Dismantling Information System (IDIS), which has information on the (obligatory) dismantling of different vehicle types and components;
- The Schwacke company, which has information on the vehicle level, e.g., technical data, (historical) list and equipment prices, valuations, forecasts, spare part residuals, and value developments.

Suppliers to the automotive industry are required to provide information about the materials that are used in the product. In a joint venture project, the companies Audi, BMW, DaimlerChrysler, Ford Motor Company, Opel, Porsche, Volvo, VW, and EDS developed a concept for the electronic collection of material data and created the basis of today’s IMDS database [61]. The IMDS database is used to exchange and manage material data throughout the automotive value chain. It has established itself as a global standard and is now used by almost all globally active OEMs. A total of 53 manufacturers and 120,000 suppliers are involved [62]. The IMDS database contains data on the chemical composition of components, semi-finished products, and materials [61].

The IDIS is a central information system for ELV treatment. The IDIS provides pre-treatment and dismantling information for dismantlers and recyclers while maintaining the environmental and safety considerations of the dismantling process. A total of 26 manufacturers from Europe, Japan, Korea, Malaysia, India, China, and the USA, 88 brands, and over 3723 models and variants of vehicles are represented. The data from the IDIS comes directly from the manufacturer and is equipped with information on safety-relevant components from the EU End-of-Life Vehicle Directive (such as HVB and airbags) [63].

The company Schwacke offers various solutions in the automotive sector. These include vehicle identification and specification, valuation, and prognosis, as well as service, maintenance, repair, and the total cost of ownership. Vehicle identification includes the unique vehicle search (make/model, VIN, HSN/TSNm, SchwackeCode). After vehicle identification, the according information is searched within the Schwacke database. It contains technical data, (historical) list and equipment prices, valuations, forecasts, spare parts, and the total cost of ownership. This data is updated weekly. In the category of valuation and prognosis, for example, residual value developments and forecasts can be tracked throughout Europe. Furthermore, market-driven and currently used vehicle values are determined for possible age and mileage scenarios for all vehicles on the market. The service, maintenance, repair, and the total cost of ownership elements include the preparation of repair cost estimates or the allocation to provide the customer with the correct spare parts [64].

3.5. Challenges and Needs

In summary, the existing databases provide information about the vehicle, the components, and the materials in the production phase ("as built") or possible forecasts at the product and component level. However, there is no information displayed about the condition of a specific vehicle, a specific component, and a specific material ("as used" and "as maintained").

However, this information is missing at the EoL when making a decision regarding the EoL treatment and the most appropriate R-Strategy to reuse or remanufacture parts or material recycling [51,65–69]. A number of approaches that try to provide EoL information for better decision making already exist. Rossi et al. developed a framework to evaluate and compare circular strategies [70]. Alamerew and Brissaud created a multi-criteria decision tool to evaluate circular product strategies from an integrated perspective, i.e., considering technical, economic, environmental, managerial, and societal aspects simultaneously [71]. Pehlken and Baumann developed a web-based decision tool that captures the reuse of used car parts and their life cycle extension [56]. All approaches refer to the fact that the information base on the condition of the products has to be improved in order to evaluate the R-Strategies.

This challenge needs to be addressed in the research. In this paper, an approach for a technological solution was derived based on the identified research gap. Furthermore, a new concept of a DT as an enabler for the CE was presented to provide the necessary "as used" and "as maintained" information. This is the main boundary condition, which entails the need for DTs as an extension to existing data on vehicles and the potential of Catena-X as a network of networks. On this basis, the feature-specific development process is described in the following (Steps 2–18).

4. Results

The results presented in this chapter show the development artifacts for the methodical development process, as well as the final software application as implemented within the research project. Firstly, the basic services and solution elements of Catena-X are introduced. These were developed based on requirements from two perspectives:

- GAIA-X compliance with regard to data sovereignty and cross-company data exchange, interoperability, and standardization, as well as open source;

- Use case, i.e., domain-specific requirements with a focus on the functionality of the end user and application provider.

4.1. General Data Exchange within Catena-X

Within Catena-X, a solution to ensure one-to-one secure data and information exchange between two partners in the network was developed. This entails mechanisms for data sovereignty settings by the data provider identified as a central enabler. It was based on the industrial data space (IDS) connector [72].

The Eclipse Data Space Connector (EDC) was one specific solution used within Catena-X as the elementary link to allow for securely exchanging data across organizations. This is particularly important when dealing with sensitive information, such as data related to vehicle components and materials. Additionally, the EDC enables direct, peer-to-peer data sharing among participants, thereby eliminating the need for a central intermediary [73]. The EDC plays a key role in facilitating the secure exchange of data from various sources, including raw material manufacturers, component manufacturers, car manufacturers, customers, and dismantlers. This allows respective domain-specific applications, such as a decision support system for ELV, to consume data from the Catena-X network and present it accordingly to the intended audience [73].

4.2. User-Centered Development of the Decision Support System for End-of-Life Vehicles

To identify the first requirements and data needs, the existing product and process boundaries were analyzed (step No. 2). The analysis was focused on the classical ELVs with their final reception, disassembly, and processing of their parts and materials at a dismantling facility. A typical dismantling company is specialized in the disassembly and handling of ELVs, as well as the respective forwarding of components and materials. Before dismantling components, all batteries must be removed. Pyrotechnical components such as the airbag must be neutralized, and liquids and gases must be drained. The process of dismantling an ELV typically involves the removal of usable parts, such as engines and transmissions, which are then sold for remanufacturing or reuse. The remaining materials, such as metal, glass, and plastics, are sent to recyclers. The dismantling company needs to carefully evaluate the estimated value of an ELV when purchasing. Herein, it is necessary to identify those most likely to yield a profit after reselling high-value components or materials at the lowest internal costs possible. The relevant information is often unavailable during the vehicle's use phase, which leaves the decision to be based on the employees' implicit experiential knowledge. The following section describes how the introduction of the decision support system for ELVs improves the dismantling company's processes.

