THESIS FOR DEGREE OF LICENTIATE OF PHILOSOPHY

# Circularity as an enabler for sustainable value chains

Managing and controlling the battery value chain for heavy trucks

STINA LUNDIN

Department of Technology Management and Economics

Division of Supply and Operations Management

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden, 2025

**Circularity as an enabler for sustainable value chains**

STINA LUNDIN



Department of Technology Management and Economics

Division of Supply and Operations Management

CHALMERS UNIVERSITY OF TECHNOLOGY

SE-412 96 Gothenburg

Sweden

Printed by Chalmers Reproservice

Gothenburg, Sweden 2025

# Circularity as an enabler for sustainable value chains

Managing and controlling the battery value chain for heavy trucks

STINA LUNDIN

*Department of Technology Management and Economics*

*CHALMERS UNIVERSITY OF TECHNOLOGY*

**Abstract**

Environmental sustainability has become a pressing challenge, with global warming underscoring the need for innovative solutions. The vehicle industry is shifting from fuel- to material-intensive systems, particularly with battery-electric heavy trucks. The automotive industry's transition towards electrification has increased the demand for critical materials, risking shortages and raising ethical and environmental concerns, which highlights the need for a circular economy. Achieving zero-emission trucking depends on efficient battery use, extending battery life, and implementing end-of-life solutions to reduce reliance on virgin materials. Circular value chains for heavy truck batteries are essential in order to secure the supply of critical raw materials and support environmentally sustainable solutions. For battery manufacturers, circularity helps avoid price volatility, supply chain disruptions, and geopolitical dependencies. However, there is limited understanding of the transformation needed to achieve large-scale industrialized circularity in battery production. This research aims to shed light on the circular opportunities of battery life.

Achieving circularity for heavy truck batteries requires key shifts, including battery design for extended use and material recovery and set-up of reverse supply chains to address material shortages and geopolitical risks. In addition, technical solutions for the recycling process and access to battery data throughout the battery journey are essential for informed decisions and circular strategies.

**Key words:** Electric vehicle batteries, Self-actualization, Circular economy, Mass customization, Servitization

**Acknowledgements**

I would like to express my deepest gratitude to my supervisor, Professor Árni Halldorsson at Chalmers University of Technology, for his guidance, encouragement, and inspiration throughout this journey. Árni's insights, expertise, and support have been invaluable in shaping both this dissertation and my approach to research.

I would like to thank all the colleagues in the Volvo Group that participated in the different studies of my research for their valuable input, knowledge, and interest. Their diverse perspectives and expertise have been instrumental in broadening my understanding of this field. In addition, I am very thankful for the inspiration and feedback that Malin Hane Hagström, Director Sustainability at Volvo Powertrain in Skövde, provided me as my industrial supervisor.

Finally, I would like to express my gratitude for the possibility to connect with so many knowledgeable and intelligent people during this research project, both in academia and in the industry. Thank you to everyone who has contributed, either directly or indirectly.

Stina Lundin
Gothenburg, Sweden 2025

# Appended Publications

The following publications are included in this thesis:

**Paper A**

Lundin, S., Halldorsson, Á. Self-actualization of electric vehicle batteries: Challenges and opportunities for circular value chains. An earlier version of this paper was presented at the Annual EurOMA conference, Leuven, July 2023.

In review for international journal

**Paper B**

Lundin, S., Halldorsson, Á. A shared battery system beyond the brand dimension: The holy grail of mass customization

In review for international journal

**Other publications excluded from the thesis**

Ellram, L., Schiffling, S., Heikkinen, H., Lundin, S., Munyoro, J., Zhuravleva, A., (2025), Unravelling Circular Economy Tensions through Paradox Theory. In review for *Journal of Supply Chain Management.*

# Contents

## List of figures



## List of tables

# 1. Introduction

Environmental sustainability has become an increasingly pressing challenge in recent years, with global warming driven by greenhouse gas emissions highlighting the need for innovative solutions. Electrification has been identified as the primary way for the transportation sector to become climate-neutral. Achieving climate neutrality through electrification requires integration of circularity throughout value chains. The urgency to address environmental issues through electrification is evident in initiatives like the European Green Deal and international climate agreements.

