NordDesign 2022
August 16-19, 2022
Kgs. Lyngby, Denmark

Towards an open digital thread for electric mobility

Nils Weiher[1], Robert Mies[2], Nicolas Senge[3], Sonika Gogineni[4]

[1]*Open Source Ecology Germany e.V.*
nils.weiher@ose-germany.de
[2] *Technische Universität Berlin, Institute for Machine Tools and Factory Management*
robert.mies@tu-berlin.de
[3] *FernUniversität in Hagen, Institute for Political Science*
nicolas.senge@fernuni-hagen.de
[4] *Fraunhofer Institute for Production Systems and Design Technology (IPK)*
sonika.gogineni@ipk.fraunhofer.de

Abstract

The material intensity and ongoing servitisation of electric mobility highlights the relevance of circular design concepts focussed on reuse, remanufacturing and recycling that contribute to the transition towards sustainable value creation. This paper gives an overview on technology trends that call for the development of an open digital thread (ODT) for electric mobility which is investigated as a tool in a digitalised, connected and collaborative circular economy. Thus, the ODT in our definition connects the stakeholders across all life cycle phases as integrated digital infrastructure of electric mobility. Using open data principles, it is envisaged to enable participation, cooperation and collaboration by creating interoperability based on accessibility and (re)usability of data. Taking a life cycle perspective reveals the potential of knowledge-based decision making to improve the environmental impacts and operational performance of electric mobility. The paper posits a definition for the ODT followed by a brief overview of relevant concepts and technologies for its development. The results of a systematic literature review are presented, to identify the implications of the circular economy for the ODT. These results provide a basis for future research, which should investigate the requirements of data ontologies for the ODT in electric mobility and beyond and the process requirements for a transition towards opening data in a bottom-up approach.

Keywords: open digital thread, electric mobility, circular economy, open data, product service systems

1 Introduction

According to estimates of the Intergovernmental Panel on Climate Change (IPCC, 2014, p. 603), the transport sector is responsible for around 23% of the global energy-related CO_2 emissions. Transport is also among the sectors with the highest reduction potential, accompanied by energy and industry. Applying circular economy principles would be expected to yield significant potential for climate change mitigation (Cantzler et al., 2020).

Electric mobility in a circular business model could contribute to various Sustainable Development Goals (SDG), namely SDG 9 (industry, innovation, infrastructure), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action) based on the efforts in SDG 7 (affordable and clean energy), etc.

Although acknowledged for its relevance to address climate change and resource scarcity, the circular economy is currently still „stuck in the future.“ It lacks enforceable criteria, applicable strategies and most importantly: a systemic transition with the active participation of all stakeholders. In order to contribute to this transition, technologies must be embedded in transformative systems. Reduce, reuse and redesign concepts would have the potential to be most transformative but they are currently the least implemented strategies (Cantzler et al., 2020). To become a driver of the transition, business models with new forms of value creation based on a collaborative circular economy and integrated digitisation are required (D'heur, 2015). New trans-organisational open innovation processes are needed that connect product information across all product creation phases. Therefore, this contribution posits the idea of an open digital thread (ODT), which represents the physical product in the digital environment joining information flows between actors in the value creation network. It thereby integrates data with different levels of openness across all product creation phases, to connect all actors as information providers and users for sustainable value creation.

This paper gives an overview on the research context before it then explores the present relevance as well as general requirements for the underlying infrastructure from a life cycle perspective and the consequential research needs.

2 Towards an open digital thread for electric mobility

The circular economy in the future irrevocably depends on digitalisation to optimise material flows and interconnect stakeholders in industry. As a complex system of products and services the mobility sector contains multiple sub-products. Shared mobility services require fleet management and maintenance, which in turn requires a digital infrastructure to track the supply chain of the final product and monitor sustainability across its life cycle. Since electric mobility has already become a digital product, the existing underlying information and communication technology (ICT) infrastructure is a key asset for sustainable development.

Leal Filho et al. (2021) provide an overview on electric mobility research from a circular economy perspective and the potential for a transition towards a sustainable automotive industry. Closed-loop traction-batteries and sustainable product service systems are essential to reduce the demand for critical raw materials. Local production of renewable energies and smart integration of vehicles into the electricity grid (vehicle-to-grid) provide an increase in energy efficiency and improve the systems impact. Considering the importance of improved services (Cherubini et al., 2015), digital technology is an important enabler for use-oriented shared mobility services which increase the efficiency of car usage during their lifetime. Moreover, a growing sustainability awareness is creating new user preferences, which suggests integrating customers into an open innovation ecosystem (Wurster et al., 2020).

To address these challenges, this paper suggests the concept of the ODT, which integrates open data principles and a holistic life cycle approach in a digital thread ontology. The concepts and technologies used in the following definition (see figure 1) will be defined in chapter 2 (state of the art). This paper defines: *The open digital thread describes the information flows between actors in the value creation network, that provide and use data* *with different levels of openness for sustainable value creation. Accessibility and (re)usability of data are a prerequisite for interoperability in the open digital thread.*

The ODT thus combines holistic life cycle information with the interoperability of the digital thread ontology. However, interoperability from an open data perspective is based on accessibility and (re)usability of data. With open data principles, the ODT connects diverging data streams with open and restricted access in a holistic, up-to-date digital model of the product. It thereby enables multi-stakeholder collaboration and real-time maintenance of the data. The corresponding information flows provide the required information in every life cycle stage. By providing critical life cycle information the ODT improves the systemic circular material flows and the individual service quality respectively. Every actor becomes both, provider and user of this information.