4.2.1. Description of the Personas and their Challenges

A user analysis (step No. 3) of players involved in ELV handling was conducted to identify current weak points in the process and uncover optimization potential by accessing DT data. Interviews and shadowing, which involve a qualitative method to observe the behavior of a test person interacting with an application in a real-life situation, were conducted. As a result, the vehicle purchaser and the dismantling lead were identified as relevant personas and core users of the decision support system for ELVs. Within the persona development phase (step No. 4) for these two main future users, a detailed analysis of tasks and data needs was conducted. The vehicle purchaser's main task is to make a purchasing decision for the ELV based on vehicle-specific information and current market prices of materials and components. One of the major challenges of a vehicle purchaser is the lack of accurate information about the vehicle from the potential seller. Missing or incorrect information can lead to wrong estimates of the vehicle's value. Another challenge is the lack of market information and experience about the potential residual value of the vehicle. In that case, the vehicle's value must be evaluated through time-consuming research on different second-hand dealer websites.

Upon successful purchase, the dismantling lead visually inspects the incoming ELVs to assess the condition and value of individual components. The vehicle is classified as a spare parts carrier or scraped based on their decision. In the process of estimating the value of components, experience plays a crucial role. However, obtaining all the necessary information for the dismantling process of a specific vehicle is a challenge, especially when it comes to changes that might have occurred during the vehicle's use phase. This factor contributes to the difficulties in making informed decisions and achieving an efficient dismantling process.

4.2.2. Current Process of the Purchasing and Dismantling Decision for End-of-Life Vehicles

This section outlines the steps involved in purchasing an ELV and its eventual scrapping at a dismantling company. The focus is on the responsibilities of the vehicle purchaser and dismantling lead. Figure 3 provides a comprehensive overview of the process steps and the information exchange required at each stage.

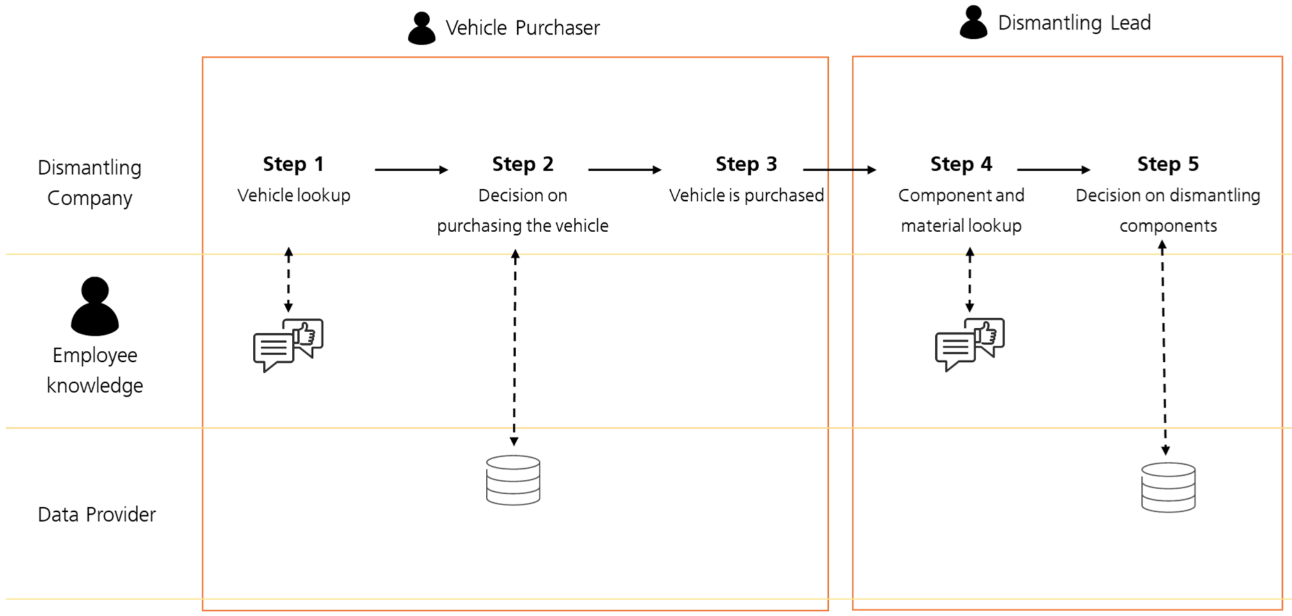

Figure 3. Current process at a dismantling company.

Step 1—Vehicle lookup: The vehicle purchaser initiates acquiring an ELV from various sources such as email, telephone, and online marketplaces or by actively searching for the vehicle as a sales representative. Then, basic information and the condition of the ELV are gathered from potential sellers. The vehicle purchaser receives information such as the vehicle's roadworthiness, the year it was manufactured, and the model from the potential seller. It should be noticed that there is a possibility of receiving incorrect or inaccurately conveyed information from the vendor.

Step 2—Decision on purchasing the vehicle: The information, e.g., vehicle's roadworthiness or model, is used to evaluate the estimated value of the vehicle, while taking into account the material and component value. The vehicle purchaser bases their calculation on the information received about the vehicle by the potential vendor.

However, this process has several challenges, including missing or incorrect information about the vehicle from the potential vendor. Additionally, if there is a lack of experience, the vehicle value must be researched on platforms such as mobile.de or eBay. Furthermore, due to a lack of data, assumptions have to be made when calculating the material value of a vehicle, thus making it difficult to estimate the vehicle's value accurately. Ultimately, the purchase decision for an ELV is made by manually comparing the residual value of the vehicle and the proposed purchase price.

Step 3—Vehicle is purchased: The purchase decision is recorded, and the relevant details, such as the vehicle's roadworthiness, location, and completeness are then relayed to the logistics team for further planning and execution.