The vehicle industry is undergoing a major technological transformation, shifting from fuel-intensive to material-intensive systems. As a reference, the critical material demand for electric vehicle batteries is expected to increase up to 26-fold by 2050 (Lehtimäki et al., 2024). The technological transformation is influencing the complete value chain, organizations, business models, and geographical footprints. This complex global challenge demands solutions that balance societal, ecological, and economic sustainability. To scale the production of battery electric heavy trucks, the battery material value chain must be established, developed, and maintained in a sustainable manner. In this thesis, the value chain concept refers to the activities that add value (Walters et al., 2000) to battery raw materials throughout their journey, in contrast to the supply chain that focuses on the flow of battery materials (Mentzer et al., 2001), without necessarily adding value.

For the heavy truck industry, as for the automotive sector in general, the shift to electrification requires the development of sustainable solutions through circular practices, which are currently not in place. Extending battery life across first- and second-use phases, repurposing them in a third life, and implementing appropriate end-of-life measures will help reduce reliance on virgin materials. Scalable solutions for the expected surge in used batteries creates opportunities for circularity, sustainable practices, and new business models.

## 1.1 Background

Currently, the original equipment manufacturers in the automotive industry are facing challenges in transforming the combustion engine value chain to a battery electric value chain; the focus of the present research is on how to industrialize the battery material recovery.

In the transportation sector, reducing $CO_2$ emissions through electrification places a high demand on raw material used for battery production. The materials needed in battery production are challenging, not only from a supply and cost perspective but from a social and an environmental sustainability perspective (Rehman et al., 2025; Tsao et al., 2024; Petzold et al., 2024). To secure the sustained supply of raw material, reasonable cost structure and environmentally sustainable solutions for a great volume of heavy trucks batteries, there is an anticipated need for circular value chains (Petzold et al., 2024). The demand for virgin materials must be reduced, while recycling and reuse of used materials should be prioritized. In the present study, moving from linear value chains to circular value chains is assumed to be a key for future resource-efficient and sustainable battery production. The installed base of batteries will be an important source of critical materials. Currently, solutions are missing; for example, electric vehicle battery recycling is not being implemented (Feng et al., 2025; Jiang et al., 2025). My view as a professional is that circular practices for battery life extension and battery material recovery are not evident. Visions and principles do exist, but, in general, circular practices for electric vehicles are not implemented. There is an urgent need to develop an understanding of how to overcome barriers and identify enablers in the transformation to an industrialized circular value chain for a heavy truck battery volume at scale. In this thesis, industrialized circular value chain refers to large scale, implemented circular practices with consistency, predictability, and efficiency.

This research contributes to our understanding of *how* to put circular value chains into action. The extant literature needs to be complemented to establish actionable knowledge. While there is extensive research on circular economy and electric vehicles, the literature could benefit from enhanced feasibility assessments and actionable insights. In most articles, it appears that circular value chains for electric vehicle batteries are already operational. However, based on my professional experience, this is not the case. Furthermore, the current literature focus is not on whether these solutions are truly effective or feasible to implement. As illustrated in Chapter 2.1, Table 1, the literature feasibility for circular battery value chains is assessed. The circularity area, as well as the value chain field, will gain knowledge by research on the topic of how the transformation can be applied in practice to reach circular value chains for heavy truck batteries. In the battery circular value chain, the access to batteries and the materials included in the batteries will be key, not only to secure supply, cost, and environmental solutions but also to secure fulfilment of current and future regulations (Terkes et al., 2024; Li et al., 2024). Our understanding of how trust, transparency, and traceability will be managed in the circular value chains for batteries needs to be reinforced (Li et al., 2024; Centobelli et al., 2021).

This research is phenomenon-driven. My personal take on the current literature is that it offers insights into potential circular solutions for electric vehicle batteries, but lacks discussion on feasibility and the practical implementation of circular practices.