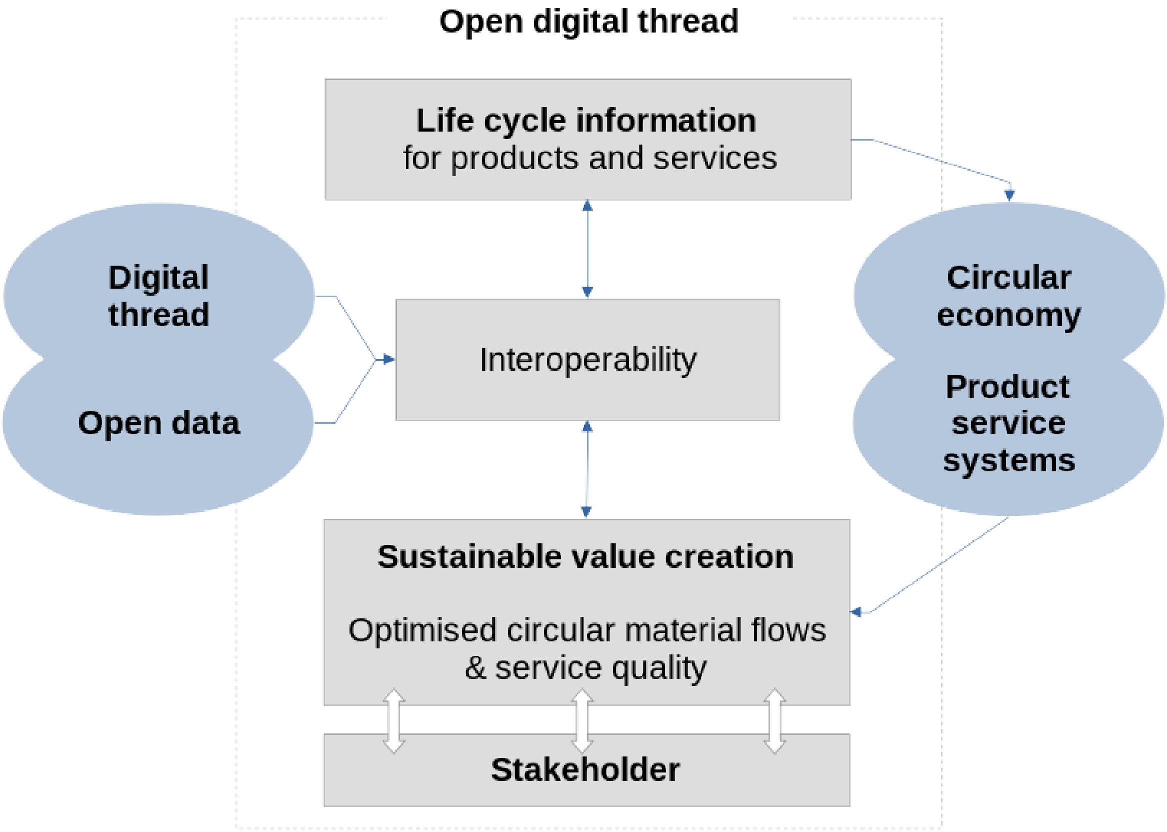


Figure 1. Organising framework for the open digital thread

This paper focuses on the research question, whether the digital twin and digital thread may be a key concept for a sustainable usage of electric mobility by optimising the information exchange and the (re)use of resources in innovative business models. As an established method to evaluate the environmental impact of products and technologies, life cycle assessment (LCA) is used to address this research question.

3 State of the art

The ODT, embedded in the circular economy context, can be viewed as part of sustainable value creation. The concept has the potential to lift the burdens of the linear economy based on holistic value creation, where companies' core businesses contribute to economic, ecological and social values. It emphasises the importance of cooperation and collaboration between all stakeholders and redefines the common value creation chain as a value creation network (D’heur, 2015). The concepts and technologies addressed by the ODT will be briefly outlined in the following paragraphs:

3.2.1 From digital twins to digital threads

Complexities involved in product development continue to rise, with demand for individualisation, personalisation and customizability. This leads to generation of variants of models and associated data. For product development in organisations, there are large investments being undertaken in developing a backbone of traceable product data (Bahrenburg et al., 2019). The reason is the need to track consecutive changes to product and data along the product life cycle. The approach of managing product-related data across its life cycle is called product lifecycle management (PLM), which aims at achieving a connected system landscape in industries. To enable such a landscape, the digital entities have to be identified and connected, leading to the development of a digital thread (Pang et al., 2021). This is an important requirement for a broader implementation of digital twins. A digital twin of a product or a product service system is its unique digital representation, which can consist of data, models, properties, characteristics among many others (Stark & Damerau, 2019). Depending on the application, the digital twin requires information from a single or multiple life cycle phases and is therefore part and parcel with the concept of the digital thread.