Step 4—Component and material lookup: Upon the arrival of an ELV, the dismantling lead conducts a thorough visual inspection to evaluate the condition of the individual components. This happens regardless of the primary purchasing decision made by the vehicle purchaser. This allows the dismantling lead to form their own opinion and make informed decisions about the vehicle's condition and value.

Step 5—Decision on dismantling components: Determining the value of an ELV is a crucial step in the decision-making process of whether to scrap or classify it as a spare parts carrier. The evaluation process involves assessing the material and component value of the vehicle and making a decision based on that information.

The derived requirements were collected in a requirements list (step No. 5). They are focused on either data needs and according to requirements or functional and non-functional requirements. Later, they were assigned to the Catena-X overarching services, such as the DT Registry, semantic hub, EDC contracting, or the FBBs of the respective feature. Here, the requirements for the FBBs were the focus.

4.3. Customer Journey Development for Purchasing and Dismantling Decision of End-of-Life Vehicles Using the Decision Support System for End-of-Life Vehicles

This section details the tasks that the selected personas performed and their interaction with the future decision support system (Customer journey, step No. 6). Basically, it depicts the process of purchasing an ELV and its eventual scrapping at a scrapping company. Therein, the tasks of the vehicle purchaser and dismantling lead are the focus. By utilizing the decision support system for an ELV, an optimized process was outlined, including the necessary steps and information exchange required at each stage, as illustrated in Figure 4.

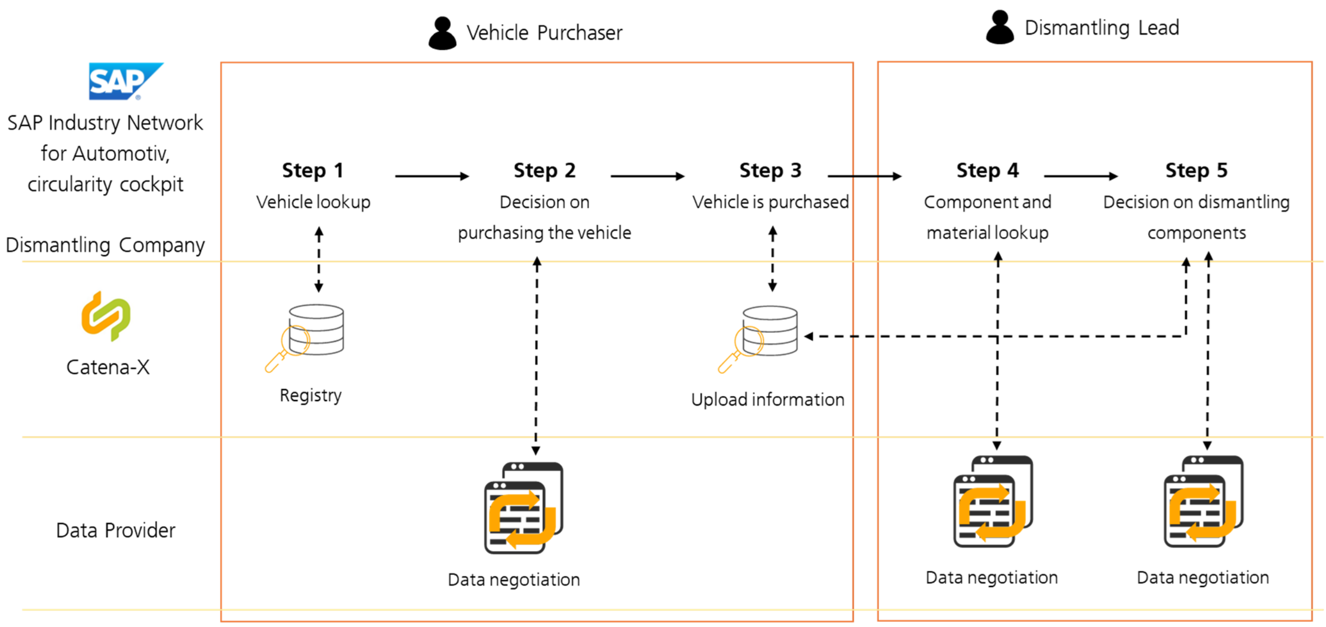

Figure 4. Target process at a dismantling company by using the decision support system for end-of-life vehicles.

Step 1—Vehicle lookup: The process of acquiring an ELV begins with the vehicle purchaser receiving inquiries from various sources such as email, telephone, or online marketplaces. To ensure the accuracy of the information provided by the vendor, the vehicle purchaser checks the associated DT of the corresponding ELV by entering its Vehicle Identification Number (VIN) into the decision support system for ELV. This allows the purchaser to verify that the vehicle's quoted information matches the DTs and is correct before proceeding with the purchase decision.

Step 2—Decision on purchasing the vehicle: To determine the value of an ELV, the vehicle purchaser requests information on the built-in components in the vehicle. Based on information from the network, the vehicle purchaser can estimate the most valuable components in the vehicle, thereby giving them an up-to-date understanding of the potential value of the ELV. Furthermore, the decision support system for the ELV displays component information of is use phase, e.g., mileage, charging, and discharging cycles, as well as the number of electromotive belt tensioners, as an indicator of the condition of the component. This information is used to make an informed decision on whether to purchase the ELV or not.

Step 3—Vehicle is purchased: The purchase decision is recorded and the necessary details, such as the vehicle's roadworthiness, location, and completeness, are communicated to the logistics team for further planning and execution. Additionally, the vehicle purchaser documents the intention to purchase the ELV in the decision support system.

Step 4—Component and material lookup: Upon the arrival of an ELV at the dismantler's yard, the dismantling lead assesses the potential for selling the vehicle by entering its VIN into the decision support system. This provides the dismantling lead with an overview of why the vehicle was purchased by the vehicle purchaser. This includes information about the potential value of the most valuable components and raw materials. Armed with this knowledge, the dismantling lead can focus on these specific components during the visual inspection, thereby making more informed decisions about the vehicle's potential for component reuse or material recycling.

