

Towards a Smart Circular Ecosystem in the Automotive Industry: The Role of Data and Digital Technologies

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Abstract

As the automotive industry transitions toward circularity, smart circular ecosystems become essential for coordinating strategies across the vehicle lifecycle. Using a design science research approach, this study identifies the key actors, data flows, and digital technologies that enable such ecosystems. The results reveal a complex ecosystem of 31 actors interconnected through material, financial, and data flows, with data exchanges being particularly intensive for slowing resource loops during the middle of life phase, which involves the greatest number of actors and transactions. The study highlights the critical role of digital technologies and interoperable digital infrastructures in facilitating data collection, storage, analysis, and application to support circular strategies across all product lifecycle phases. A conceptual model is proposed that integrates principal ecosystem components, emphasizing key actors, technologies, and data flows. By providing theoretical insights and practical guidance for implementing circular strategies in the automotive sector using digital technologies, this study advances understanding of how circular ecosystems can be effectively orchestrated, emphasizes the critical role of data governance, and addresses the coordination challenges inherent in multi-actor, cross-organizational settings within the emerging smart circular economy field.

Keywords Smart Circular Economy · Circular Ecosystem · Digitalization · Data · Digital Technologies · Automotive Industry

1. Introduction

The automotive industry faces significant challenges due to material shortages and supply chain disruptions (IMF, 2025; Jadhav & Prakash, 2024). As one of the world's most resource-intensive sectors, its strong dependency on raw materials (European Commission, 2025; van Dam & Bakker, 2024), and substantial environmental impacts (UNEP, 2019) highlight the need for circular economy (CE) transformation. In 2023, private vehicles accounted for more than 25 percent of the world's oil consumption and contributed to approximately 10 percent of the CO₂ emissions related to global energy use (IEA, 2023). Simultaneously, the disruptive transition from combustion to electric engines necessitates a comprehensive reevaluation of the entire lifecycle of cars. This involves reconfiguring complex value chains, considering new ownership models, enhancing collaboration with stakeholders, and leveraging technologies like blockchain (Du et al., 2025). Current CE efforts in the automotive industry, however, remain predominantly focused on recyclability rather than on value-preserving strategies such as reuse, repair or remanufacturing (Prochatzki et al., 2023), indicating a misalignment between CE objectives and implementation (Mihai, 2025). Addressing these challenges requires actors to narrow, slow, and close resource loops through coordinated action within smart circular

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ecosystems. In this study, smart circular ecosystems are defined as digitally enabled, multi-actor networks that implement circular strategies and practices across the product lifecycle and enable collaboration, knowledge exchange, and value creation among a diverse set of actors (Aryee et al., 2025; Bressanelli et al., 2022). Thus, circularity requires companies to rethink value creation and operations through a holistic approach that connects organizational actors across traditional boundaries (Aryee et al., 2025; Barquete et al., 2022; Trevisan et al., 2022). Yet, research on business ecosystem collaboration to advance CE objectives remains limited (Aryee et al., 2025; Bressanelli et al., 2022; Konietzko et al., 2020), particularly in the automotive sector (Valladares Montemayor & Chanda, 2023).

Effective collaboration within circular ecosystems relies fundamentally on information sharing, coordinated activities, and mutual trust across organizations (Araujo et al., 2025). Digital technologies facilitate this transition by enabling trustworthy data exchange and enhancing supply chain transparency (Bressanelli et al., 2022; Bühler et al., 2025b; Franzò et al., 2025; Schallmo et al., 2025). Nevertheless, systematic exploration of digital technologies within circular ecosystems remains insufficiently explored (Alcayaga & Hansen, 2025). The emerging Smart Circular Economy (SCE) field is still in the process of incorporating established methodologies from related disciplines to strengthen its theoretical foundations and develop integrated approaches connecting CE principles, digital technologies, and business ecosystem dynamics (Corvellec et al., 2022; Kanda, 2023; Khan et al., 2024). Finally, existing circular ecosystem research has neglected the automotive industry (Aryee et al., 2025), despite its economic and ecological significance.

This study aims to identify key components of a smart circular business ecosystem in the automotive sector. The Design Science Research (DSR) methodology (Peffer et al., 2007) is employed to develop an ecosystem model for SCE guided by the overarching research question: Which actors, data types, and digital technologies are critical within a circular automotive ecosystem, and how do these elements interact? To answer this question, the study examines data flows among ecosystem participants and the role of digital technologies in facilitating data collection, storage, analysis, and application for circular strategies. Data are collected through focus group sessions (Tremblay et al., 2010) and expert interviews (Gläser & Laudel, 2010), with template analysis (King et al., 2015) applied for data interpretation and e3-value notation used for visual modeling.

This study makes several theoretical contributions by exploring SCE through an ecosystem lens, integrating perspectives on digitalization, data, and circularity, and introducing a novel instantiation of the ecosystem framework by Adner (2017) to present an ideal SCE ecosystem model, thereby addressing gaps in existing SCE research. From a practical perspective, the study provides guidance for managers and practitioners in the automotive sector on implementing circular strategies, clarifying the roles of key actors, data flows, and digital technologies.

The remainder of this study is structured as follows: Section 2 establishes the theoretical framework. Section 3 explains the research design, while Section 4 presents the findings, focusing on the identified ecosystem actors, data transactions, and digital technologies. Section 5 offers a discussion of the results where the empirical findings are interpreted, and corresponding propositions are articulated. Finally, in Section 6, the theoretical contributions, managerial implications, limitations, and directions for future research are presented.

2. Theoretical Background

2.1. Smart Circular Economy

The concept of a CE is centered on improving the efficiency and productivity of products, materials, and processes to foster sustainable development. It is recognized for its ability to prevent, reduce, and reverse the loss and destruction of value, such as by decreasing emissions, reducing pollution, and alleviating biodiversity and habitat loss associated with resource extraction (EMF, 2015). CE is investigated using interconnected levels (Kirchherr et al., 2017; Saidani et al., 2017): nano (product, component, material), micro (company, business model), meso (business ecosystem, industry network, sector), and macro (city, region, nation and beyond). This study focuses on the meso level by defining the elements of a smart circular ecosystem in the automotive industry (Aryee et al., 2025).

Prominent CE concepts encompass the 9R-framework (Potting et al., 2017), the ReSOLVE framework (EMF, 2015), and the circular strategies by Konietzko et al. (2020). These frameworks offer structured methodologies for applying CE principles and often exhibit similar strategies. The ReSOLVE framework

transfers CE principles into six actions for businesses: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange, offering a practical lens for operationalizing CE-principles in industry. Due to their high visibility and applicability, this study employs the 9R-Framework and the circular strategies by Konietzko et al. (2020) to describe circular strategies identified within circular ecosystems. The 9R framework prioritizes strategies according to their circularity potential: efficient production and utilization (R0-R2) offer the highest potential, followed by extending product life (R3-R7), while material recovery (R8-R9) ranks lowest, as it typically involves quality and material losses or eliminates future use (Potting et al., 2017). These strategies align with circular approaches across the product lifecycle: **narrowing** loops through Refuse, Rethink, and Reduce (R0-R2), mostly during the beginning of life (BoL) phase of a product; **slowing** loops via Reuse, Repair, Refurbish, Remanufacture, and Repurpose (R3-R7) during middle of life (MoL); and **closing** loops through Recycle and Recover (R8-R9) at a product's the end of life (EoL) (Konietzko et al., 2020; Li et al., 2015). In the automotive industry, companies increasingly emphasize R0-R2 by innovating mobility concepts (e.g. shared and subscription models), rethinking ownership, and designing vehicles with reduced primary material input and higher efficiency (e.g. BMW, 2025; Polestar, 2025). Extending vehicle life remains equally critical, with design for and execution of reuse, repair, refurbishment, and remanufacturing enabling longer use and component circulation (Martins et al., 2021). Across all strategies, data and digital technologies play a key role by **informing** the loop (Konietzko et al., 2020), supporting the execution of all circular strategies. The circular concepts introduced here are synthesized in a tabular format in the Results section.

To highlight the essential role of digital technologies in achieving a CE, this study is situated within the SCE research domain, as defined by Bressanelli et al. (2022, p. 9): “an industrial system that uses digital technologies during the product lifecycle phases to implement circular strategies and practices, aiming at value creation through increased environmental, social, and economic performance.” Digital technologies offer significant potential to enhance collaboration, track resource flows, and identify complementarities across actors in circular ecosystems, addressing gaps in data collection, integration, and sharing to support circular strategies and ensure resource availability for reprocessing (Rossi & Srari, 2025). This way, digital technologies help create the information flows necessary to make resource flows more circular.

Digital technologies encompass interconnected technological advancements (Kristoffersen et al., 2020). Following Bühler et al. (2025a), a distinction is made between specific digital technologies like blockchain and digitalization concepts like digital twins, which combine several digital technologies. Both are categorized along the data value chain according to their value-adding activities: data discovery, integration, analysis, and application (Faroukhi et al., 2020). Data discovery refers to gathering and transferring data, integration to storing and organizing data, analysis to generating knowledge, and application to creating value from this knowledge (Bühler et al., 2025a). This study investigates the data flows and digital technologies (including combinations thereof, i.e. digitalization concepts) that enable circular strategies in an automotive ecosystem. For readability, the term “digital technologies” is utilized predominantly, unless specified otherwise.

2.2. Circular Ecosystems

Collaboration among actors in ecosystems is a crucial step to realize the full potential of CE. Circularity requires a rethinking of value creation and business operations, which includes a systemic perspective linking different organizations (Aryee et al., 2025; Barquete et al., 2022; Trevisan et al., 2022). Few publications address how business ecosystems (can) act to achieve common CE goals, although scholars argue that the business model perspective is too narrow to achieve higher levels of CE (Aryee et al., 2025; Bressanelli et al., 2022; Konietzko et al., 2020). The advancing use of digital technologies and the interconnectedness of industrial value networks promise new capabilities and opportunities for realizing circular ecosystems, which, however, are still insufficiently researched (Alcayaga & Hansen, 2025; Bressanelli et al., 2022; Franzò et al., 2025; Koren et al., 2023; Rossi & Srari, 2025).

