Digital Twins for Circular Economy

Enabling Decision Support for R-Strategies

Janine Mügge, Inka Rebekka Hahn, Theresa Riedelsheimer, Fraunhofer IPK
und Johannes Chatzis, tec4U-Ingenieurgesellschaft mbH

Digitale Zwillinge für die Kreislaufwirtschaft – Entscheidungsunterstützung für R-Strategien

Als Teil des digitalen Datenökosystems bieten Digitale Zwillinge (DT) für die Kreislaufwirtschaft (CE) einen vielversprechenden Ansatz für eine nachhaltigere Wertschöpfung. Durch die Analyse und Aufbereitung von produkt-, bauteil- und materialspezifischen Daten entlang des Lebenszyklus ist es möglich, aktuelle Herausforderungen wie Klimawandel und Ressourcenknappheit zu adressieren. Im deutschen Forschungsprojekt Catena-X werden auf Basis dieser unternehmensübergreifend ausgetauschten Daten und Informationen konkrete Lösungen entwickelt. In diesem Rahmen wird der„R-Strategie Assistent" vorgestellt. Dabei handelt es sich um eine Anwendung, die auf Basis von DT-Daten die beste CE-Strategie am Ende des Lebenszyklus eines Fahrzeugs ermittelt.

Schlüsselwörter:

Digitaler Zwilling, Kreislaufwirtschaft, Digitalisierung, Catena-X

Janine Mügge arbeitet als wissenschaftliche Mitarbeiterin am Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK in der Abteilung Nachhaltige Produkt-Ökosysteme.

Inka Rebekka Hahn arbeitet als wissenschaftliche Hilfskraft am Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK, Abteilung Nachhaltige Produkt-Ökosysteme.

Theresa Riedelsheimer leitet die Abteilung Nachhaltige Produkt-Ökosysteme am Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK.

Johannes Chatzis ist Geschäftsführer der tec4U-Ingenieurgesellschaft mbH und verantwortet unter anderem den Bereich Produkt Compliance und das IDIS Projekt (International Dismantling Information System).

theresa.riedelsheimer@ipk.fraunhofer.de
www.ipk.fraunhofer.de

Digital twins (DT) for circular economy (CE) offer a promising approach as part of digital data ecosystems for more sustainable value creation. By mapping and analyzing product, component and material specific data along the lifecycle, it is possible to address current challenges such as climate change and resource scarcity. Within Catena-X, specific solutions based on this cross-company exchanged data and information are developed. Here, the "R-Strategy Assistant" is presented. It is an application, which identifies the best CE-Strategy based on DT data at the end of a vehicle's life.

The topic of sustainable value creation has become increasingly important in the last few years and is now an indispensable goal of national and international business. With the EU Green Deal and the UN Sustainable Developments Goals, the vision of a greenhouse gas-neutral and resource-efficient economy is already firmly anchored in politics [1]. As one of many industries, the automotive industry is forced to adapt to increasing scarcity of natural resources and the growing demand for sustainability. The End-of-Life Vehicles (ELV) Directive 2000/53/EC regulates ELV by setting clear targets on reuse, recycling and recovering within the European Union [2]. To reduce the environmental impact along the whole lifecycle of a vehicle, the cooperation of all stakeholders along the value chain is inevitable. In the research project Catena-X 28 partners currently address secure cross-company data exchange, circular economy (CE) and digital twins (DT) under the banner of data sovereignty [3]. The concept of a DT for CE is a promising approach to build a data-driven ecosystem based on vehicle, component and material specific information, opening up new business and value creation models from SMEs to large corporations with the goal of using resources as efficiently as possible [3]. In Germany alone, there are about 50 million registered vehicles, of which around 500,000 ELV arrive at the dismantler yard each year. These vehicles offer the potential to reuse and recycle components [4].