Step 5—Decision on dismantling components: Determining the value of an ELV is essential in deciding whether to scrap it or classify it as a spare parts carrier. With the help of the End-of-Life Vehicle Decision Support System, this process is easier. This is achieved by providing real-time data about the vehicle, its components, and materials in a user-friendly format, thereby allowing for more informed and efficient decision making.

The dismantling lead, who receives an overview of the vehicle's components and materials, is provided with information on the component's health status, age, mileage, and the dismantling effort, e.g., dismantling instructions and legal dismantling duties. With this information, the dismantling lead can make an informed decision as to whether to dismantle the component or not.

The decision support system for the ELV should simplify this process by providing up-to-date data on the vehicle, its components, and materials in an easy-to-understand format. As a result, the vehicle purchaser and dismantling leads can make more informed decisions. This is important for making the most efficient and effective use of resources in the CE.

Use Case Scoping (Step No. 7)

A use case diagram is suitable for a general overview of a software's individual requirements and functionalities. In this context, it is used to define the appropriate scope. This contains the use cases, the connection of these, as well as the involved stakeholders. Thus, a use case diagram supports the determination of requirements for the application and clarifies the totality of the application's requirements. Each use case describes a piece of the system behavior from the user's point of view and represents a typical interaction [74].

The use case diagram for the decision support system for an ELV is shown in Figure 5. It is primarily intended to support the vehicle purchaser's decision to purchase the ELV by providing relevant information about the vehicle, its components, and materials. The dismantling lead demands more detailed information about a vehicle, its components, and materials, which are displayed to support the dismantling process.

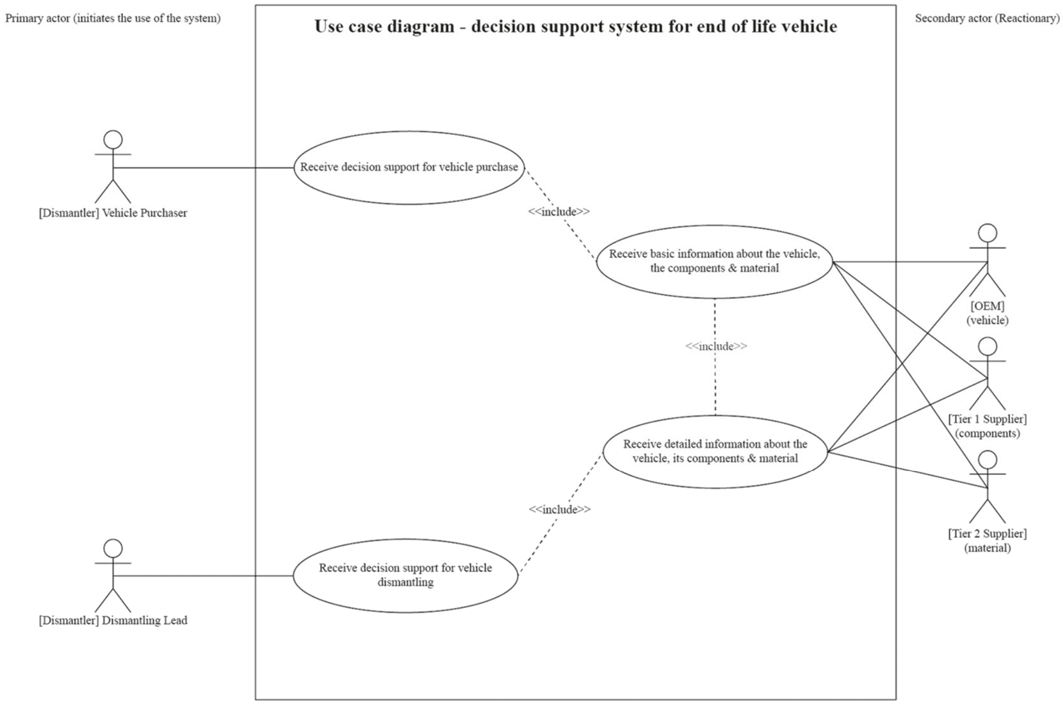

Figure 5. Use case—decision support system for End-of-Life Vehicles (excerpt) during the use case-specific phase.

After the scoping and decision for the persona of a vehicle purchaser, the development process of the functions and architecture is initiated. All the previous developed diagrams and artifacts function as an important basis for the architecture.

The core values of the activities in the research project Catena-X are specifications of the data exchange scenario, defined standards (e.g., data models or calculation methods for interoperability), and the evaluation results of case studies. The following section describes the results of the specification of the data exchange for a decision support system for an ELV as described in chapter 2.

The next step (step No. 8) for the architectural specification is the definition of FBBs as part of the service design. Within this paper, the business model was not detailed further. The FBBs describe the expected data exchange scenarios to cope with the goals the user wants to achieve, which are stated in the customer journeys and use case diagrams. The blocks are solution neutral, meaning that they do not depend on or define which software components and modules will be used in the implementation. Exemplary blocks for the previously described step 1 of the data exchange for a decision support system for ELV include the following:

- **DT Lookup**: Find a DT of the vehicle based on some generic information such as the VIN. This step also includes filtering for a desired twin, e.g., of a specific lifecycle phase.
- **Get information on available data for twin**: Show which data is available for the DT. Typical data includes, for example, used materials, included components in the form of a Bill-of-Materials (BoM), or physical dimensions of the vehicle.
- **Request specific data:** The data has to be requested from the data provider. In Catena-X, data sovereignty is a key element, and, therefore, each data offer gets policies assigned, which define who can access and use data. The request for the data includes the negotiation of a contract that complies with the policies.
- **Visualize specific data:** The data has to be visualized for the end user. This means the user gets to see a list of components, the used materials, physical dimensions, or user-requested data.

The blocks were then combined in a flow diagram (step No. 9, functional diagram) where the sequence or dependency between these functions was shown. This requires that a DT needs to be identified before specific data can be requested.