This study follows the business ecosystem perspective proposed by Moore (1993, 1996), which is valuable for analyzing interconnections and co-value creation opportunities among organizations (Kanda et al., 2021; Teece, 2007). Moore (1993, 1996) argues that long-term success depends on collaboration within a suitable ecosystem, where complementary activities and resources from various actors drive co-evolution and value creation (Jacobides et al., 2018). Adner (2017) builds on Moore's work and introduces the ecosystem-as-a-structure framework, which this study applies to analyze a digitally connected, circular ecosystem. This framework focuses on the central value proposition, the necessary activities, and the coordinating actors and

their transactions, applied here to enhance circularity in the automotive sector through circular strategies, key actors, and their monetary, material and data flows. In line with the rapidly expanding research area of ecosystems in the CE, this study follows the comprehensive definition of circular ecosystems by Aryee et al. (2025, p. 7): “A circular ecosystem is a set of autonomous actors who interact through collaboration and sometimes competition to co-create value using CE strategies in an interdependent, non-hierarchical, co-evolutionary and complimentary structure.”

3. Research Design

This research employs the DSR methodology as outlined by Peffers et al. (2007), a user-centric approach commonly utilized in CE studies (Baldassarre et al., 2020; Coffay & Bocken, 2023; Das et al., 2023; Haase et al., 2025). DSR offers both practical relevance through useful artifacts and scientific rigor via design theories (Baskerville et al., 2018). It comprises four artifact types (March & Smith, 1995): constructs (concepts and vocabulary of a domain); models (constructs and their relationships); methods (processes to perform tasks); and instantiations (implementations that operationalize constructs, models, and methods). This study aims to develop a model artifact and follows these stages (Peffers et al., 2007): (1) problem identification; (2) setting solution objectives; (3) design and development; (4) demonstration; (5) evaluation; and (6) communication. The initial two steps are covered in the introduction, with this study concentrating on the third step, while the remaining steps will be conducted subsequently (figure 1). The focus is on the car body structure, a significant component with a notable environmental footprint in both battery electric (BEV) and hybrid electric vehicles (Pipitone et al., 2021). Findings are organized along the three product lifecycle stages BoL, MoL, and EoL, connecting them to circular strategies and improving the clarity of the visual model.

This study employs two complementary approaches for data collection: Focus group workshops (Tremblay et al., 2010) facilitate dynamic discussions that capture diverse viewpoints, while semi-structured expert interviews (Gläser & Laudel, 2010) provide detailed domain insights. Employing these methods ensures a thorough understanding of both collective and expert perspectives. Template analysis was applied to analyze data from focus groups and expert interviews (King et al., 2015), offering a structured, rigorous framework for organizing insights while remaining sufficiently flexible to accommodate emergent themes. Visual ecosystem models were created for each lifecycle phase using the e3-value modeling language (Gordijn & Akkermans, 2001). This method offers a comprehensive approach to modeling ecosystems by visually representing the structural elements outlined by Adner (2017), i.e. actors, activities, and transactional flows, facilitating a detailed examination of interdependencies within circular ecosystems. Digital technologies were evaluated based on their value-adding roles (Faroukhi et al., 2020) and functional characteristics (Bühler et al., 2025a).

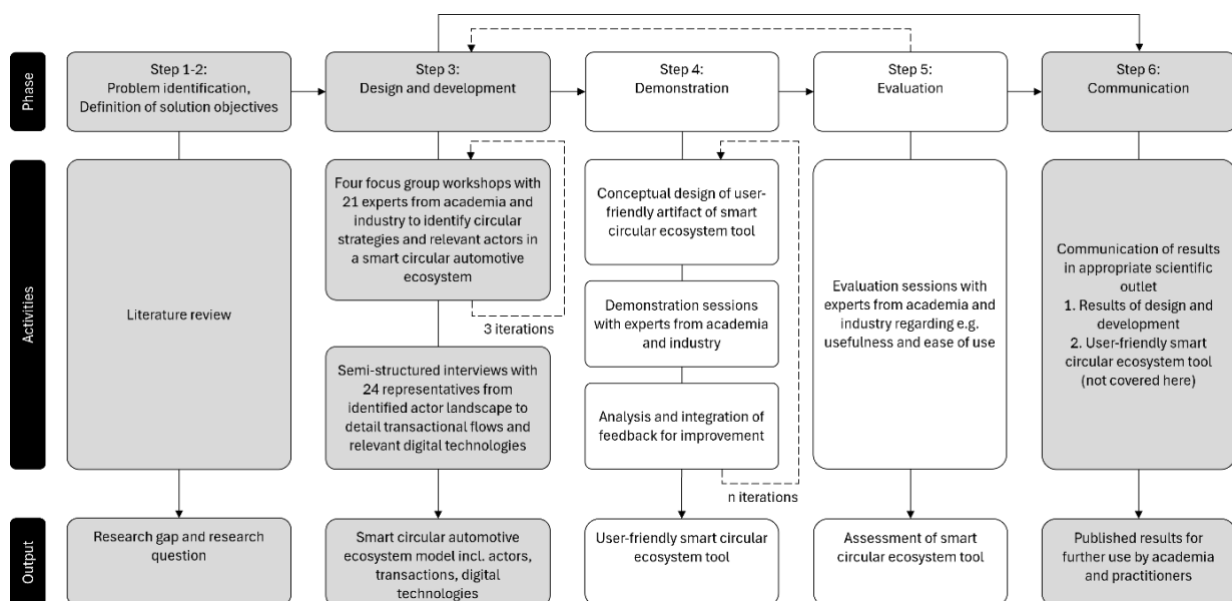


Figure 1. DSR method used in this research (adapted from Hoang and Böckel (2024), Coffay and Bocken (2023), Peffers et al. (2007); authors’ own presentation). Areas marked in gray are subject of the present study.

Collectively, these methodological choices provide a robust foundation for the interpretative statements and propositions presented in the Discussion section, explicitly connecting empirical findings to the theoretical framework, and highlighting their significance for advancing understanding of smart circular ecosystems in the automotive industry. The following subsections describe the procedure for data collection, analysis, and ecosystem modeling.

3.1. Data Collection Process

Initially, one pilot and three exploratory focus group workshops (Tremblay et al., 2010) were conducted with 21 experts from industry and academia between April and July 2024, averaging 161 minutes. Experts needed a master's degree and professional background in CE or the automotive industry with a minimum of two years' experience (table 1). Participants identified circular activities across the car body lifecycle phases and outlined necessary actors for implementation. The online workshops were recorded, transcribed, and documented using Conceptboard, with insights continuously refined through subsequent groups to maintain the DSR process.

Subsequently, semi-structured interviews were conducted with 24 experts to gather insights into transactional flows among actors and enabling technologies (Gläser & Laudel, 2010). Interviewees represented the identified actor landscape, following the same selection criteria as workshop participants (table 1). Respondents comprised representatives from internationally active German automotive manufacturers, suppliers, industry associations, recyclers, and further actors, as well as from a Ghanaian development agency and automotive cluster, one of the largest in the world. Interviews conducted between July and September 2024 averaged 66 minutes, were recorded and transcribed. The interview guide (Kallio et al., 2016) covered professional knowledge, circular strategies, key actors, transactional exchanges, and enabling technologies. Following Gläser and Laudel (2010), questions were open-ended, and the guide was tested and adapted after the first interview. The workshops and interviews provided detailed insights, with 45 participants contributing 389 years of combined experience. In total, 30.5 hours of recordings were transcribed for analysis.

Table 1. Overview of focus group workshop and interview participants (authors' own work).

#	Type of actor	Position	Data collection instance	Area of knowledge								Exp.	Dur.	
				CE	SCE	ECO	CBM	CPD	OTH	AU	MAN			
1	Knowledge / technology provider	Research assistant / Academic expert	Pilot focus group	x	x	x	x	x			x	x	5	120
2	Knowledge / technology provider	Research assistant / Academic expert	Pilot focus group	x	x	x	x					x	2	120
3	Knowledge / technology provider	Research assistant / Academic expert	Pilot focus group	x	x							x	2	120
4	Knowledge / technology provider	Student research assistant	Pilot focus group	x									2	120
5	Knowledge provider	Junior research group leader	Focus group 1	x	x	x							6	180
6	Knowledge provider	Research assistant / Academic expert	Focus group 1	x	x		x						2	180
7	Knowledge / technology provider	Group manager	Focus group 1	x				x	x				6	180
8	Knowledge provider	Research assistant	Focus group 1	x				x		x			2	180
9	Industry association	Specialist circular economy & sustainability	Focus group 2	x					x	x			10	150
10	OEM	Circular economy specialist, Design for recycling	Focus group 2	x	x		x			x			5	150
11	Knowledge / technology provider	Director automotive / Global lead sustainable mobility	Focus group 2	x	x	x	x		x	x			12	150
12	Knowledge / technology provider	Senior manager	Focus group 2	x			x		x	x	x		3	150
13	Knowledge / technology provider	Senior consultant	Focus group 2				x		x	x	x		4	150
14	Knowledge / technology provider	Project manager	Focus group 3		x						x	x	6	180
15	Knowledge provider	Academic expert	Focus group 3	x									2	180
16	Knowledge / technology provider	Group manager	Focus group 3	x									2	180
17	Industry association	Project officer / Senior manager	Focus group 3	x									4	180
18	Knowledge / technology provider	Senior consultant	Focus group 3	x			x						3	180
19	Knowledge / technology provider	Solution architect sustainable product design	Focus group 3	x				x		x			5	180
20	Industry association / Knowledge provider	Project lead battery and vehicles	Focus group 3	x		x							10	180
21	Knowledge / technology provider	Senior sustainability consultant	Focus group 3	x			x			x			6	180
22	Knowledge provider	Research assistant / Academic expert	Expert interview	x			x						3	95

Legend: **CE**: Circular Economy, **SCE**: Digitalization / Industry 4.0 / Smart CE, **ECO**: Business Ecosystems / Innovation Ecosystems, **CBM**: Circular / Sustainable Business Models, **CPD**: Circular / Sustainable Product Design, **OTH**: Other sustainability related topics, **AU**: Automotive industry, **MAN**: Manufacturing industry, **Exp.**: Related experience (years), **Dur.**: Workshop / interview duration (minutes).