The digital thread is an instrument of digitalised industrial development, used for continuous development over all life cycle phases (Hedberg, 2018). Every phase is cross-linked with processes that create and update product lifecycle data for knowledge-driven decision making. A key of the underlying ontology is the data certification and traceability. By ensuring authentication, authorisation and traceability of data it builds trust throughout the product life cycle. Product-data quality (PDQ) services integrate, verify and validate datasets using digital fingerprints and cryptographic services with digital certificates. Trusted linked data enables the central administration of data in registered databases. Near real-time updating of domain-specific information is provided by machine learning and artificial intelligence (ibid.).

However, developing and implementing digital thread systems, in individual organisations or as closed source, is expensive and time consuming (West and Blackburn, 2017; Pang et al., 2021). Hence, reliance on standards, reuse of suitable modules, development and usage of open systems are some suggested sustainable options.

3.2.2 Open Data

Open data contains universal data standards but also encompasses different ways of data access. The openness of data is a relevant prerequisite for a collaborative digital thread that supports value co-creation. According to the Open Knowledge Foundation, open data is data that “can be freely used, re-used and redistributed by anyone” (OKF, 2021). The rights of open data grant availability and access as well as the reuse and redistribution of information. To allow universal participation, interoperability is a critical element of the concept: Interoperability is the exchange of information between diverging systems and organisations. The availability of data is measured in its level of openness, which is usually defined as access under equal terms and minimal costs (OKF, 2021). Open data affects contents and software as well as hardware. In open data business models, the level of openness can be described by two variables (Janssen & Zuiderwijk, 2014): The access to data determines the state of pre-structuring and processing that the shared data has received, and how it can be reused. The level of dialogue then determines the possibilities of manipulating the data. Transitioning from proprietary to open data for sustainability purposes will be a gradual learning process for companies in particular as they will require needed guidance by intermediary structures (Kivimaa et al., 2019).

3.2.3 Circular economy

The circular economy is a counter-design to the classic linear economic model (Berg & Wilts, 2019) in which materials are extracted, processed, used, and finally disposed of by incineration or landfill. While this creates numerous ecological problems, it also means that these materials can no longer be used to generate economic value (SRU, 2020). In contrast, a circular economy seeks to “preserve the value of utilised resources and materials as long as possible, to use them as frequently as possible, and to produce as little waste as possible (ideally none at all). The concept covers all aspects of economic activity, from resource extraction through production, storage and consumption, ending with disposal or ideally recycling” (Wilts, 2016, p. 6). To preserve the value of the material input as well and as long as possible, the circular economy attempts to extend the product life cycle, to increase the use intensity, to keep the residual amount of waste as low as possible and to recycle it as well as possible. Thus, the circular economy is a systemic and holistic design concept that aims at a closed resource and material cycle to minimise the negative environmental impact of economic activity and thereby contributes to sustainable value creation.

By extending the use phase and increasing the use-intensity, resource consumption and waste can be reduced to a minimum. As a corollary, the instrumentation of a circular economy can lead to striking reductions in greenhouse gas emissions (SRU, 2020). But the circular economy not only offers numerous opportunities to reduce the environmental impact of economic activity, it also can achieve a range of economic advantages - such as cost-saving potential for companies and consumers or increased competitiveness through independence from price volatilities of crucial materials (Ellen MacArthur Foundation, 2016). Based on these facts, the European Commission has emphasised in its 2020 Circular Economy Action Plan that the transformation to a circular economy will be central to the future competitiveness of European industry (EC, 2020). Nevertheless, only marginal progress in the implementation of a circular economy is currently discernible. Contrary to initial assumptions, the obstacles are not due to a lack of technology, but rather to information deficits (Berg & Wilts, 2019). As digital technologies are ideally suited to solve problems such as high information asymmetries, low market transparency and low information standards, they can make an important contribution to create a circular economy.

3.2.4 Product service systems

Suitable circular business models are indispensable to move the circular economy from theory into practice (SRU, 2020), as they make the transformation economically viable (Ellen MacArthur Foundation, 2016) while increasing customer convenience and thus technology adoption. Given the fact that the problems lie in particular in the lack of availability of the necessary (or correct) information, ICT-oriented business models provide promising starting points (Berg and Wilts, 2019). By providing services offering the functions of products instead of individual products, product service systems (PSS) can contribute to a reduction in resource consumption. PSS models combine a physical product with a service component. While customers use the products, these remain the property of the service provider. Depending on whether the focus is on product or service, there are various design options along a continuum between product and service orientation. Essentially, three variants can be distinguished (Tukker, 2015): Product-oriented services create business models around the sale of products and additional services (product-related, advice and consultancy). In use-oriented services the ownership of the product remains at the service provider. Typical forms are product-leasing, -renting, -sharing and -pooling. Result-oriented services are independent of the product. Typical forms of these services are: activity management, pay-per-service-unit and selling functional results.