For each of these FBBs, requirements were refined (step No. 10) based on the first requirements from step No. 5. These requirements included data requirements, i.e., which data inputs can be given for the solution of the FBBs, in which format the data needs to be responded, how many data requests the functionality has to support, etc. These requirements are important to evaluate the possible components to solve the functionalities and to specify how data can be exchanged in a standardized way. For the DT lookup, the FBB of the decision support system for the ELV requirements include that the VIN should be a possible input, and up to 500 data requests have to be supported daily.

Evaluating the requirements and components for the implementation of data exchange scenarios was identified (analysis of status quo, step No. 11) and specified. Evaluation of the usage of shared components of Catena-X was performed, as they need to cope with data sovereignty requirements, data model formats, and further boundary conditions. The lookup of the DT was, for example, solved by the usage of the application programming interface (API) of the DT registry configured in Catena-X based on the Asset Administration Shell (AAS) standard of the international DT association (IDTA). As specified at the time of writing, this component diagram is depicted in a reduced form in Figure 6.

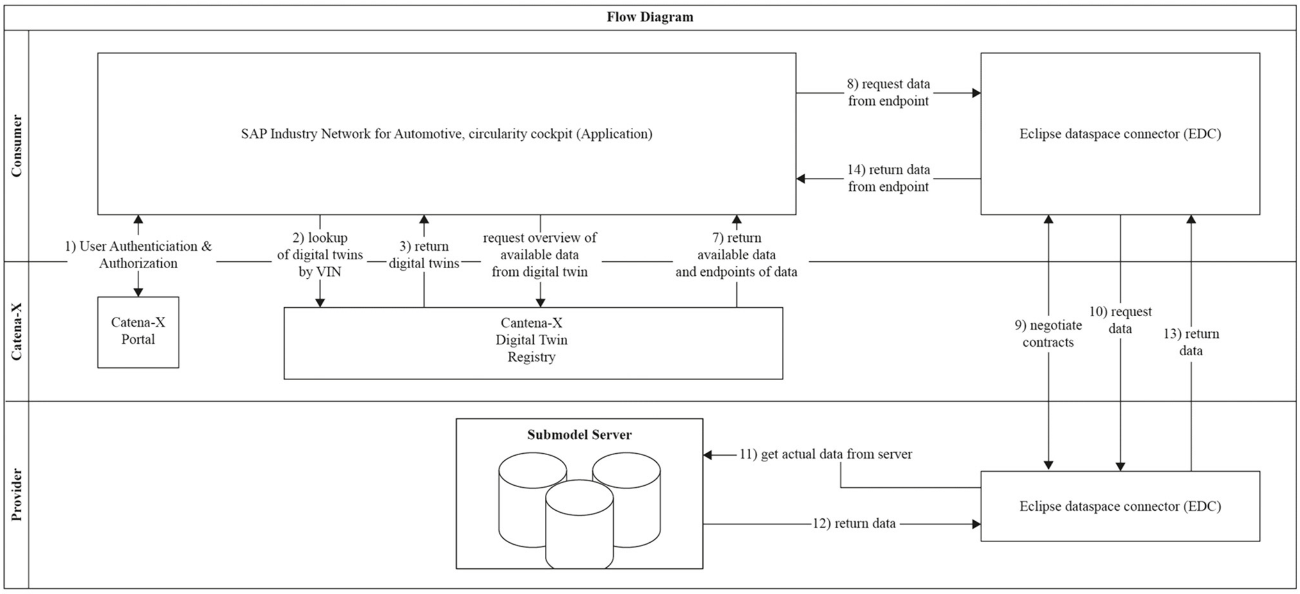

Figure 6. Component diagram of decision support system for End-of-Life Vehicle specification in reduced form.

The diagram in Figure 6 depicts lanes for the environment of:

- a data consumer, i.e., somebody using the decision support system for an ELV to get decision support for buying the right components;
- a data provider, i.e., somebody who has information on the materials used in a vehicle
- Catena-X as network and aggregation of shared components.

The components included the EDC specified by Gaia-X and configured for Catena-X for both the consumer and provider, a currentl central DT registry containing information on all twins registered in Catena-X, the Catena-X Portal as the identity data provider, and a submodel server where the actual data, e.g., on the material, was stored (see Section 4.1).

The actual interactions between the components in the form of API calls and exchanged data were described in one or multiple sequence diagrams. These sequence diagrams were used for the technical specification of the data exchange between applications, e.g., as standardization documents for other applications that want to exchange data. Given that these diagrams go mainly into the technical details of the specific component APIs, these are not published within this article. However, standardization is one major objective of Catena-X, and a publication of standardized APIs is to be expected.

4.4. System Architecture Definition

As part of the system architecture definition, the basic architectural components of Catena-X were used (step No.12). The data provider and data consumer can either be companies with their own Identity Access Management (IAM) applications or SEMs, who can use shared services by Catena-X. These services are depicted in the middle of the Figure 7 as part of the "federated operating environment" and offer the registration of DTs, a unified interface for the application usage, and contracting. The exchange of operational data was executed via EDC and between the partners directly so that the Catena-X network mainly functioned as an enabler.