Table 1 (cont.). Overview of focus group workshop and interview participants (authors' own work).

#	Type of actor	Position	Data collection instance	Area of knowledge								Exp.	Dur.	
				CE	SCE	ECO	CBM	CPD	OTH	AU	MAN			
23	Knowledge / technology provider	Managing director	Expert interview	x							x		3	62
24	OEM	Project lead circularity	Expert interview	x				x			x		3	90
25	Data ecosystem provider	Circular economy specialist, Catena-X member	Expert interview	x	x	x		x			x		5	65
26	Steel / aluminium plant	Head of recycling and sustainability	Expert interview	x						x	x		29	58
27	OEM	Manager end-of-life vehicle management	Expert interview	x							x		10	65
28	Reverse logistics provider	Sustainability consultant	Expert interview	x			x				x		7	59
29	Reverse logistics provider	Sustainability consultant	Expert interview	x			x				x		2	59
30	Industry association	Legal advisor / European affairs officer	Expert interview	x						x			2	59
31	OEM	Project manager car body, sustainability, end to end recycling	Expert interview	x		x		x	x	x			27	60
32	Tier 1 supplier	Product pre-development supervisor	Expert interview					x			x		22	61
33	Knowledge provider	President	Expert interview	x						x	x		8	44
34	Tier 1 supplier	Team lead material & process development	Expert interview					x			x		10	59
35	Tier 1 supplier	Sustainability manager	Expert interview	x	x					x	x		13	59
36	Tier 1 supplier	Sourcing group manager	Expert interview							x	x		12	59
37	OEM	Development engineer car body, exterior, interior	Expert interview	x	x			x			x		12	142
38	OEM	Development engineer vehicle, sustainability, metals	Expert interview	x		x	x			x	x		21	142
39	Steel / aluminium plant	Director environmental & sustainability policy	Expert interview			x				x	x		30	51
40	Tier 1 supplier / Industry association	Managing partner / CEO / Board member circular economy	Expert interview	x	x	x	x			x	x		42	44
41	Repair service provider	Managing director	Expert interview							x	x		4	27
42	Development agency	Technical advisor automotive	Expert interview	x			x	x	x	x	x	x	4	62
43	Automotive cluster	CEO	Expert interview	x			x	x	x	x	x	x	8	62
44	Shredder / recycler	Managing director	Expert interview	x						x	x		10	50
45	Dismantler	Head of project management	Expert interview	x						x	x		3	45

Legend: **CE**: Circular Economy, **SCE**: Digitalization / Industry 4.0 / Smart CE, **ECO**: Business Ecosystems / Innovation Ecosystems, **CBM**: Circular / Sustainable Business Models, **CPD**: Circular / Sustainable Product Design, **OTH**: Other sustainability related topics, **AU**: Automotive industry, **MAN**: Manufacturing industry, **Exp.**: Related experience (years), **Dur.**: Workshop / interview duration (minutes).

3.2. Data Analysis Procedure

The transcripts and Conceptboard documentation were analyzed using template analysis, following six steps (King et al., 2015). First, researchers familiarized themselves with the collected data. Second, preliminary coding was conducted based on a priori themes and data, focusing on CE strategies, actors, technologies, and transactional flows. These themes were subdivided into more granular codes, e.g. with CE strategies coded by lifecycle phase and R-strategy per Potting et al. (2017). The third step involved organizing emerging themes into clusters and hierarchies, followed by defining an initial coding template. In the fifth step, the template was applied to data and modified as needed, following King's (2004) guidelines for insertion, deletion, scope and classification changes. Two coders processed data iteratively, coding different files, saving memos, reviewing collaboratively, and adjusting the template. Ultimately, the template was finalized and applied to the full data set. The coding results were compared for consistency, with discrepancies resolved through discussion until consensus was reached. The team revised the coding template over three rounds before finalizing and applying codes to the complete data set, ensuring thorough analysis.

3.3. Smart Circular Business Ecosystem Modeling

The findings from data analysis, which comprised a list of actors and transactional flows detailing type, content, source, and target of each transaction, were used to create visual models of the SCE business ecosystems using the software draw.io according to the e3-value method (Gordijn & Akkermans, 2001). They provide detailed graphical representations of the ecosystems' key components, including actors involved, their primary activities, and the transactional flows that connect them.

4. Results

4.1. Identified Ecosystem Actors

A total of 31 actors were identified, encompassing original equipment manufacturers (OEMs), tier 1-n suppliers, recyclers, steel and aluminum manufacturers, technology and knowledge providers, data ecosystem operators, logistics providers, dismantlers, and other stakeholders. Across the lifecycle phases, 16 actors were identified being active in the BoL phase (creation, design, and production of products), 25 in the MoL phase (distribution, use and maintenance), and 19 in the EoL phase (recycling or disposal) (table 2).

Table 2. Number of actors, transactions and data transactions across product lifecycle phases and circular strategies (authors' own work).

Product Lifecycle Phase	BoL	MoL	EoL
Related circular strategies	Refuse, Rethink, Reduce	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Recycle, Recover
Loop type	Narrow the loop	Slow the loop	Close the loop
Utilization of digital technologies (Inform the loop)	✓	✓	✓
# Actors	16	25	19
# Total transactions	75	225	142
# Data transactions	43	92	63

Some actors participate in circular activities across all product lifecycle phases. These include OEMs, tier 1-n suppliers, data ecosystem providers and participants, among others (table 3), and represent 39 percent of actors. More peripheral actors operate only within specific phases. For example, plant and tool manufacturers are active only in the BoL phase; distributors, exporters, international users, municipal authorities, logistics providers, and sorting and diagnosis centers, along with remanufacturers, are primarily active in the MoL phase; while shredders / recyclers, and other industries focus exclusively on the EoL phase. It should be noted though that in a circular system, recyclers produce secondary materials that are once again utilized as inputs during the BoL phase.

Table 3. Description of identified actors (authors' own work).

Actor type	Key CE-related activities	BoL	MoL	EoL
OEM	Product definition, production, and distribution according to customer requirements. Requirements management for the circularity of products, incl. design for Re-X principles. Reconditioning and sale / rental of used vehicles and components.	x	x	x
Data ecosystem provider	Collection and provision of static and dynamic information across the entire life cycle to ecosystem participants. Ensure data exchange between different partners, enable cost savings through standardized data exchange, and digital twins and information across the entire product life cycle.	x	x	x
Data ecosystem participants	Provision and use of data and services in the data ecosystem.	x	x	x
Tier 1-n supplier	Development of new design and material concepts with OEM. Retrieval of parts from MoL and EoL. Repair, re-use, remanufacturing, and refurbishing components.	x	x	x
Dismantler	Removal of components in accordance with EoL vehicle regulations, expansion of marketable spare parts, separation of material fractions for high-quality recycling.	x	x	x
User	Use of product-as-a-service solutions, e.g. car sharing. Acceptance and use of reprocessed parts and vehicles, and recycled materials. Use of service offers (maintenance, repair), which extends the service life of vehicles and components. Participation in return and recycling processes.	x	x	x

Table 3 (cont.). Description of identified actors (authors' own work).

Actor type	Key CE-related activities	BoL	MoL	EoL
Repair service provider	Diagnostics and inspections, maintenance, repairs, and replacements. Decision on R-strategies based on usage data, cost-effectiveness etc. Procurement and provision of spare parts.	X	X	X
Knowledge / technology provider	Development of decision support systems, recycling technologies, solutions that promote the use of secondary materials, technologies for the traceability and reuse of components and materials. Development of CE applications, prototypes, guidelines and tools for the evaluation and optimization of CE strategies incl. business models.	X	X	X
National / international legislator	Creation of regulatory frameworks, uniform standards and norms for CE, incl. export/import of recycled materials and reuse of components and materials. Investment in CE research projects.	X	X	X
National industry association	Promotion of laws, standards, and guidelines to support CE, support cooperation between companies, research institutions and other associations for cross-industry CE activities, establish platforms for the exchange of best practices and the development of joint CE projects.	X	X	X
Certifier / standardization organization	Test, inspect and certify technical systems, materials (e.g. new circular materials), facilities, and objects to minimize hazards and prevent damages.	X	X	X
International industry association	Promotion of laws, standards, and guidelines to support CE, support cooperation between companies, research institutions and other associations for international cross-industry CE activities, establish platforms for the exchange of best practices and the development of joint international CE projects.	X	X	X
Steel / aluminium plant	Use of recycled materials to reduce the consumption of primary raw materials. Integration of pre- and post-consumer scrap in material production. Production of recyclable products for reprocessing at EoL.	X		X
Reverse logistics provider	Return and storage of vehicles and components (collection, identification, evaluation). Diagnosis and preselection of a suitable R-strategy. Digital networking and tracking. Optimization of the logistics chain.		X	X
Data provider	Collecting, maintaining, analysing, and archiving materials used for automobile manufacturing (e.g. IMDS). Provision of a database with information on treatment information for EoL vehicles (e.g. IDIS).	X		X
Authority	Central registration authority: Registration and decommissioning of vehicles.		X	X
Development agency	Advice and knowledge transfer on CE topics. Collaboration with and empowerment of local organizations and authorities. Identification of gaps and transformation needs. Provision of financial support.		X	X
Plant manufacturer	Development, production & distribution of manufacturing systems with low energy and material consumption.	X		
Tool manufacturer	Development, production & distribution of machine tools and tools with low energy and material consumption and ability to process circular materials.	X		
Digital marketplace	Provide a platform for secure data exchange between stakeholders to promote transparency and collaboration. Use digital technologies for monitoring, traceability, and optimization of resource flows. Promote interoperability, linking different actors and systems.		X	
Automotive cluster	Reuse, reconditioning and repair of vehicles, processing, repurpose and recycling of components. Training of members in safe, professional, sustainable and CE practices.		X	
Point of Sale / distributor	Sales, rental and leasing of vehicles (BEV).		X	
Exporter	Export of EoL vehicles or components e.g. to automotive clusters that carry out vehicle repair, reconditioning, and spare parts recovery.		X	
Logistics provider	Provision of transport and storage solutions.		X	
International user	Use and sale of imported vehicles and components.		X	
Government & ministries	Support and expansion of national economic sectors and growth markets incl. CE-related topics.		X	

Table 3 (cont.). Description of identified actors (authors' own work).