In Catena-X, various stakeholders throughout the automotive value chain have been methodically interviewed, that represent supplier of material as well as automotive components, an OEM and a dismantling company. The results show that they all face the challenge to reach an informed and environmentally sound decision on the best strategy to implement CE:

- they do not have access to existing data on the relevant Key-Performance-Indicators (KPI) for CE from the actual lifecycle of components or assets,
- there is no standardized calculation logic to determine the best CE-Strategy option based on these KPI considering the individual KPIs for different components or material,
- there is no platform or network for exchanging and managing the necessary data and information across companies and lifecycle phases.

Therefore, as one specific application, the R-Strategy Assistant - a decision support tool regarding possible CE-Strategies of an ELV – is being developed within Catena-X.

Circular Economy and R-Strategies

CE is an economic model that – in its most narrow sense - pursues the goal of acting in a resource-conserving manner by extending the product life

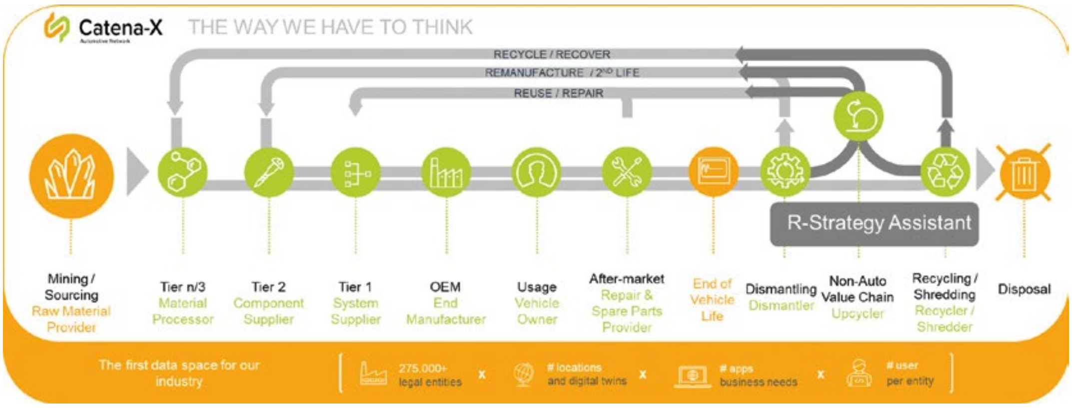

Figure 1: R-Strategy Assistant within the automotive lifecycle.

and returning components and materials to the cycle at the end of their life [5]. In practice, this means that discarded products are reused or recycled, minimizing waste and requiring fewer natural resources to make new products [5]. In a broader sense, there are several strategies that address different phases of the product life cycle. Referring to the 9R-Framework these are recover, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink and refuse – ranging from low to high circularity. A higher degree of CE means that materials stay in the loop longer and fewer resources are needed to keep materials in the loop [6]. In general, the choice of the most environmentally and economically sound CE-Strategy depends upon a large number of different factors, where some are globally applicable and some are highly individual depending on the specific vehicle or component. In the context of the R-Strategy Assistant, it is referred to Potting's 9R framework, shortened R-Strategies.

Digital Twins

To understand individual instances of vehicles or components, the concept of DT comes into play. There are several definitions of DT in different application environments. The Catena-X consortia refers to the Industrial Digital Twin Association and defines the DT as a virtual representation of assets and adheres to a set of characteristics [7, 8]:

- The DT has at least one Catena-X-wide unique ID.
- DT are organized by a set of aspects, which can be extended over lifetime.
- An aspect of a DT includes structural as well as behavioral data and models.
- The semantics of an aspect can be described via semantic models.
- 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 including (e. g. planning phase, production, sales, use and decommissioning phase). However, in practice there may be more than one twin with different IDs representing different lifecycle phases (e. g. a twin for types and multiple twins for instances).
- An asset can have more than one DT and they can reference each other.
- DT can provide individual asset and fleet-related knowledge.