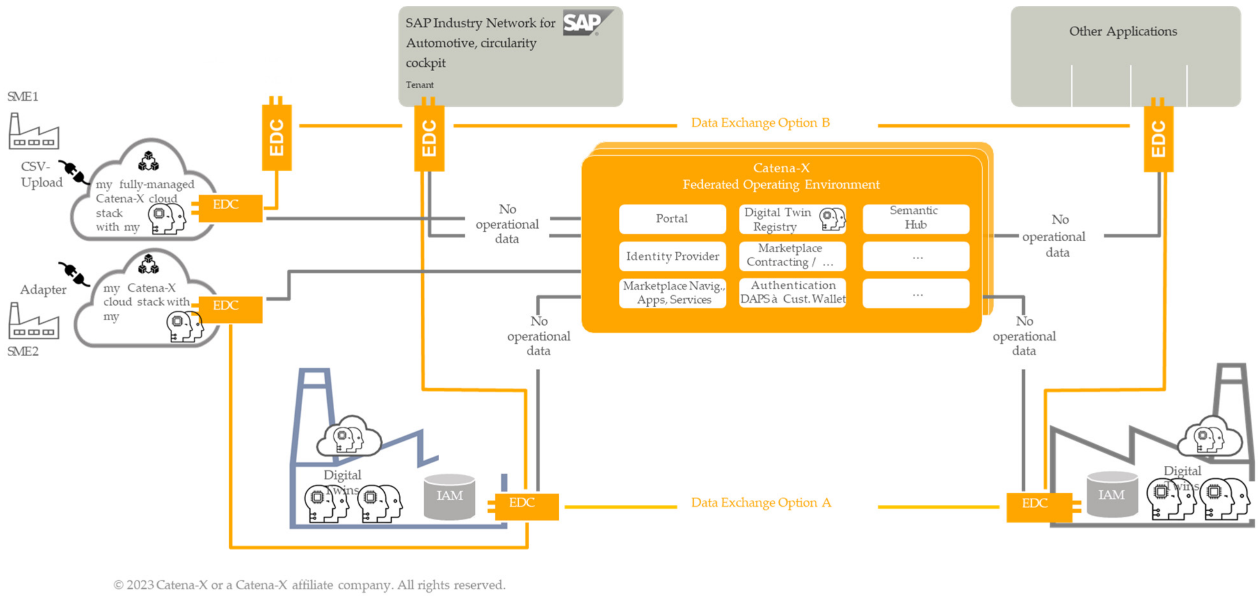

Figure 7. Overview of the data exchange within the SAP Industry Network for automotive circularity cockpit demonstrator, adapted with permission from Ref. [73].

The decision support system for an ELV, specifically, consists of the backend, which enables the usage and analysis of data provided by the Catena-X network, respectively, its partners and the frontend, and a user-friendly interface that presents data in a clear, graphical format. It aims to provide information about vehicles, their components, and materials from various stakeholders throughout the value chain.

The following steps of the definition of the UUID and DT registration (step No. 13), as well as the interface design (step No. 14) and testing steps (step No. 16–18) are explained with the exemplary implementation in the following section.

4.5. Implementation Results of the SAP Industry Network for Automotive Circularity Cockpit

As an implementation partner, the SAP has developed the decision support system for ELVs into a project demonstrator (SAP Industry Network for Automotive, circularity cockpit, short circularity cockpit) that reflects these concepts and presents the data in a clear graphical format (step No. 15). The demonstrator focuses on purchasing an ELV and its eventual scrapping at a dismantling company. The emphasis is on the responsibilities of the vehicle purchaser and the dismantling lead. In the following, two screenshots of the circularity cockpit are shown as examples.

Step 1—Vehicle lookup: Via the search input field, the vehicle purchaser uses the circularity cockpit to check the DT of the ELV by entering its VIN. This can be seen in

Figure 8. This provides the vehicle purchaser with a range of general information about the vehicle, including its model, variant, manufacturer, fuel type, production date, engine size, and mileage, which can be used to verify the information provided by the vendor. The purchaser can also access a more detailed view of the car's information if needed.

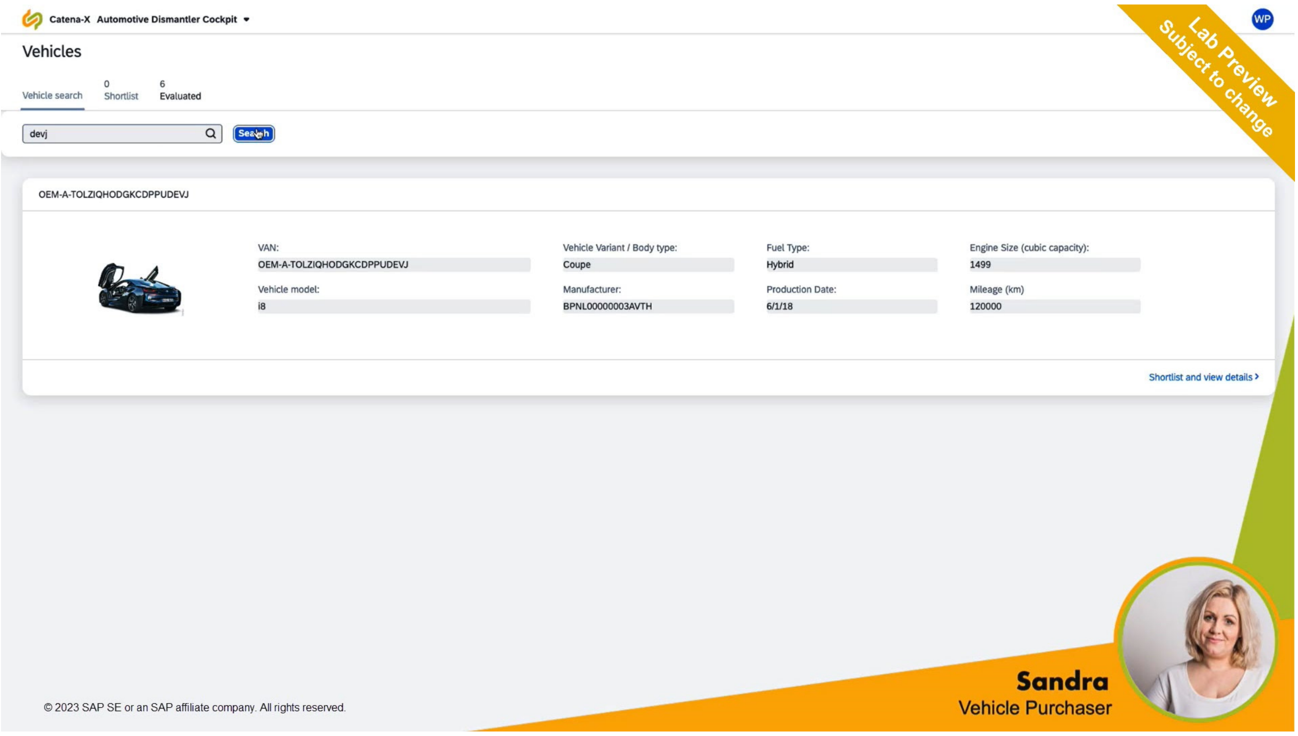

Figure 8. Display of Step 1—vehicle lookup in the circularity cockpit.