Actor type	Key CE-related activities	BoL	MoL	EoL
Economic development financial institution	Provision of loans and grants to governments of low- and middle-income countries for the purpose of economic development, incl. CE-strategies.		x	
Sorting and diagnosis center	Sorting of products and components, initial CE-related diagnostics, warehousing.		x	
Remanufacturer	Diagnostics and remanufacturing of components, certification, development of decision support systems and automated dismantling solutions.		x	
Shredder / recycler	Shredding vehicle wrecks, sorting by materials, further processing, separation and cleaning of metal alloys and sale of alloys to steel/aluminum plants.			x
Other industries, e.g. infrastructure	Utilization of secondary materials from automotive industry for other applications, e.g. steel in buildings.			x

4.2. Identified Data Transactions

Data transactions play a central role in enabling circular strategies within a business ecosystem. The analysis of 442 documented material, data and financial transactions shows that data exchanges account for 45 percent of all interactions, underlining the critical importance of information sharing across lifecycle phases. The number of data transactions different actors engage in varies significantly, with OEMs accounting for the highest number at 46 data transactions, followed by data ecosystem providers (35) and their participants (30), tier 1-n suppliers (27), dismantlers (19), users (15) and repair service providers (13). On the other end of the spectrum, actors such as remanufacturers, logistics providers and distributors engage in less than five data transactions. The highest number of data transactions occurs during the MoL phase (93), followed by EoL (63) and BoL (43).

Some types of data are shared across **all lifecycle phases** and between multiple actors to enable circularity, including regulatory information, technical assessments, material data, and artificial intelligence (AI)-supported decisions for circular strategies. Both static and dynamic product data are crucial, covering material specifications, joining techniques, repair instructions, and real-time product condition and history data.

To effectively **narrow resource loops during BoL**, it is crucial to incorporate essential data like circular design requirements, material specifications, and collaborative development among key actors including OEMs, suppliers, repair providers, recyclers, and customers to improve product design. Consequently, actors like recyclers and users are relevant even at this early stage. Additionally, assessments of potential smart circular business models are considered. To **slow resource loops during MoL**, information on component and vehicle condition is shared, along with maintenance, repair, and reuse data, including predictive maintenance, spare parts management, crash statistics, and failure reports. These R-strategies require circularity, compliance, and lifecycle tracking, including component compatibility, safety, orders, and customer insights. For **closing resource loops during EoL**, data like material composition, treatment, material accounting and traceability, recycling rates, process data, and forecasts for secondary materials, as well as regulatory compliance and certification for dismantling and recycling become particularly important.

Some ecosystem participants engage in frequent mutual data exchanges, e.g. OEM and tier 1-n during BoL for product design, during MoL for implementing aftermarket strategies and remanufacturing, and during EoL when accessing secondary materials for new designs (BoL). Likewise, data exchange often occurs between ecosystem participants and an ecosystem provider, who is responsible for gathering and distributing static and dynamic data throughout the lifecycle. The provider ensures secure data exchanges, facilitates cost reductions through standardization, and promotes sharing of digital twins across the automotive value chain. It processes data from ecosystem participants such as repair service providers and shares the processed data with others, such as remanufacturers. Catena-X, managed by Cofinity-X GmbH, exemplifies such an ecosystem.

4.3. Key Components and Enablers of Smart Circular Ecosystems in the Automotive Industry

In order to collect, store, analyze and utilize data across ecosystem participants and for implementing circular strategies, digital technologies are required (Bühler et al., 2025a). The data value chain framework (Faroukhi et al., 2020) and the categorization by Bühler et al. (2025a) were applied to describe the results. A third category called “digital ecosystem enablers” was added to include two specific examples which were mentioned by several workshop and interview participants (table 4). These enablers represent two real-life applications which combine several digital technologies and digitalization concepts.

Identified **digitalization concepts** encompass the Internet of Things, big data analytics, artificial intelligence and machine learning, cyber-physical systems, and digital twins. A digital twin, for instance, serves as a dynamic, virtual model of a physical product or system, which is continuously refreshed with real-time data regarding the usage, performance, and condition of a product or component. It can illustrate the extent of wear or damage to specific parts and identify material recyclability and suitable processing routes. Additionally, this data can assist in categorizing components and materials based on their remaining lifespan, thereby optimizing the selection of the optimal circular strategy for each individual part.

Table 4. Identified digitalization concepts, digital technologies and enablers of circular ecosystems (adapted from Bühler et al. (2025a); authors’ own work).

	Data Discovery	Data Integration	Data Analysis	Data Application
Digitalization concepts				
IoT (Internet of Things) technology enables real-time tracking of parts and materials using embedded sensors and connectivity. It enhances transparency, improves traceability along the supply chain, and supports predictive maintenance, reuse, and recycling strategies.	x	x		
Big Data Analytics processes large volumes of vehicle and usage data to enable seamless data flow between OEMs, vehicles, and service providers. It forms the foundation for advanced digital technologies like the Digital Product Passport and Digital Twin by enabling real-time insights, informed decision-making, and optimized circular economy strategies.		x	x	
Artificial Intelligence (AI) and Machine Learning (ML) are applied to analyze usage data, predict component conditions, and optimize maintenance, repair, and logistics in vehicle systems. In recycling, they support material flow management and enhance sorting precision via machine vision and robotics. AI-based simulations also aid in developing durable, recyclable products and conducting life cycle analyses to support circular economy objectives.			x	
Cyber-physical systems like machine vision combine sensor technology and intelligent image processing to recognize and sort materials, particularly in the pre- and post-shredder process. They enhance the quality and efficiency of material recovery by distinguishing different waste fractions and metal alloys.	x	x	x	x
Digital twins are virtual representations of vehicles or assemblies that allow e.g. for the analysis of properties, conditions, and predictive maintenance needs. By recording real-time and historical vehicle data, they support informed decisions on the maintenance, reuse, and optimization of both existing and future components.	x	x	x	x

Table 4 (cont.). Identified digitalization concepts, digital technologies and enablers of circular ecosystems (adapted from Bühler et al. (2025a); authors' own work).

	Data Discovery	Data Integration	Data Analysis	Data Application
Digital technologies				
Sensor technologies , as part of IoT systems, collect data on the location, condition, and usage of components. They support traceability, real-time monitoring, and data-driven decision-making for maintenance, reuse, and recycling in circular economy applications.	x			
Blockchain enables secure, tamper-proof tracking of material flows and proof of origin across the value chain. It ensures transparent data exchange on material and recycling processes and supports the issuance of digital recovery certificates, facilitating compliance and circular economy documentation.		x		
Database management and apps involve collecting, processing, and providing data through digital platforms and user interfaces. They help companies comply with regulatory requirements like the Digital Product Passport by ensuring structured and accessible information across the value chain.		x		
Digital platforms create new markets for the resale of components and products by connecting stakeholders across industries. They enable real-time tracking of returns and component conditions in aftersales, enhance reverse logistics, and foster collaboration between industry associations.		x		x
Digital simulations refer to virtual models used by OEMs to replicate the life cycle, performance, and material behavior of vehicles and components. They support the design, testing, and optimization of products by simulating wear, environmental impact, and recycling potential, ultimately enabling more durable, repairable, and recyclable designs.			x	
Augmented and virtual reality (AR/VR) technologies are used to support and streamline manual processes such as maintenance, repair, and disassembly of components, for example by identifying individual parts and analyzing material compositions. They provide visual guidance and interactive environments that improve process efficiency and precision.				x
Robotics technology is used to automate and accelerate manual disassembly processes. When combined with AI and machine vision, robotics improves efficiency, reduces labor intensity, and increases recovery rates in end-of-life vehicle processing.				x
Digital ecosystem enablers				
The Digital Product Passport (DPP) is a standardized, digital record containing detailed information on the origin, manufacture, usage, and disposal of vehicles and components. It enables traceability, supports repair, reuse, and recycling, and enhances data-driven circular economy strategies through integration with technologies like blockchain and digital twins.		x		x
Catena-X is a data ecosystem built on the Gaia-X architecture that facilitates secure and interoperable data exchange across the automotive value chain. It supports digital technologies like digital twins, AI, and big data analytics, and simplifies regulatory processes such as the certification of reuse or remanufacturing under the ELV Regulation.		x		x

Identified **digital technologies** include sensor technologies, blockchain, database management systems, digital platforms, digital simulations, augmented and virtual reality and robotics. For instance, blockchain

technology allows for the secure and tamper-resistant monitoring of material flows and verification of origin throughout the value chain. It guarantees transparent data sharing regarding e.g. materials used and recycling processes, and facilitates the issuing of digital recovery certificates, which are crucial for compliance and CE-relevant documentation. Digital platforms are instrumental in creating new marketplaces for reselling products, components, and materials by linking stakeholders across various industries. They facilitate real-time monitoring of returns and component conditions in aftersales, improve reverse logistics, and promote collaboration among industry associations.

Throughout **all product lifecycle stages**, the same digital technologies and concepts are applicable, albeit for varying circular strategies. For instance, digital platforms can function as marketplaces for trading scraps and secondary alloys to close resource loops at EoL, as well as for components used as spare parts to slow resource loops during MoL.

Finally, the Digital Product Passport (DPP) and Catena-X were highlighted as specific **digital ecosystem enablers** of SCE in the automotive industry. Once implemented, the DPP will offer detailed information about vehicles and their parts throughout their entire lifecycle, covering aspects such as materials, repairs, maintenance, disassembly, and environmental effects. At EoL, this level of transparency facilitates targeted disassembly, enhances material recovery, and minimizes the effort and costs associated with sorting and processing materials. Catena-X supports the implementation of the DPP and digital twins by creating a networked platform for data exchange and interoperability between entities. Data protection concerns and high implementation costs were cited as barriers to DPP implementation. A data ecosystem such as Catena-X could help overcome these obstacles by providing secure, standardized interfaces and protocols.