Moreover, DT can help to decrease the environmental impact of assets by optimizing the asset itself and thus reducing the CO_2 footprint [9]. Furthermore, DT can address resource-efficient manufacturing of the product and uncover reuse potentials at the end of the asset's life, thereby supporting CE [10, 11].

How do Digital Twins foster Circular Economy?

One prerequisite for CE is to enable all stakeholders within the product life cycle to make qualified decisions based on data related to the product or asset at any stage. The advancing digitalization of the supply chain and the concept of DT can help to untie the complexity of this task [11].

CE considerations start already at the design, development and production phases before bringing the product into the market [9, 11, 12]. Here, the application of a DT supports inter alia the evaluation and simulation of the recyclability of a product, increases the resource efficiency of the production or just evaluates current and future product compliance in relation to e. g. regulated substances as substances of very high concern that might influence future reuse or recycling. In the use phase it is essential to keep the DT up-to-date to ensure qualified decisions for the further product life. By mapping the physical instance of an asset with its DT,

KPI	Description
Remaining Lifetime	Remaining Lifetime depends on how the vehicle was used (city traffic vs. highway) and the component specific lifetime.
Quality	Quality defines the state of health of a component e.g. paint damages, dents, corrosion.
Material Composition	Material Composition includes the type of (forbidden) material and the percentages per kg.
Exclusion List	Exclusion list includes components that may not be reused, such as the airbag.
Disassembly Capability	Disassembly Capability checks on whether it is fulfilled for the respective R-Strategy, e.g. non-destructive disassembly possible.
Cleanability	Cleanability checks on whether a component can be cleaned (important for remanufacturing).
Assemblability	Assemblability checks on the possibility to reassemble the component (important for remanufacturing).
Restorability/Upgradability	Restorability/Upgradability checks on the possibility to update the component (important for remanufacturing).
Designed for Recycling	Designed for Recycling means whether the vehicle is designed from the beginning-of-life for the R-Strategies at the end-of-life.

Figure 2: Key-Performance-Indicators of the technical viability for the R-Strategy-Assistant.

operational data as operating hours, failures, maintenance and similar events enable informed decisions on the potential end-of-life (EoL) of a product, e. g. if and when a remanufacturing is economically feasible, a reuse possible or the material recycle the most valuable solution [13].

If a second life strategy as remanufacturing or reuse is no longer feasible, the DT provides essential information on the material break down of the product, its ingredients and composition [14]. Upcoming regulatory requirements, such as the mandatory use of recycled content in polymers and other materials, will increase the need of detailed and more accurate material information as provided by a DT to be able to distinguish between recycled and non-recycled material [15-18].

Why Catena-X?

CE requires data, but the availability of data depends on the connectivity throughout the complete supply chain [19]. Therefore, the objective of Catena-X is to provide the infrastructure for a decentralized end-to-end connectivity and to enable the digital flow of information across the entire supply chain. The development of Catena-X is done within 10 use cases, where some focus on the needed infrastructure and shared services, and others concentrate on practical applications. The use case CE is demonstrating the capabilities of Catena-X by using the achievements of the other use cases to develop innovative solutions that address current and future environmental issues. Besides the R-Strategy Assistant , solutions like a dashboard to support dismantling decisions for authorised treatment facilities and a marketplace as cross-industry trading platform for components and raw materials are already on the way [3].

While the equal and decentralised data structures foster competition on application level, the benefits of interoperability within the network and among the applications prevail. Hereby, the R-Strategy Assistant plays a key role as information provider and analytical resource for CE. By recommending the most feasible treatment strategy for components and complete vehicles it supports the sound treatment of ELVs through the dismantling dashboard, either through naming the most valuable parts for dismantling and reuse or indicating material recycling as the best solution, economically and environmentally. Furthermore, it helps to evaluate components and raw materials for the marketplace, by considering their life cycle events, their material composition and considerable further ingredients as regulated substances of very high concern that influence the further use of the raw material [3].