Step 2—Decision on purchasing the vehicle: The circularity cockpit presents the vehicle purchaser with a list of the ELV's most valuable components and their potential value in the after-sales market. The cockpit also displays demand for a specific component through return requests and provides current market prices for each component, thereby helping the vehicle purchaser make an informed decision on purchasing the vehicle. This is illustrated in Figure 9.

Step 3—Vehicle is purchased: The vehicle purchaser records the purchase decision in the circularity cockpit by entering their reasoning for purchasing the vehicle, along with any additional information such as the vehicle's roadworthiness, location, and completeness.

Step 4—Component and material lookup: Upon arrival at the dismantler's yard, the dismantling lead can assess the potential for selling an ELV by entering its VIN into the circularity cockpit. This provides a table view with information on the purchase decision, the latest updates, and additional comments, thereby giving the dismantling lead an understanding of why the vehicle was acquired.

Step 5—Decision on dismantling components: The dismantling lead has access to a comprehensive view of the vehicle's components and materials, along with information on its health status, such as age and mileage, and the effort required to dismantle it, such as instructions and legal requirements. The dismantling lead can also consult tabs for detailed information, market price, and documents to decide which components to dismantle.

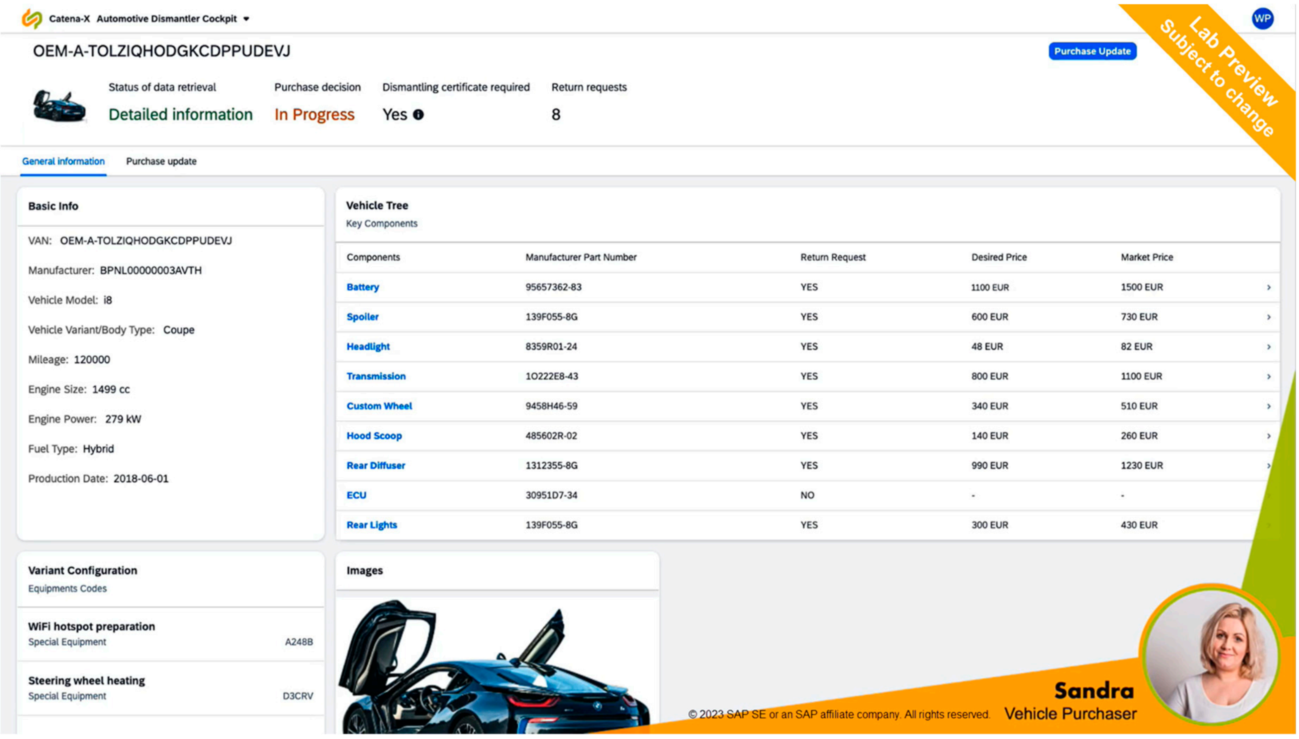

Figure 9. Display of Step 2—decision on purchasing the vehicle in the circularity cockpit.

4.6. Customer Feedback

The customer feedback (step No.18) was conducted as part of the CE business domain. This involved the review of the user journey by the end users who also tested the application from a user-acceptance perspective. The goal was to improve their understanding (pain points, needs, environments, capabilities). The customer feedback involved 6 companies throughout the value chain, 40 participants in the end user test execution day, and a technical integration of an external partner. Learning from the customer feedback flows back into the agile development process of the SAP solution and is not explicitly mentioned in this paper. In general, 8 out of 10 end users gave feedback that they would like to use the tested journey in real life. Furthermore, the end users wished to conduct further case studies to consider the usage policies.