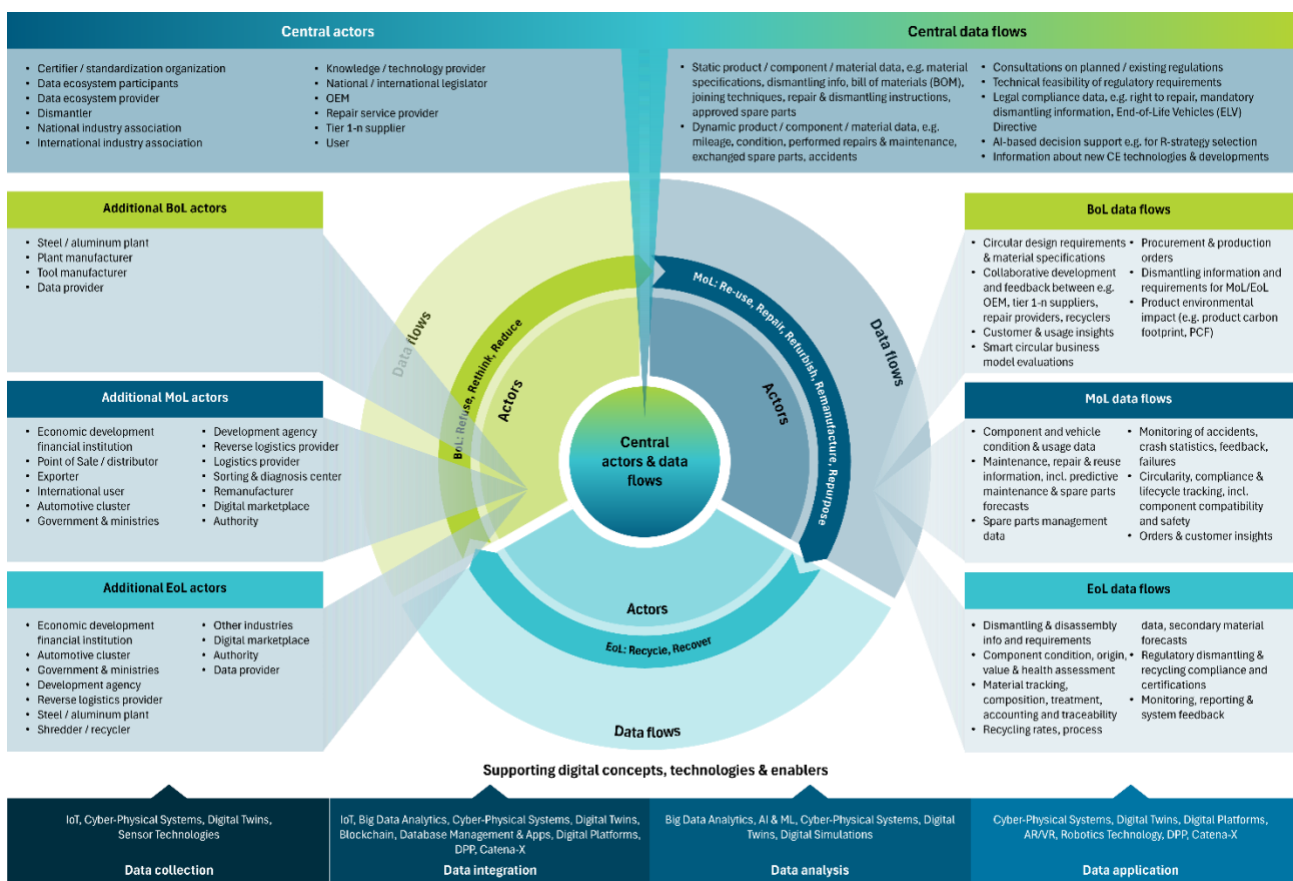


Figure 2. Principal components of a smart circular ecosystem within the automotive industry (authors’ own work).

Figure 2 summarizes the principal components of a smart circular ecosystem within the automotive industry. It highlights the central actors and data flows, alongside the digital concepts, technologies, and enablers that are crucial throughout all phases of the product lifecycle. Additional actors and data flows relevant for specific lifecycle phases, integral to corresponding circular strategies, are noted separately.

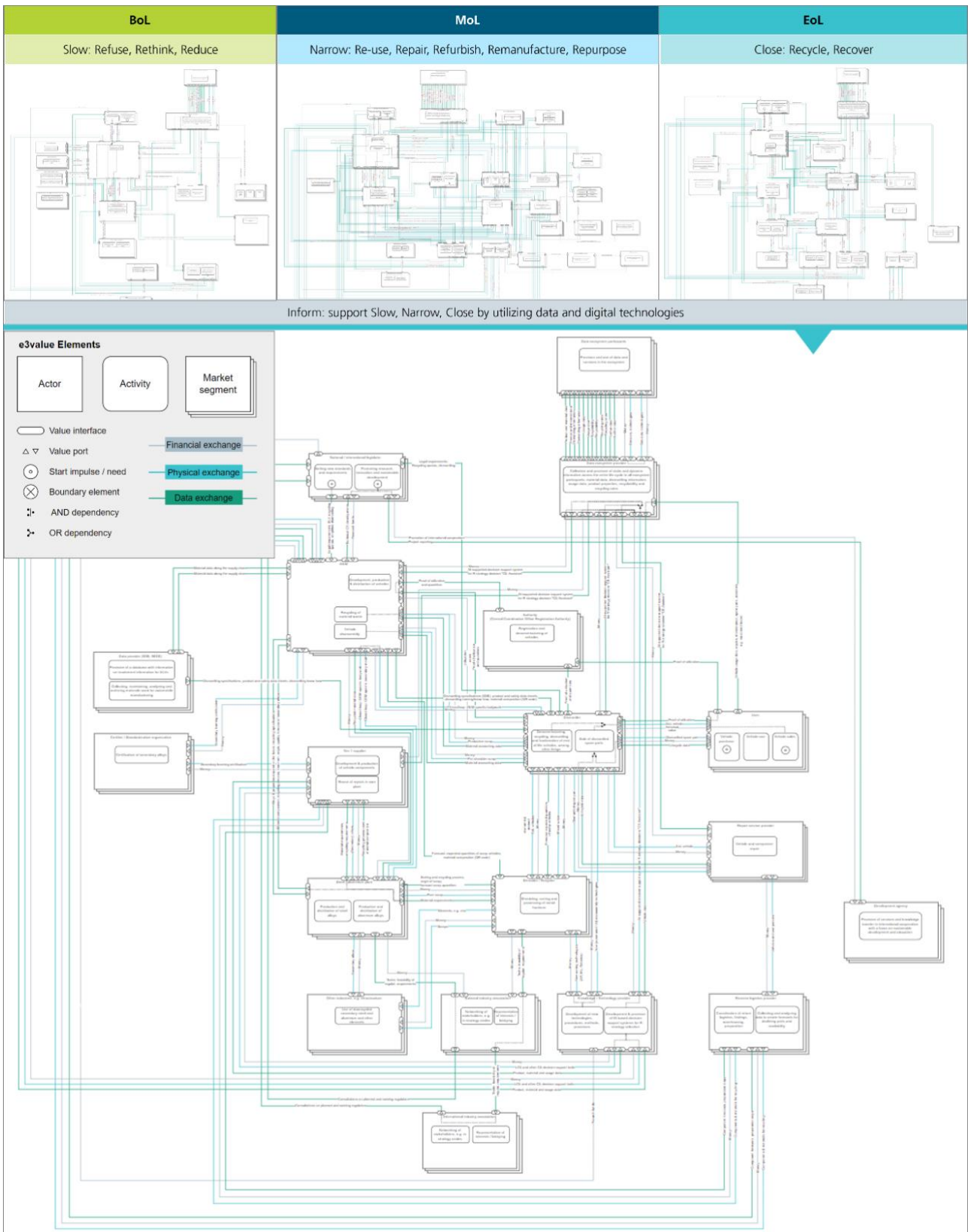


Figure 3. Smart circular ecosystem models for BoL, MoL, and EoL phases using e3-value notation. Detailed view of EoL ecosystem (authors' own work).

4.4. Visual Ecosystem Model

Figure 3 presents a visualization of actors, their activities and transactions, integrating the structural ecosystem elements according to Adner (2017) by employing the e3-value modeling language (Gordijn & Akkermans, 2001). Actors are represented within square boxes, while their primary activities are shown in rounded boxes. They are interconnected through material (blue), data (green), and financial (gray) flows. These exchanges occur through value ports that indicate the direction of transactions, which are then grouped into value interfaces that organize related transactions. The results integrate both current actors and flows that contribute to a CE, as well as additional identified components that are crucial for enhancing circularity. Figure 3 is not intended to be readily interpreted by readers due to the extensive information embedded within the ecosystem models. Instead, it aims to visually represent the varying levels of complexity across the BoL, MoL, and EoL ecosystems. Table 3 provides an overview of all identified actors, detailing their main activities and involvement across the three product lifecycle phases. Appendix A offers a comprehensive overview of all data transactions between these actors and their assignment to the respective lifecycle phases.

The application of the e3-value method allows for a nuanced understanding of the ecosystems' dynamics. It enables participants to identify and analyze various actors' roles and their contributions to the overall system. The models' emphasis on transactional flows highlights the interdependencies between actors and helps reveal potential bottlenecks or opportunities for optimization. By bundling value ports through value interfaces, the method also provides insights into how different actors interact and exchange value, facilitating a holistic view of the ecosystems' functioning and potential areas for improvement or innovation.

5. Discussion

Building on the findings of this study, five research propositions are presented that explore two future research directions identified by Aryee et al. (2025): the role of actors and the orchestration capabilities and governance within circular ecosystems, with a particular emphasis on the impact of digital technologies and data governance. In accordance with qualitative research practices, the term "propositions" refers to statements derived from empirical findings and informed by theory. These propositions, detailed below, summarize the study's principal insights and serve as a foundation for future investigation: (1) digital technologies act as critical enablers of circularity in automotive ecosystems; (2) the MoL phase introduces substantial complexity, requiring advanced interoperability across diverse actors; (3) federated data ecosystems and the DPP enhance multilateral data exchange and collaboration in automotive circular ecosystems, (4) simultaneous involvement of both central and specialized actors improves effectiveness, while reliance on central actors might decrease ecosystem resilience, and (5) alignment between actor heterogeneity and ecosystem governance type increases the effectiveness of data governance.