R-Strategy-Assistant

The R-Strategy Assistant provides a data-based decision support logic for the most economically and environmentally sound R-Strategy. It supports different stakeholders along the product lifecycle regardless of their experience. For the development, a user centered approach is applied, so that the future user or data consumer is the main starting point. In the initial phase of the R-Strategy Assistant, the role of dismantling lead is considered as well as the vehicle developer at the OEM as a first step, focusing on component and material

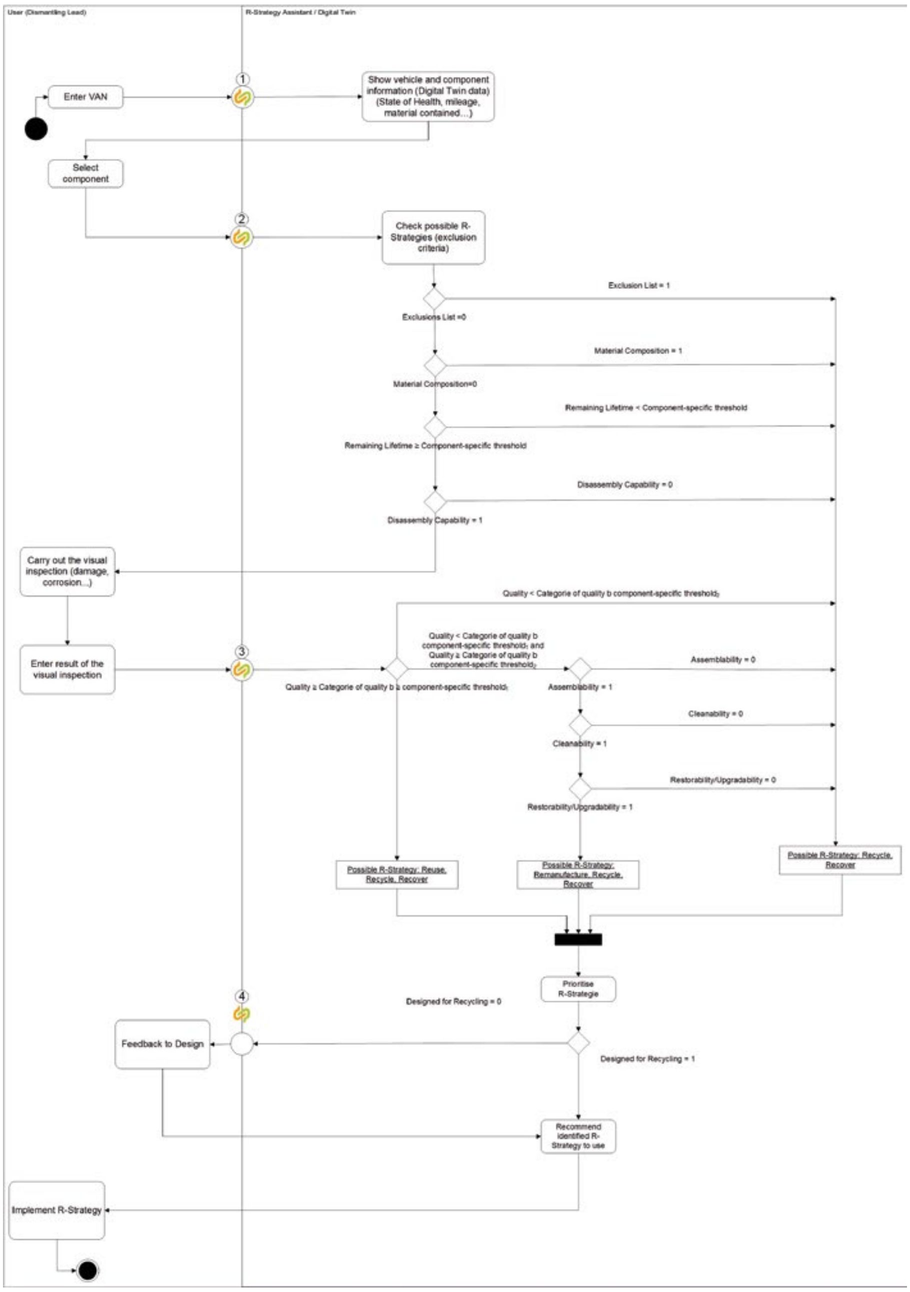

Figure 3: Activity diagram of the/regarding the technical feasibility in UML.

suppliers as a second step. The dismantling lead's goal is to decide on the best R-Strategy for each specific ELV. This is where instance-based data is critical. The developer on the other hand wants feedback on the planned R-Strategies of ELV at the fleet level of several assets.

Figure 1 shows the application of the R-Strategy Assistant within the automotive lifecycle and the main stakeholders involved. The current focus lies on the technical feasibility of the R-Strategies: Reuse, Remanufacture, Recycle and Recover.

The selection of the best R-Strategy depends on many KPI, which have been identified within Catena-X with experts and described in Figure 2.

Figure 3 shows the individual steps of the decision logic for evaluating technical feasibility.

The vehicle-specific VAN (without personal data) entered into the R-Strategy Assistant triggers the Catena-X data request (see No. 1 in Figure 3). On the basis of registered companies as data providers in the Catena-X network and the registration of assets and respective sub-models, vehicle specific data can be requested. The Catena-X shared services execute the search for existing data models, the contracting, access control and ultimately, the data provision while ensuring data sovereignty. The R-Strategy Assistant then shows first information, such as corresponding vehicle, component and material based on data from the DT. After that, the user selects a specific component and requests detailed information via Catena-X (see No. 2 in Figure 3). The decision