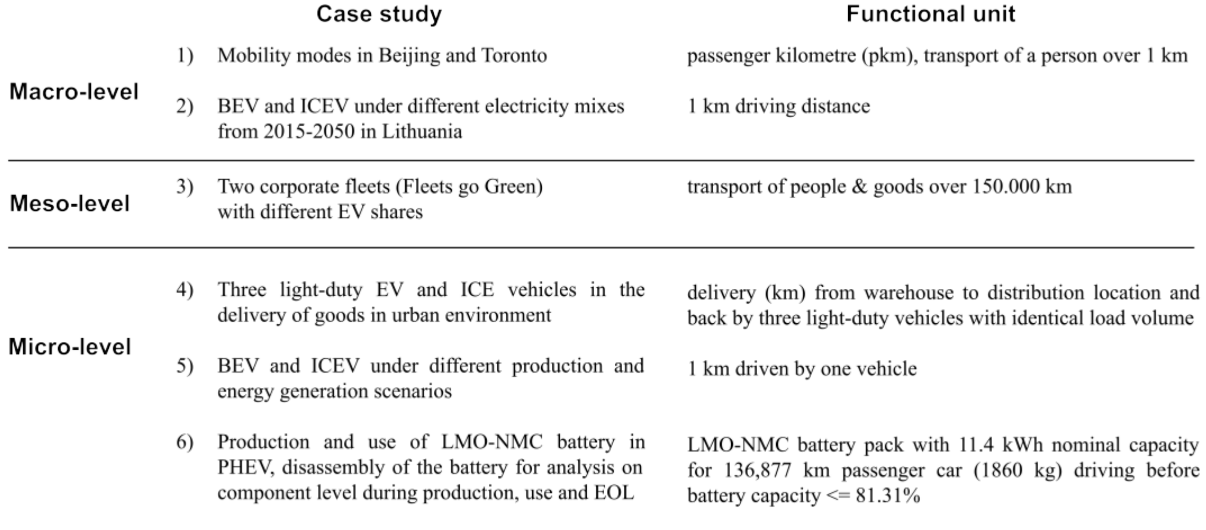
From a sustainability perspective, product-oriented services have the least impact, as they change the architecture of value creation only marginally. Although the use-oriented models contribute to resource efficiency, these can be partially offset by rebound effects. Accordingly, by shifting the perspective of value creation from product to service, result-oriented services offer the highest potential for the creation of sustainable value (Tukker, 2015). Thus, product service systems are a relevant concept for optimising the environmental impact and service-quality of electric mobility by higher use-intensity and convenience.

4 Results of systematic literature review

To investigate the implications of the circular economy for the ODT, a systematic literature review was performed. Using life cycle assessment studies, the main drivers for the environmental impact could be identified. A meta-study by the European Environment Agency (EEA, 2018) further helped to verify the results and identify implicated design paradigms of the life cycle perspective. The results are then combined to reveal the critical information flows of the ODT from a life cycle perspective.

4.1 Life cycle assessment analysis

Life cycle assessment (LCA) is a method for environmental impact evaluation of products and processes, standardised in ISO 14040:2006 and ISO 14044:2006. Although the method does not cover all dimensions of circularity, it is a suitable and accepted format to analyse the environmental impact of products and technologies**.** The data basis for the systematic literature review are LCA studies between 2015 and 2021 containing the keywords “life cycle assessment” in combination with “electric mobility” or “electric car-sharing” on the platform scopus. The results are then narrowed down by availability, English language (n=26) and peer-reviewed studies according to ISO (see above, n=14). Subsequently representative studies for critical service elements connected to electric mobility were selected, containing primary data, comparable impact evaluation and sufficient validity checks (n=6). The functional unit, in LCA, compares different systems by their main function.



		Case study	Functional unit
Macro-level	1)	Mobility modes in Beijing and Toronto	passenger kilometre (pkm), transport of a person over 1 km
	2)	BEV and ICEV under different electricity mixes from 2015-2050 in Lithuania	1 km driving distance
Meso-level	3)	Two corporate fleets (Fleets go Green) with different EV shares	transport of people & goods over 150.000 km
Micro-level	4)	Three light-duty EV and ICE vehicles in the delivery of goods in urban environment	delivery (km) from warehouse to distribution location and back by three light-duty vehicles with identical load volume
	5)	BEV and ICEV under different production and energy generation scenarios	1 km driven by one vehicle
	6)	Production and use of LMO-NMC battery in PHEV, disassembly of the battery for analysis on component level during production, use and EOL	LMO-NMC battery pack with 11.4 kWh nominal capacity for 136,877 km passenger car (1860 kg) driving before battery capacity <= 81.31%

Figure 2. Evaluated case studies; (1: Sun & Ertz, 2021; 2: Petrauskienė et al., 2020; 3: Dér et al., 2018; 4: Marmiroli et al., 2020; 5: Tagliaferri et al., 2016; 6: Cusenza et al., 2019)

The resulting studies (figure 2) are classified according to their scope corresponding to the eLCAr guidelines (Duce et al., 2013). The guidelines differentiate studies in micro and macro/meso levels, depending on the decision context, to consider the systemic interdependencies. The vehicles referred to in the studies are electric vehicles (EV), battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV) and internal combustion engine vehicles (ICEV). Across all studies the most referenced topic is climate change mitigation. Hence, electric vehicles are mostly discussed for their potential to reduce carbon dioxide emissions. Exhaust emissions are reduced to almost zero, depending on the share of renewable energies used for operation. However, EVs require an increased amount of metals and chemicals, which increases their negative impact during production, specifically related to human- and ecotoxicity impacts. Thus, the transition to EV causes a **burden shifting** from fossil to abiotic resource-related impacts. **Energy-related impact** (**ERI**) factors (e.g. global warming potential, cumulative energy demand, abiotic depletion of fossil fuels) are concentrated on the electricity provision for vehicle operation and manufacturing processes. The **resource-related impact** (**RRI**) factors (e.g. abiotic depletion, eutrophication, acidification) are primarily focussed on the raw material extraction and production.