The results indicate that 198 out of 442 value flows (45 percent) in the ecosystem are data-related, underscoring the critical role of digital technologies as enablers of smart circular ecosystems within the automotive industry. They facilitate comprehensive data exchange among diverse ecosystem participants, enhancing transparency, traceability, and real-time insights into the flow and condition of materials and components. This enables the optimization of circular strategies, such as predictive maintenance, repair, remanufacturing, efficient disassembly and sorting, while also supporting data-driven marketplaces for secondary materials and components to promote economic incentives for circularity. Furthermore, digital tools strengthen reverse logistics and collaborative planning, aligning operational decisions with sustainability goals. As these ecosystems grow increasingly complex, particularly during the MoL phase where multiple actors and transactions intersect, effective data collection, integration, analysis, and sharing become essential. These findings show that digital technologies do not simply support CE practices but fundamentally reorganize how circular activities are coordinated across actors. This extends prior work by e.g. Rossi and Srai (2025) and Trevisan et al. (2022) by highlighting that granular, real-time data flows are essential for orchestrating complex circular strategies across actors.

- **Proposition 1:** Circular automotive ecosystems with a higher adoption of digital technologies will achieve more seamless integration among partners and realize higher levels of circularity.

Furthermore, the results demonstrate that CE strategies in the automotive industry vary in complexity across lifecycle phases, as reflected by the number of actors and data transactions involved. The BoL phase is the

simplest, involving the fewest actors (16) and data-related flows (43), as strategies like refuse, rethink, and reduce primarily involve OEMs and tier 1-n suppliers. The EoL phase shows moderate complexity, with 19 actors and 63 data transactions, as recycling and recovery processes engage multiple stakeholders such as reverse logistics providers and recyclers. By contrast, the MoL phase presents substantial opportunities for circularity but also significant cooperation challenges, requiring coordination among 25 diverse actors and 92 data-related transactions for strategies like repair, remanufacturing, and refurbishing. The findings emphasize the critical need for interoperable digital infrastructures to enable seamless data exchange and collaboration, particularly to slow resource loops, where effective use of digital technologies can address coordination challenges which might be complicated by heterogeneous data quality and digital maturity levels across actors. This suggests that slowing loops requires more advanced digital integration and governance than narrowing or closing loops, providing novel insights into the complexity levels of lifecycles which, as far as known, have not been addressed in prior research.

- **Proposition 2:** The development of interoperable digital infrastructures for slowing resource loops is more complex than for narrowing or closing loops in circular automotive ecosystems.

In this context, federated data ecosystems provide a promising model to facilitate multilateral data exchange by allowing decentralized data ownership while enabling interoperability and secure sharing across organizations. The DPP emerges as a key enabler, offering a standardized yet extensible framework to track and trace product- and component-level information throughout the entire lifecycle. To realize its full potential particularly in the complex MoL phase, the DPP must function across organizational boundaries, jurisdictions and varying digital maturities. Multilateral data exchange models are required to support this, involving not only bilateral data sharing but also dynamic, many-to-many interactions. These infrastructures must address issues of semantic interoperability, access rights, and identity verification to enable scalable and secure collaboration in circular ecosystems. This analysis illustrates that federated data ecosystems and the DPP can mitigate fragmentation and underscores their potential as structural enablers of circularity, particularly when MoL transactions demand cross-organizational visibility and trust. This finding corroborates and expands research showing that DPP-based ecosystems enhance interoperability and circularity among automotive organizations, while previous studies have not differentiated these effects across circular strategies or lifecycle phases (Rossi & Srail, 2025).

- **Proposition 3:** In circular automotive ecosystems that adopt federated data ecosystems and implement a DPP to enable multilateral data exchange, cross-organizational collaboration and interoperability are higher, resulting in higher circularity than in ecosystems that do not adopt these practices, with the greatest impact on strategies aimed at slowing resource loops.

Moreover, the implementation of circular strategies in the automotive sector involves a network of actors with varying participation across the product lifecycle. Key players including OEMs, data ecosystem providers, tier 1-n suppliers, and dismantlers are involved throughout all phases and numerous circular strategies. Their importance is demonstrated by their data transactions volume, with OEMs leading at 46 transactions, followed by data ecosystem providers (35), tier 1-n suppliers (27), and dismantlers (19). Other actors play more specialized roles in specific lifecycle stages. Plant and tool manufacturers operate at the BoL phase, while sorting and diagnosis centers and remanufacturers focus on the MoL stage. Shredders and recyclers primarily work in the EoL phase. This specialization enables actors to develop expertise in particular areas, contributing to the efficiency of circular strategies in the automotive sector. Previous research has identified that heterogeneous specialized actors and a central orchestrating actor are crucial for effective circular ecosystems. Furthermore, central platforms and orchestrators may create risks related to power and dependency, such as lock-in, gatekeeping, and data control (Frank et al., 2025; Trevisan et al., 2022). This study confirms that specialized and central actors can accumulate significant influence as key players and gatekeepers within these ecosystems, potentially leading to dependency risks and bottlenecks in CE implementation, highlighting the need to balance specialization with distributed capability to ensure ecosystem resilience.

- **Proposition 4:** In circular automotive ecosystems, the presence of both central and specialized actors enhances the effectiveness of circular strategy implementation, but greater reliance on central actors may increase dependency risks and reduce overall ecosystem resilience.

Lastly, the expansion of circular strategies, particularly slowing the loop strategies during the MoL phase, poses significant data governance challenges, such as issues of data ownership, access control, liability, and trust. Unlike linear value chains, circular ecosystems are dynamic and non-hierarchical, making traditional centralized governance unsuitable. Key concerns include establishing data-sharing agreements, ensuring compliance with regulations, managing intellectual property, and enabling traceability while maintaining confidentiality. To address this, emerging data governance models as outlined by Micheli et al. (2020), offer tailored solutions: Data Sharing Pools, often OEM-led, rely on contractual access and medium data sovereignty, supported by API gateways and data lakes, making them suitable for platform-driven ecosystems. Data Cooperatives use a democratic, member-driven model with high sovereignty, employing distributed ledgers and token systems, ideal for multi-stakeholder collaboration. Public Data Trusts operate under trustee-led, legally bound frameworks with high sovereignty, combining legal and social mechanisms for non-governmental or governmental contexts. Personal Data Sovereignty emphasizes individual control with very high sovereignty, using technologies like Self-Sovereign Identity (SSI) or Solid Pods for self-managed access. These models are particularly relevant in MoL ecosystems, where diverse actors and complex interactions require adaptive governance to balance interests, foster trust, and avoid fragmentation or dominance by powerful players. The results suggest that the effectiveness of data governance models depends on their alignment with ecosystem heterogeneity, supporting the notion that “one-size-fits-all” governance is insufficient. Tailoring governance to actor diversity appears essential for enabling collaboration, trust, and circularity outcomes, especially in MoL ecosystems. Previous research broadly shows that governance models must align with ecosystem structure and actor heterogeneity (Rossi & Srai, 2025; Trevisan et al., 2022). However, no explicit link of governance types to lifecycle phases has been established before.

- **Proposition 5:** In circular automotive ecosystems, the effectiveness of data governance models is positively influenced by the alignment between actor heterogeneity and governance type, such that diverse ecosystems, particularly in the MoL phase, achieve higher effectiveness with cooperative or trust-based models (e.g., data cooperatives or public data trusts), whereas more homogeneous ecosystems, such as BoL or EoL phases, achieve higher effectiveness with centralized models (e.g., data sharing pools).

Together, these propositions deepen the understanding of how digital infrastructures, governance models, and actor roles jointly shape circularity outcomes in automotive ecosystems. They highlight the conditions under which smart circular ecosystems can scale and provide a foundation for advancing theory and guiding future research.

6. Conclusion

6.1. Theoretical Contributions

6.1.1. Methodological Advancement This study makes a methodological contribution by employing a DSR approach to develop a conceptual smart circular ecosystem model tailored to the automotive industry. By integrating focus group workshops, expert interviews, template analysis, and e3-value ecosystem modeling, the study advances methodological rigor in the field. This combined qualitative-visual approach allows the capturing of complex inter-organizational data flows and actor interactions across product lifecycle phases. Embedding Adner (2017)'s ecosystem-as-structure framework within a DSR logic operationalizes theoretical constructs and yields a replicable artifact that enriches the methodological and theoretical toolkit for analyzing digitally enabled circular business ecosystems.

6.1.2. Empirical Insights Refining Circular Ecosystem Theory The findings refine theoretical understanding of circular ecosystems by empirically demonstrating how circular strategies vary in complexity across the lifecycle and by revealing the central role of data transactions and digital technologies in enabling these strategies. By mapping 31 ecosystem actors and 442 transactional flows, with a notable 45 percent involving data exchanges, the research challenges simplistic models of circular ecosystems and highlights the centrality

of digital infrastructures. Moreover, the identification of federated data ecosystems and the DPP as key enablers advances theory by positioning multilateral data governance, semantic interoperability, and cross-organizational coordination as critical mechanisms for ecosystem orchestration, particularly in the MoL phase where collaboration complexity peaks.

6.1.3. Theoretical Synthesis and Future Research Pathways The discussion synthesizes empirical results into five propositions that extend SCE theory by explicating the relationships between actor heterogeneity, digital technology adoption, data governance configurations, and ecosystem resilience. These propositions move beyond descriptive accounts and contribute toward explanatory and predictive theorizing in the SCE domain, laying a foundation for future theory-building. It invites empirical validation and comparative studies, thereby contributing to the development of a more comprehensive and dynamic theoretical landscape that captures the multifaceted nature of circular ecosystems in industrial contexts.