The testing showed that DTs can help to provide information about the vehicle, the components, and the materials, as well as provide the relevant stakeholders with the relevant information transparency about the product life cycle. Individual stakeholders have unique information needs, so it is inevitable to involve future stakeholders in the data exchange process. Other stakeholders that might be relevant to enable the CE are shredders and recyclers. For example, the dismantling lead needs more detailed vehicle information than the vehicle purchaser. In contrast, the vehicle purchaser must estimate the total value of the potential vehicle. The first customer feedback showed that the decision support system for the ELV not only supported the purchaser's decision-making process, but also supported the dismantling lead by providing more specific data on components and vehicles. Herein, digital technologies such as the DT can be used to provide instance-specific data. This provides a data-based decision support system that supports various stakeholders throughout the product life cycle, regardless of their experience. However, it must be added that the validation took place within the consortium of Catena-X and an external partner and that widespread validation took place.

5. Final Remarks

Within Catena-X, the data exchange for a decision support system for ELVs was developed by the specification team, implemented by SAP in an initial demonstrator, and then evaluated by end users in a case study. The main limitations of the development process lie in the restricted availability of real data, especially from the use phase of vehicles and from partners outside of the development project. Also, user testing was focused on the representatives from the participating application partner. This might lead to a restricted list of requirements and a bias with regard to the added value. Therefore, broad user testing should be conducted in the future. Also, the development was solely focused on the German perspective of dismantling. It should be extended to European or even worldwide application. In total, there are 13.000 authorized dismantlers in Europe who can benefit from the decision support tool and who are suitable as end-users for testing [75]. With the help of the decision support tool, the dismantler can make a more informed decision about the ELV dismantling. The provided information enables a classification of the vehicle as a spare part or material carrier. At the same time, the dismantler can identify high-value components for resale, restock internal inventories, and react to the current market situation. The results showed feasible approaches to integrate CE-relevant aspects from Catena-X into a decision support system. On this basis, further APIs currently standardized within Catena-X can be integrated to offer even more CE-relevant functionalities, such as visualizing battery passes or calculating PCF values and the estimated rest of life of components.

Sharing data and information using DTs across companies results in challenges regarding data sovereignty and legal requirements. Furthermore, many suppliers in the automotive industry are uncertain about the added value of sharing their data and rate the risk of data loss or negative consequences as high. Competition-related data is often not shared across companies to avoid losses in competitive advantages. Therefore, data providers need to stay in control of their data and its use. Therefore, usage policies can be defined in the Catena-X network for each data asset. They specify the access of data and information (access policies) and on what conditions they are allowed to be used (usage policies). These policies can be integrated with the EDC, which enables secure and sustainable peer-to-peer data exchange that is decentralized and interoperable. The EDC implements a framework agreement for sovereign, inter-organizational data exchange. Therein, it is designed to be extensible to support alternative protocols and to be integrated into different ecosystems.

Other challenges need to be addressed to use DTs for the collection and management of data across the product lifecycle. The required data is usually scattered across multiple databases, applications, and companies. In order to exchange the data, standardized data models must be developed in Catena-X. Also, standardization is one major objective of Catena-X and a publication of standardized APIs is to be expected.

For further research, it is necessary to evaluate the CE requirements for the decision support system for ELVs and harmonize them with the IT infrastructure on the data consumer side. This is essential to ensure that the data generated by these systems can be effectively managed, processed, and shared in a manner that is both sustainable and compliant with data governance regulations. By harmonizing the CE requirements with the IT infrastructure, decision makers can make informed decisions that promote sustainable practices while effectively managing data throughout the vehicle's lifecycle. This includes, for example, standardized components, APIs, and data models.

The decision support system should be provided with more detailed product, component, and material information. Furthermore, it is possible to define standardized KPIs that enable evaluation and optimization throughout several life cycles of components and materials and to recommend, such as a CE strategy for secondary components. This decision should be recommended for the most economical, environmentally friendly, and socially responsible CE strategy. Examples of possible standardized KPIs are environmental KPIs of EoL strategies, such as CO_2 footprint of EoL treatment, recycling and remanufacturing process kg CO_2 eq. avoided during remanufacturing, or kg CO_2 eq. avoided during raw material extraction [70,71]. Further examples on the component level are the remaining lifetime, the basic reuse potential, or the degree of damage [52,56]. Societal KPIs can be exposure to hazardous materials or compliance with legislation [52,70,71]. Economic KPIs can be market demand or revenue selling potential [52,71]. For this purpose, methods of life cycle costs and life cycle assessment can be used, which are based on methods of a life cycle approach [70,71].

To finally close the loop of the material flow, a trading platform for secondary components or materials is needed (marketplace). The trading platform is essential to match the demand and supply of secondary materials and components effectively by providing transparency on their availability. By doing so, stakeholders in the automotive aftermarket are offered new selling channels and can access a wider range of products and materials. A close connection between the decision support system and the trading platform may further ease the CE practice. The standardization of calculation logic and data provision to assess the economic and ecological impact of products and processes described in the decision support system can be implemented in the trading platform. The standardization of calculation logic can also help to promote transparency and accountability in the trading platform.

Overall, both tools should be extended to other industry network approaches and need to be applicable within global networks, i.e., they need to consider different regulations and industry challenges. CE-based digital solutions will only be successful if cross-application, cross-domain, and cross-company thinking is established along the value chains.

To summarize, the following core findings can be highlighted:

- Application development should be developed and driven by user demand and focused on data and information demand for individual vehicles or product types;
- The standardization of APIs and data models is a key factor for scaling cross-company data exchange, which is independent from applications and company specific characteristics;
- Technological solutions need to implement mechanisms for contract negotiation and usage policies from the data provider perspective;
- The data provisioning at companies needs to be enabled by preparing data and the respective IT-system architecture for providing the defined data models;
- The data consumer side needs to be integrated with the applications and should allow an effective use of the provided data, e.g., by automatically integrating it within current processes;
- There is a need to integrate the environmental impacts of different R-strategies (PCF or CO_2 footprint);
- Decisions on CE strategies should consider the economical perspective, the environmental impact, and social responsibility;
- To support a closed material flow, a trading platform for secondary components and material should be developed;
- The consideration of a European and global perspective, i.e., regulations and material demand, is necessary to scale the CE.

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