Necessarily, the interpretation of results depends on the assessed categories and chosen allocation models, which differ among the studies. Raw material extraction is often contained in the production phase and the benefits of recycling are mostly limited to the end-of-life phase. However, as will be discussed next, the uncertainties do not affect the end results.

4.2 Implications of circular design for electric mobility

For uncertainty reasons the results are compared to the report of the European Environment Agency (EEA, 2018) which summarises the results of several research and LCA studies for electric mobility. Overall, the conclusions were found to be equivalent. While our research focussed on the information flows the EEA meta study further discusses the implications of the most significant impacts and the critical factors for circular design.

The use phase is dominant over the whole life cycle of all vehicle types and is determined by the energy generation. Thus, the energy generation mix and charging efficiency are the primary parameters for the impact optimisation of electric mobility. During material extraction and production energy efficiency is the most relevant, especially for the energy intensive manufacturing of batteries.

Material efficiency can lift the burdens of resource-intensive electric vehicles. The EEA report names recycling and light-weighted design as concepts to increase the material efficiency and reduce the amount of required critical raw materials. The end of life phase in most LCA studies is restricted to incineration and limited recycling, representing the status quo. On the contrary, material flows in a circular system offer a tremendous potential to increase the component/material reuse and recovery rates. The EEA report highlights reuse, repair, redistribution, refurbishment and remanufacturing as end of life concepts.

The critical distance when the environmental benefits of the use-phase surpasses the higher burdens of production (see *2.1 Life cycle assessment analysis*, burden shift) is called the **(ecological) break-even point**. This point is influenced by the use-intensity and service life of electric vehicles. Shared mobility can increase the use-intensity by reducing the number of owned cars and optimisation of the vehicle proportions per use case. Cherubini et al. (2015)

further highlights the relevance of service elements in electric mobility, which increase the convenience and technology acceptance alongside with service life by optimal maintenance.

4.3 Implications for the open digital thread

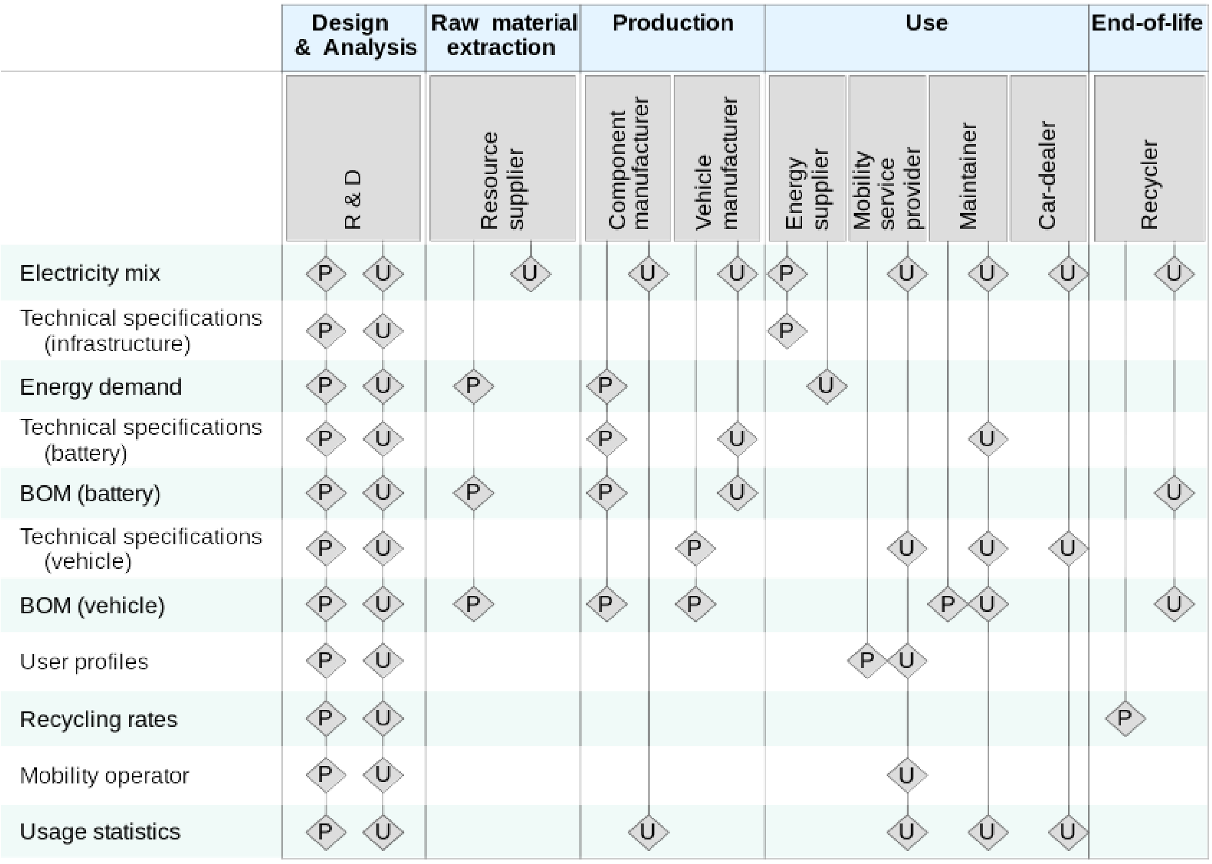
The parameters identified above relate to the critical service elements in the electric mobility network from a life cycle perspective. They allow to derive some data requirements regarding circularity in the ODT. While LCA is focussed on material flows in the product life cycles, a holistic ODT must also consider the supporting life cycle phases required for improving the product service system network. Thus, for the purpose of the information flow analysis, central life cycle phases from industrial manufacturing (Hedberg, 2018) will be integrated: Design: Innovations and product development; Raw material extraction: Material extraction and processing; Production: Manufacturing of components and products; Use: Operation of vehicles; provision of energy, maintenance and mobility services; EOL: Recycling of the vehicles' components; Analysis: Product and process assessment for quality assurance and optimisation. The optimisation of the critical service elements requires a couple of information flows which will be outlined briefly in table 1. The index numbers refer to the studies in which the parameters were identified.