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logic is applied for this component and the possible R-Strategies are identified. This means in a chronological order: Exclusion list, material composition and resulting remaining lifetime in comparison with the specific thresholds and the disassembly capability. If the component does not fulfill one or more of these criteria, it can only be assigned to recovery or recycling at this point. If there is the possibility of disassembly, a manual visual inspection is now carried out and the results are entered into the system by the user. Here, the data can also be provided in the Catena-X network as an update of the DT (see No. 3 in Figure 3). The R-Strategy Assistant subsequently conducts a quality comparison with the corresponding component-specific threshold values. Depending on the outcome of this comparison, assemblability, cleanability and restorability/upgradeability are checked, if necessary, in order to technically check remanufacturing if the quality is not sufficient for reuse.

The result, the possible R-Strategies, can be provided via the Catena-X network to e. g. enable feedback to design (see No. 4 in Figure 3).

Conclusion & Outlook

DT for CE as a holistic approach to an open and digital data ecosystem in the automotive industry offers promising answers to sustainably change value creation. A DT for CE provides the opportunity to transparently represent supply chains and to build an end-to-end and standardized data network across value chains. By leveraging and analyzing existing ecological data into valuable information along the product lifecycle, new business and value creation models can be created. The R-Strategy Assistant provides a conceptual framework for the decision logic for a DT for CE by identifying relevant KPI and incorporating them into the decision logic. The key objectives of the R-Strategy Assistant is to make an informed decision regarding the possible R-Strategy for ELV, minimizing the risk for inefficiencies. This will enable even inexperienced dismantlers to make a standardized, transparent decision based on relevant CE KPI with the help of the DT. In regard to the variety of different influencing factors, the framework was only deliberately based on technical feasibility. Furthermore, the decision logic should be extended to the economic implementation in the next step. For this purpose, the developed framework should be considered as a starting point, which needs to be further detailed with the findings from the validation of real data, the inclusion of all R-Strategies and future research. In this context, it should also be defined how the feedback resulting from the exploitation process can be fed back to the development department.

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