6.2. Managerial Implications

The managerial implications of this article are crucial for the automotive industry's transition towards CE. **Regarding data, digital technologies and infrastructure**, the study provides comprehensive support for companies implementing CE strategies within complex ecosystems, offering guidance on identifying and leveraging relevant data sources, technologies, and networking partners across the product lifecycle. **With respect to actor roles and collaboration**, this research is particularly valuable for the automotive sector, which has been underrepresented in existing SCE literature. The findings assist managers across various ecosystem actors by clarifying key actors, roles and responsibilities in a smart circular ecosystem, aligning circular strategies with their position in the value chain and optimizing SCE-activities along the product lifecycle. **In terms of data governance and the DPP**, the study provides managers with insights on how to design effective data-sharing arrangements, establish clear access and ownership rules, and select governance models that fit the heterogeneity of their ecosystem partners. This enables companies to build trust, reduce coordination barriers, and ensure interoperability to scale circular strategies across the ecosystem. These implications support managers in designing and implementing smart circular strategies, ultimately contributing to United Nations Sustainable Development Goal 12 "Responsible Consumption and Production" (Dantas et al., 2021; Kristoffersen et al., 2020; Schroeder et al., 2019).

6.3. Limitations and Future Research

This study, while comprehensive, has several limitations that should be acknowledged. The focus on car body structures may limit transferability to other car components, necessitating future research to evaluate the relevance of these results for the broader automotive industry. The selective nature of interviews, while covering key actors, did not include all industry stakeholders. Further studies could benefit from a wider range of participants. The results need to be reduced in complexity and converted into an accessible artifact, which can be demonstrated and evaluated with additional experts to fully grasp the benefits and possible uses of the findings. The idealized ecosystem model provides valuable insights into key actors, data flows, and digital technologies; however, it may need periodic updates to stay aligned with the rapidly evolving industry. Furthermore, the study's broad scope, covering CE strategies across the entire product lifecycle, may reduce the granularity of insights for specific strategies or phases, potentially introducing some degree of vagueness. Future research could thus focus on specific lifecycle phases for more detailed and targeted results, especially BoL strategies, given the significant impact of product design and business model choices on circularity and environmental performance.

Table 5. Propositions derived from empirical findings and future research directions (authors' own work).

Propositions derived from empirical findings	Future research directions
1. Circular automotive ecosystems with a higher adoption of digital technologies will achieve more seamless integration among partners and realize higher levels of circularity.	Comparative studies across circular automotive ecosystems with varying levels of digitalization to test whether higher adoption translates into measurable integration and circularity outcomes. Longitudinal research exploring how digital adoption trajectories affect ecosystem maturity over time.
2. The development of interoperable digital infrastructures for slowing resource loops is more complex than for narrowing or closing loops in circular automotive ecosystems.	Investigations into technical and organizational challenges of building digital infrastructures for slowing loops, compared to narrowing and closing loops.
3. The adoption of federated data ecosystems and the DPP improves multilateral data exchange, cross-organizational collaboration and interoperability in automotive circular ecosystems, and results in higher circularity, especially for slowing resource loops.	Empirical analyses which examine the effectiveness of federated data ecosystems and DPPs in practice, including pilot projects in the automotive sector. Studies which explore governance and standardization requirements for scaling these solutions across industries.
4. In circular automotive ecosystems, the presence of central and specialized actors enhances the effectiveness of circular strategy implementation, but greater reliance on central actors may increase dependency risks and decrease ecosystem resilience.	Network analyses and simulation studies, which examine how different configurations of central and specialized actors in circular automotive ecosystems influence dependency risks (notably network centrality, density, structural holes). Studies which investigate how governance mechanisms or policy interventions can mitigate these risks to maintain or enhance overall ecosystem resilience.
5. The effectiveness of data governance models is positively influenced by the alignment between actor heterogeneity and governance type.	Studies investigating the effectiveness of different governance models under varying degrees of actor heterogeneity. Comparative case studies across ecosystems with different compositions providing insights into designing adaptive and inclusive governance frameworks.

The propositions developed herein offer a fruitful ground for further empirical validation and theoretical advancement through cross-industry testing, longitudinal and comparative methods, and exploration of governance and policy mechanisms to mitigate dependency risks while fostering collaboration (table 5). In addition, future studies could examine the role of federated data ecosystems and DPPs in practice, investigate the complexity of infrastructures for slowing loops, and assess how actor heterogeneity shapes effective data governance.

This study contributes to the emerging SCE literature by investigating how digital technologies and data transactions enable circular strategies in the automotive industry. By integrating circular strategies, digital technologies, and ecosystem perspectives, this study offers a foundation for advancing the SCE discourse and supports both scholars and practitioners in shaping more circular business ecosystems.

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Declarations

Competing Interests The authors declare no competing interests.

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Appendix

Appendix A. Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

Please note: Transactions with the same ID are part of the same value port. Transactions were identified through focus group workshops and expert interviews. They may not include all possible transactions, but they focus on those which are important for creating circular strategies in the automotive industry.

ID	Source	Target	Content	BoL	MoL	EoL
1	National industry association	National / international legislator	Consultation on planned / existing regulations	x	x	x
2	International industry association	National / international legislator	Consultation on planned / existing regulations	x	x	x
3	National / international legislator	OEM	Legal requirements, e.g. Right to Repair, ELV Directive (mandatory dismantling information)	x	x	x
4	OEM	National / international legislator	New CE technologies / developments	x	x	x
5	OEM	Plant manufacturer	Relevant changes to product / material (which might cause changes at plant level)	x	x	
6	OEM	Tool manufacturer	Relevant changes to product / material (which might cause changes at tool level)	x	x	
7	OEM	Data provider	Material data across supply chain	x	x	x
7	Data provider	OEM	Material data across supply chain	x	x	x
8	OEM	Data provider	Mandatory dismantling information	x		
9	Tier 1-n supplier	Data provider	Material & product data across supply chain	x	x	
9	Data provider	Tier 1-n supplier	Material & product data across supply chain	x	x	
10	OEM	Tier 1-n supplier	Design-for-CE requirements	x		
10	Tier 1-n supplier	OEM	Feedback on requirements, joint development, material specifications etc.	x		
11	Tier 1-n supplier	OEM	Product / component / material data, e.g. material specifications, dismantling information, bill of material (BOM), CAD models, joining techniques, repair & dismantling instructions, approved spare parts	x	x	
11	OEM	Tier 1-n supplier	Order	x	x	
12	OEM	Tier 1-n supplier	User / usage data and analyses, e.g. for improving component design and mitigating failures	x	x	
13	OEM	Knowledge / technology provider	Static & dynamic product / component / material data	x	x	x
14	Tier 1-n supplier	Knowledge / technology provider	Static & dynamic product / component / material data	x	x	x
15	National industry association	International industry association	Technical feasibility of regulatory requirements	x	x	x
16	Knowledge / technology provider	Tier 1-n supplier	Evaluation of potential smart circular business model options at BoL	x		

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
17	Knowledge / technology provider	OEM	Evaluation of potential smart circular business model options at BoL	x		
18	Tier 1-n supplier	Repair service provider	Product / component / material data, e.g. material specifications, dismantling information, bill of material (BOM), CAD models, joining techniques, repair & dismantling instructions, approved spare parts	x	x	
19	OEM	Repair service provider	Product / component / material data, e.g. material specifications, dismantling information, bill of material (BOM), CAD models, joining techniques, repair & dismantling instructions, approved spare parts	x	x	
20	Dismantler	OEM	Dismantling possibilities and problems regarding vehicles and components (for improving product design during BoL in line with Design-for-CE)	x		x
21	OEM	Dismantler	Dismantling requirements, product and safety sheets, dismantling know-how (communicated at production start of vehicle and continuously for vehicles' EoL)	x		x
22	Data ecosystem provider	OEM	AI-based decision support system, e.g. for R-strategy selection, "CE-Assistant"	x	x	x
23	Data ecosystem provider	OEM	Vehicle usage data for informing the redesign of products during BoL in line with Design-for-CE	x		
24	Data ecosystem provider	Tier 1-n supplier	Component usage data for informing the redesign of products during BoL in line with Design-for-CE	x		
25	User	OEM	Customer preferences	x	x	
26	User	Data ecosystem provider	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents	x	x	x
27	Data ecosystem provider	Data ecosystem participants	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents	x	x	x
27	Data ecosystem participants	Data ecosystem provider	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents	x	x	x
28	Data ecosystem provider	Data ecosystem participants	Product Carbon Footprint (PCF) comparison for different products / components	x	x	
28	Data ecosystem participants	Data ecosystem provider	Product Carbon Footprint (PCF) comparison for different products / components	x	x	
29	Data ecosystem provider	Data ecosystem participants	Product / component / material data, e.g. material specifications, dismantling information, bill of material (BOM), CAD models, joining techniques, repair & dismantling instructions, approved spare parts	x	x	x

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
29	Data ecosystem participants	Data ecosystem provider	Product / component / material data, e.g. material specifications, dismantling information, bill of material (BOM), CAD models, joining techniques, repair & dismantling instructions, approved spare parts	x	x	x
30	Data ecosystem provider	Data ecosystem participants	Dismantling information incl. maps, ELV-requirements, bill of material (BOM), parts identification (communicated at production start of vehicle and continuously for vehicles' EoL)	x		x
30	Data ecosystem participants	Data ecosystem provider	Dismantling information incl. maps, ELV-requirements, bill of material (BOM), parts identification (communicated at production start of vehicle and continuously for vehicles' EoL)	x		x
31	Data ecosystem provider	Data ecosystem participants	Recyclability information for vehicle / components / materials	x	x	x
31	Data ecosystem participants	Data ecosystem provider	Recyclability information for vehicle / components / materials	x	x	x
32	Data ecosystem provider	Data ecosystem participants	Further data required for optimizing CE activities across vehicle lifecycle	x	x	x
32	Data ecosystem participants	Data ecosystem provider	Further data required for optimizing CE activities across vehicle lifecycle	x	x	x
33	OEM	OEM	Compatibility of components / vehicles across brands and models, reconditioning & repair options		x	
34	Reverse logistics provider	OEM	Component demand forecasts, origin & processing steps for returned components (regarding reuse, repair, refurbish, remanufacture)		x	
35	Reverse logistics provider	Tier 1-n supplier	Component demand forecasts, origin & processing steps for returned components (regarding reuse, repair, refurbish, remanufacture)		x	
36	Certifier / standardization organization	OEM	Accident statistics, failure rates and comparisons across brands and models		x	
37	Repair service provider	OEM	Information on repairability and disassembly capabilities and problems of components and vehicles, as well as failure frequencies		x	
38	OEM	Knowledge / technology provider	Product data, e.g. for optimizing R-strategy selection		x	
39	Repair service provider	OEM	Spare part order for repair		x	
39	OEM	Repair service provider	Spare part condition, origin, lifecycle data, dismantling/repair information, material composition (for original spare parts ordered from OEM)		x	