Table 1. Critical service elements of electric mobility and their mitigation potential

Service element	**Parameter**	**Impact mitigation potential** (negative impacts)	**Required information**
Resource Supply	Energy efficiency [5]	Higher efficiency of resource extraction and refining processes reduces energy demand and thus **ERI.**	**Energy demand** (resource extraction)
Component and vehicle manufacturing	Energy efficiency [5]	Higher efficiency in battery assembly reduces energy demand and thus **ERI.**	**Energy demand** (battery assembly)
	Material efficiency [3,5,6]	Higher material efficiency in production reduces the absolute amount of abiotic raw materials and thus **RRI.**	**BOM** (battery, vehicle)
	Battery lifetime [6]	Battery lifetime substantially reduces **RRI** (per trip) by extended vehicle lifetime without battery replacement.	**Technical specifications** (battery), **BOM** (battery)
	Drivetrain and auxiliary energy demand [3,4,6]	Energy efficiency & rate of regenerative braking determine energy demand and EV range, reducing **ERI.**	**BOM** (battery, vehicle)**, User profiles**
Energy supply	Electricity production [2,3,4,5,6]	Renewable energy production potentially reduces **ERI** to zero.	**Electricity mix** with share of renewable energies
	Distribution efficiency [4]	Efficiency is determined by energy losses and materials used for the required infrastructure and reduces **ERI** and **ERI.**	**Technical specifications** (infrastructure)
Mobility -service	Mobility modes [1]	Choice of mobility service characteristics (e.g. station based, free-floating) substantially influences RRI and ERI considering required infrastructure, rebalancing and deadheading rates.	**Mobility operator**, **User profiles**, **Usage statistics**
	Service life [1]	Length of service life determines the share of manufacturing impact accounted for per trip, reducing **RRI**.	**Technical specifications** (vehicle, battery), **BOM** (vehicle, battery)**, Usage statistics**
	Use-intensity [1]	Use-intensity of vehicles depends on service	**Technical**

		lifetime and occupancy within the different mobility modes. High use-intensity reduces the burdens of **RRI** per trip.	**specifications** (vehicle), **Mobility operator**, **Usage statistics**
Recycling	Recycling rate [6]	Designs for disassembly and recycling improve the number and rate of materials recovered and thus reduce **RRI.**	**BOM** (vehicle, battery)
	Recycling efficiency [6]	Increased efficiency reduces **ERI** burdens and thus positive recycling impacts can easier surpass the higher energy costs	**Recycling rate**
Reuse	Use-intensity [6]	Reuse concepts improve use-intensity and thus **RRI** by using batteries < 80% capacity in non-critical stationary applications.	**Usage statistics, Technical specifications** (battery)

The **technical specification** only contains the basic dimensions. The **bill of materials (BOM)** on the other hand contains the manufacturing data of vehicles and batteries. It encompasses detailed information on the components, their assembly and the used materials. Based on the technical information, products can be dimensioned according to the use cases. Further, products can be optimally designed for reuse and material recovery at the end of life, thus supporting knowledge-based decision making along the life cycle. **User profiles** contain data about the personal preferences of vehicle users regarding the driving parameters and use of auxiliary systems. The **mobility operator** is a statistical measure of the different mobility modes used on a transport system scale. **Usage statistics** contain information on the average lifetimes of vehicles within different **mobility modes**. The usage data can be utilised to optimise service offers by choosing the best vehicles and mobility modes regarding the use cases and convenience of customers.



	Design & Analysis	Raw material extraction	Production		Use				End-of-life
	R & D	Resource supplier	Component manufacturer	Vehicle manufacturer	Energy supplier	Mobility service provider	Maintainer	Car-dealer	Recycler
Electricity mix	P U	U	U	U	P	U	U	U	U
Technical specifications (infrastructure)	P U				P				
Energy demand	P U	P	P		U				
Technical specifications (battery)	P U		P	U			U		
BOM (battery)	P U	P	P	U					U
Technical specifications (vehicle)	P U			P		U	U	U	
BOM (vehicle)	P U	P	P	P			P U		U
User profiles	P U					P U			
Recycling rates	P U								P
Mobility operator	P U					U			
Usage statistics	P U		U			U	U	U	

Figure 3. Critical information flows (P=provision, U=use) in the digital thread from life cycle perspective

In order to utilise the potentials and improve the environmental impact of electric mobility, the stakeholders in the value creation network of electric mobility need to be connected. Therefore, the digital twin needs to contain the critical information for knowledge-based decision making. This, again, depends on the active collaboration of the stakeholders and information providers. The ODT would combine these requirements by creating accessibility, (re)usability and interoperability of the data and providing the required infrastructure for a real-time exchange of the critical information. The information flow provision identified as critical from a life cycle perspective is presented in figure 3.

5 Summary and outlook

This paper attempted to outline the potential of the ODT to contribute to sustainable value creation in a circular economy context. It thereby provides a basis for future research regarding the development of a digitalised, connected and collaborative circular economy and the related infrastructure.

5.1 Summarising implications

The LCA analysis provided insights on the burden shift from energy related to resource related impacts, caused by the higher material demand of EV production. Material design and the recovery of materials at the end of life can compensate for the higher resource requirements. This highlights the relevance of circular design concepts that favour reuse, remanufacturing and recycling and integrate them over the whole life cycle. The usage data further enables different aspects of participation, cooperation and collaboration, based on open data principles. The data is generated by the users and mostly utilised by service providers, to improve use-intensity and service life. The information flows in the ODT integrate the stakeholders in the sustainable value creation network. Thereby, they allow a continuous development process across all life cycle phases using technical data and knowledge-based decision making. By allowing different levels of openness, stakeholders can participate in accordance with their business models, which supports a systemic transition towards opening up data but keeping control over it.

5.2 Future research on the open digital thread

The ODT, first of all, demands further theoretical investigation. Based on a solid definition integrating interoperability, accessibility and usability, a data ontology for the ODT can be constructed, both for electric mobility and in a generic approach. As addressed by Hedberg (2021), the digital thread is based on universal open data standards to exchange information. The standards need to be compatible with both open and proprietary data formats used during the products’ life cycle. The ODT additionally suggests the progressive opening of data access, to continuously improve the information quality for development and decision making. Initiatives such as Catena-X and GAIA-X, which aim at supporting and developing a collaborative data ecosystem in the mobility sector, are promising developments in the direction of an ODT (Catena-X Automotive Network, 2021). This transition process requires a bottom-up approach in close dialogue with the involved stakeholders. Hence, for the practical implementation of an ODT for electric mobility, the representatives from the connected industries need to be involved, in order to verify the theoretical results.

6 References

Bahrenburg, S.; Munk, S.; Fischer, J.; Rützel, H.; Fuchs, B. (2019): Studie „Future PLM“.

Product Lifecycle Management in der digitalen Zukunft – Wegbereiter für IoT, Industrie 4.0 und Digital Twin. BearingPoint. Available online at https://www.bearingpoint.com/files/PLM_BearingPoint_Studie.pdf?download=0&itemId=564780.

Berg, H., & Wilts, H. (2019). Digital platforms as market places for the circular economy—Requirements and challenges. *NachhaltigkeitsManagementForum| Sustainability Management Forum*, *27*(1), 1–9.

Cantzler, J., Creutzig, F., Ayargarnchanakul, E., Javaid, A., Wong, L., & Haas, W. (2020). Saving resources and the climate? A systematic review of the circular economy and its mitigation potential. *Environmental Research Letters*, *15*(12), 123001. https://doi.org/10.1088/1748-9326/abbeb7

Catena-X Automotive Network (2021): Catena-X is proud to be the first Gaia-X industrial lighthouse project. Available online at https://catena-x.net/en/news-en/nov-18th-2021-catena-x-is-proud-to-be-the-first-gaia-x-industrial-lighthouse-project.

Cherubini, S., Iasevoli, G., & Michelini, L. (2015). Product-service systems in the electric car industry: Critical success factors in marketing. *Journal of Cleaner Production*, *97*, 40–49. https://doi.org/10.1016/j.jclepro.2014.02.042

Cusenza, M. A., Bobba, S., Ardente, F., Cellura, M., & Di Persio, F. (2019). Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Journal of Cleaner Production*, *215*, 634–649. https://doi.org/10.1016/j.jclepro.2019.01.056

Dér, A., Erkisi-Arici, S., Stachura, M., Cerdas, F., Böhme, S., & Herrmann, C. (2018). Life Cycle Assessment of Electric Vehicles in Fleet Applications. In C. Herrmann, M. S. Mennenga, & S. Böhme (Eds.), *Fleets Go Green* (pp. 61–80). Springer International Publishing. https://doi.org/10.1007/978-3-319-72724-0_5

D'heur, M. (2015). shared.value.chain: Profitable Growth Through Sustainable Value Creation. In *Sustainable Value Chain Management: Delivering Sustainability Through the Core Business* (pp. 1–108). Springer International Publishing. https://doi.org/10.1007/978-3-319-12142-0

Duce, A., Egede, P., Öhlschläger, G., Dettmer, T., Althaus, H., Bütler, T., & Szczechowicz, E. (2013). ELCAr—Guidelines for the LCA of electric vehicles. January 31, 2013: Proj. No. 285571. *Report from Project "E-Mobility Life Cycle Assessment Recommendations", Funded within the European Union Seventh Framework Programme—FP7/2007-2013*.