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
40	Digital marketplace	OEM	Vehicle / component condition, origin, price etc. (in cases where OEM buys back own or competitors' spare parts for e.g. remanufacture)		x	
41	OEM	Digital marketplace	Vehicle / component condition, origin, price etc. (in cases where OEM sells own or competitors' spare parts online)		x	
42	Digital marketplace	Tier 1-n supplier	Vehicle / component condition, origin, price etc. (in cases where tier 1-n buys back own or competitors' spare parts for e.g. remanufacture)		x	
43	Tier 1-n supplier	Digital marketplace	Vehicle / component condition, origin, price etc. (in cases where tier 1-n sells own or competitors' spare parts online)		x	
44	Tier 1-n supplier	OEM	Spare part condition, origin, lifecycle data, dismantling/repair information, material composition (in cases where OEM orders spare parts from tier 1-n)		x	
45	Dismantler	OEM	Lifecycle information about dismantled component, price, condition (in cases where OEM buys back own or competitors' spare parts for e.g. remanufacture)		x	
46	Dismantler	User	Lifecycle information about dismantled component, price, condition (in cases where user buys spare parts for performing repairs)		x	
47	Point of sale / distributor	OEM	Complaint and defect description (in cases where user reports failure)		x	
48	OEM	Development agency	Disassembly, repair, and remanufacturing training		x	x
49	Development agency	Automotive cluster	Disassembly, repair, remanufacturing and recycling training		x	x
50	OEM	User	Driving distances, driving behavior, consumption, comparison with other users, tips on ecologically friendly usage etc.		x	
51	Development agency	National / international legislator	Project reporting regarding funded activities		x	x
52	Data ecosystem provider	Knowledge / technology provider	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents	x	x	x
53	Dismantler	Tier 1-n supplier	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents (in cases where tier 1-n supplier buys back own or competitors' spare parts for e.g. remanufacture)		x	
54	Tier 1-n supplier	Knowledge / technology provider	Product data, e.g. for optimizing R-strategy selection		x	

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
55	Tier 1-n supplier	Repair service provider	Spare part condition, origin, lifecycle data, dismantling/repair information, material composition (for original spare parts ordered from tier 1-n)		X	
55	Repair service provider	Tier 1-n supplier	Spare part order for repair		X	
56	Tier 1-n supplier	User	Spare part condition, origin, lifecycle data, dismantling/repair information, material composition (for original spare parts ordered from tier 1-n)		X	
56	User	Tier 1-n supplier	Spare part order for repair		X	
57	Reverse logistics provider	Knowledge / technology provider	Static & dynamic vehicle and component data		X	X
58	Dismantler	Knowledge / technology provider	Static & dynamic vehicle and component data		X	X
59	Dismantler	Repair service provider	Static & dynamic vehicle and component data (read out from vehicle or component bought by repair service provider or at EoL)		X	X
60	Digital marketplace	Repair service provider	Vehicle / component condition, origin, price etc. (in cases where repair provider buys from digital marketplace)		X	
61	Repair service provider	Digital marketplace	Vehicle / component condition, origin, price etc. (in cases where repair provider sells to digital marketplace)		X	
62	Dismantler	Digital marketplace	Component condition, origin, price etc. (in cases where dismantler sells components to digital marketplace for reuse, repair, refurbish, remanufacture)		X	
63	Digital marketplace	User	Vehicle / component condition, origin, price etc. (in cases where user buys from digital marketplace for reuse, repair, refurbish, remanufacture)		X	
64	User	Digital marketplace	Vehicle / component condition, origin, price etc. (in cases where user sells to digital marketplace for reuse, repair, refurbish, remanufacture)		X	
65	Dismantler	User	Component condition, origin, price etc. (in cases where user buys from dismantler for reuse, repair, refurbish, remanufacture)		X	
66	Repair service provider	User	Information about driving behavior, consumption, eco-variants, tips on ecologically friendly usage etc. (when user comes in for inspection or repair)		X	
66	User	Repair service provider	Driving distances, driving behavior, consumption, e.g. via OEM app (when user comes in for inspection or repair)		X	

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
67	Repair service provider	Reverse logistics provider	Vehicle / component condition, origin, price etc. (in cases where reverse logistics provider handles returns of vehicles or components for e.g. OEM or tier 1-n supplier)		x	
68	User	Point of sale / distributor	Complaint and defect description (in cases where user reports failure)		x	
69	Point of sale / distributor	Reverse logistics provider	Information regarding spare parts demand to create forecast		x	
70	Reverse logistics provider	Logistics provider	Pick-up order		x	
71	User	Municipal authority	Vehicle usage data (for municipal vehicle on demand fleet)		x	
72	Data ecosystem provider	Data ecosystem participants	Recycling rates			x
72	Data ecosystem participants	Data ecosystem provider	Recycling rates			x
73	Data ecosystem provider	Data ecosystem participants	Performed reuse, repairs, refurbishment, remanufacturing		x	
73	Data ecosystem participants	Data ecosystem provider	Performed reuse, repairs, refurbishment, remanufacturing		x	
74	Data ecosystem provider	Data ecosystem participants	Spare part and material requirements		x	
74	Data ecosystem participants	Data ecosystem provider	Spare part and material requirements		x	
75	Data ecosystem provider	Data ecosystem participants	Component versioning (# reuse, reman etc.)		x	
75	Data ecosystem participants	Data ecosystem provider	Component versioning (# reuse, reman etc.)		x	
76	Data ecosystem provider	Data ecosystem participants	Safety check level (ASIL, SC, CC)		x	
76	Data ecosystem participants	Data ecosystem provider	Safety check level (ASIL, SC, CC)		x	
77	Data ecosystem provider	Data ecosystem participants	Component compatibility across brands and models		x	
77	Data ecosystem participants	Data ecosystem provider	Component compatibility across brands and models		x	
78	Data ecosystem provider	Data ecosystem participants	Remaining useful life / state of health of vehicles and components		x	
78	Data ecosystem participants	Data ecosystem provider	Remaining useful life / state of health of vehicles and components		x	
79	Data ecosystem provider	Data ecosystem participants	Predictive maintenance & spare parts forecast		x	
79	Data ecosystem participants	Data ecosystem provider	Predictive maintenance & spare parts forecast		x	
80	Data ecosystem provider	Data ecosystem participants	Crash & failure statistics		x	x

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
80	Data ecosystem participants	Data ecosystem provider	Crash & failure statistics		x	x
81	Reverse logistics provider	OEM	Component and materials forecast for recycling			x
82	Reverse logistics provider	Tier 1-n supplier	Component and materials forecast for recycling			x
83	Data provider	Dismantler	Dismantling specifications, product and safety data sheets, dismantling know-how			x
84	OEM	Certifier / standardization organization	Secondary alloy technical specifications			x
85	Tier 1-n supplier	Certifier / standardization organization	Secondary alloy technical specifications			x
86	OEM	Steel / aluminium plant	Alloys & properties required in the future, recycling requirements			x
86	Steel / aluminium plant	OEM	Material composition, recycling process, treatment, origin, quality, forecast of secondary alloys			x
87	Tier 1-n supplier	Steel / aluminium plant	Alloys & properties required in the future, recycling requirements			x
87	Steel / aluminium plant	Tier 1-n supplier	Material composition, recycling process, treatment, origin, quality, forecast of secondary alloys			x
88	Tier 1-n supplier	Steel / aluminium plant	Today's material & recycling requirements			x
88	Steel / aluminium plant	Tier 1-n supplier	Recycling process used, material composition			x
89	Shredder / recycler	Steel / aluminium plant	Sorting and recycling process, origin of scraps, scrap forecast			x
89	Steel / aluminium plant	Shredder / recycler	Material & recycling requirements, e.g. specifications of fractions			x
90	OEM	Shredder / recycler	Forecast: expected amount of EOL vehicles and their material composition			x
91	Dismantler	OEM	Lifecycle usage data, e.g. mileage, condition, performed repairs & maintenance, exchanged spare parts, accidents			x
92	Dismantler	OEM	Material accounting data			x
93	Dismantler	Tier 1-n supplier	Material accounting data			x
94	Dismantler	OEM	Certificate of Destruction (CoD) and quantities			x
95	OEM	Authority	Certificate of Destruction (CoD) and quantities			x
96	National / international legislator	Dismantler	Regulatory requirements, e.g. recycling quotes and dismantling procedures			x
97	Dismantler	Authority	Certificate of Destruction (CoD) and quantities			x

Appendix A (cont.). Overview of all data transactions between actors and assignment to product lifecycle phases (authors' own work).

ID	Source	Target	Content	BoL	MoL	EoL
98	Shredder / recycler	Other industries, e.g. infrastructure	Material condition, origin, price etc. (in cases where other industries buy materials which were generated from EoL vehicles, e.g. steel for construction)			x
99	Steel / aluminium plant	National industry association	Technical feasibility of regulatory requirements			x
100	Dismantler	National industry association	Technical feasibility of regulatory requirements			x
101	Other industries, e.g. infrastructure	Shredder / recycler	Material condition, origin, price etc. (in cases where other shredder / recycler buys materials from other industries to use in recycling processes)			x
102	User	Authority	Certificate of Destruction (CoD)			x
103	Dismantler	User	Certificate of Destruction (CoD)			x
104	Dismantler	Shredder / recycler	Forecast: expected amount of EOL vehicles and their material composition			x
105	Exporter	Authority	Vehicle treatment status (cannot be EoL vehicle)		x	
105	Authority	Exporter	Decision on export permit (cannot be EoL vehicle)		x	
106	Dismantler	OEM	Static & dynamic vehicle data (read out from vehicle at EoL)			x
SUM TOTAL				43	92	63