EC (2020). *A new Circular Economy Action Plan For a cleaner and more competitive Europe*. European Commission (EC).

EEA (2018). *Electric vehicles from life cycle and circular economy perspectives: TERM 2018 : Transport and Environment Reporting Mechanism (TERM) report.* European Environment Agency (EEA), https://data.europa.eu/doi/10.2800/77428

Ellen MacArthur Foundation. (2016). *The New Plastics Economy—Rethinking the future of plastics*. World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company. http://www.ellenmacarthurfoundation.org/publications

Hedberg, T. D. (2018). *Enabling Connections in the Product Lifecycle using the Digital Thread* [Dissertation, Faculty of the Virginia Polytechnic Institute and State University].https://vtechworks.lib.vt.edu/bitstream/handle/10919/85627/Hedberg_TD_D_2018.pdf?sequence=1&isAllowed=y

Hedberg, T. D., Sharp, M. E., Maw, T. M. M., Helu, M. M., Rahman, M. M., Jadhav, S., Whicker, J. J., & Barnard Feeney, A. (2021). Defining requirements for integrating information between design, manufacturing, and inspection. *International Journal of Production Research*, 1–21. https://doi.org/10.1080/00207543.2021.1920057

IPCC. (2014). *Climate change 2014: Mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the IPCC*. Cambridge University Press, Intergovernmental Panel on Climate Change (IPCC).

Janssen, M., & Zuiderwijk, A. (2014). Infomediary Business Models for Connecting Open Data Providers and Users. Social Science Computer Review, 32(5), 694–711. https://doi.org/10.1177/0894439314525902

Kivimaa, P., Hyysalo, S., Boon, W., Klerkx, L., Martiskainen, M., & Schot, J. (2019). Passing the baton: How intermediaries advance sustainability transitions in different phases. *Environmental Innovation and Societal Transitions*, *31*, 110–125.

Leal Filho, W., Abubakar, I. R., Kotter, R., Grindsted, T. S., Balogun, A.-L., Salvia, A. L., Aina, Y. A., & Wolf, F. (2021). Framing Electric Mobility for Urban Sustainability in a Circular Economy Context: An Overview of the Literature. *Sustainability*, *13*(14), 7786. https://doi.org/10.3390/su13147786

Marmiroli, B., Venditti, M., Dotelli, G., & Spessa, E. (2020). The transport of goods in the urban environment: A comparative life cycle assessment of electric, compressed natural gas and diesel light-duty vehicles. *Applied Energy*, *260*, 114236. https://doi.org/10.1016/j.apenergy.2019.114236

OKF. (2021, August 13). *What is Open Data?* Open Knowledge Foundation (OKF). http://opendatahandbook.org/guide/en/what-is-open-data/

Pang, T. Y., Pelaez Restrepo, J. D., Cheng, C.-T., Yasin, A., Lim, H., & Miletic, M. (2021). Developing a Digital Twin and Digital Thread Framework for an ‘Industry 4.0’ Shipyard. *Applied Sciences*, *11*(3), 1097. https://doi.org/10.3390/app11031097

Petrauskienė, K., Skvarnavičiūtė, M., & Dvarionienė, J. (2020). Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *Journal of Cleaner Production*, *246*, 119042. https://doi.org/10.1016/j.jclepro.2019.119042

SRU. (2020). *Circular economy: Putting ideas into practice, Environmental Report 2020 Chapter 3 (abridged version)*. German Advisory Council on the Environment (SRU).

Stark, D. R., & Damerau, T. (2019). Digital Twin. In *CIRP encyclopedia of production engineering* (pp. 1–8). Springer Berlin Heidelberg.

Sun, S., & Ertz, M. (2021). Environmental impact of mutualized mobility: Evidence from a life cycle perspective. *Science of The Total Environment*, *772*, 145014. https://doi.org/10.1016/j.scitotenv.2021.145014

Tagliaferri, C., Evangelisti, S., Acconcia, F., Domenech, T., Ekins, P., Barletta, D., & Lettieri, P. (2016). Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chemical Engineering Research and Design*, *112*, 298–309. https://doi.org/10.1016/j.cherd.2016.07.003

Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

West, T.; Blackburn, M. (2017): Is Digital Thread/Digital Twin Affordable? A Systemic Assessment of the Cost of DoD’s Latest Manhattan Project. In Procedia Computer Science 114, pp. 47–56. DOI: 10.1016/j.procs.2017.09.003.

Wilts, H. (2016). *Germany on the Road to a Circular Economy?* Friedrich-Ebert-Stiftung, Division for Economic and Social Policy.

Wurster, S., Heß, P., Nauruschat, M., & Jütting, M. (2020). Sustainable Circular Mobility: User-Integrated Innovation and Specifics of Electric Vehicle Owners. *Sustainability*, *12*(19), 7900. https://doi.org/10.3390/su12197900