## 1.2 Research focus

The phenomenon and background: Anticipated shortage, and associated risks, as well as lack of sustainable supply of battery materials, demands a transition towards circularity. There is a wide spectrum of risks such as geopolitical tensions, mining bottlenecks, price volatility due to increased demand, as well as sustainability and ethical concerns, that draw attention to battery materials. Battery raw material metal mining is controlled by a few actors, mainly from China. China has made heavy investments in Africa and Latin America to secure access to raw materials for battery cell production. In addition, a few countries and companies dominate the refining of battery materials, with China controlling a significant share of the battery refining and processing market (European Commission 2024; Li et al., 2024).

The complete life cycle of material with a special focus on the critical materials needs to be understood. The life cycle of materials includes the full supply chain, from raw material extraction, production, use during first and second life and the process of reuse, refurbish, repurpose and recycling at the battery end of life. Within the realm of the battery material life cycle, in this research I focus on how to extend the use of battery raw materials and battery raw material recovery; currently, circular solutions are missing.

The lifetime of a vehicle with a combustion engine is significantly longer than the lifetime of the battery electric vehicle or the battery in the vehicle (Chirumalla et al., 2024; Tang et al., 2023; Alfaro-Algaba, 2020). It is worth noting that the technology is evolving rapidly, and some suggest that future battery lifespans may exceed the lifetime of the vehicle itself. The cost for the battery drive line, as we know it today, is far higher than the fuel drive line. Considering the *battery lifetime* and *cost*, the business models will most likely be impacted due to the total cost of ownership (Zhou et al., 2025; Jiao et al., 2016). The effect of the societal push for sustainable solutions is evident in the truck market and the traditional truck ownership business model is likely to change. A prolonged lifetime and increased use of batteries and battery materials is necessary in order to increase the economic value of a battery electric vehicle supporting the electrification to take off, resulting in greenhouse gas emission reductions. Increased electric truck sales provide a future increased battery return volume stressing the circular solutions for the battery value chain.

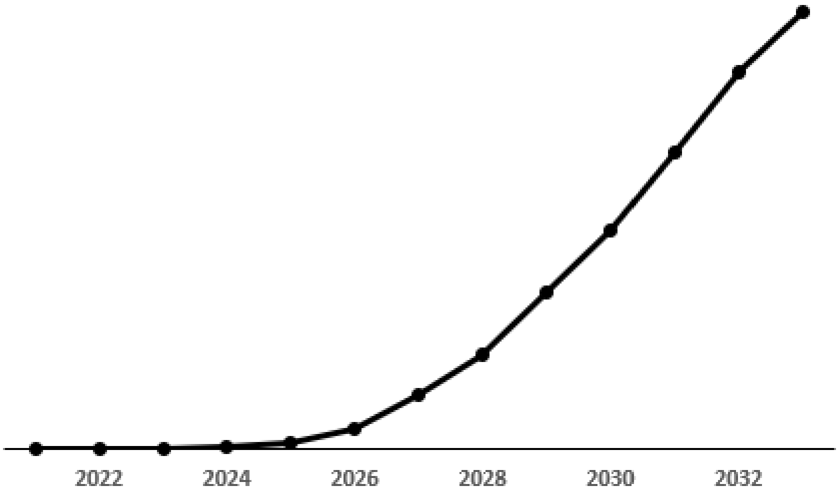


*Figure 1. Estimated battery return volume*

Considering the estimated volume of the return flow of batteries, as illustrated in Figure 1, the reuse of materials is necessary, not only to fulfil the volume demand of new batteries, but also to secure environmentally sustainable solutions for the batteries at the end of useful life and thereby limit the use of substances of concern (Rehman et al., 2025; Koech et al., 2024; Niri et al., 2024). The need to implement circular end-of-life practices is urgent in order to manage the battery return volume when it arises. Critical materials such as nickel, cobalt, and lithium have a significant resource impact from both environmental and societal perspectives (Niri et al., 2024; Chordia et al., 2021). Disassembly and automated industrial disassembly of batteries is the only way to achieve economic and environmentally sustainable solutions (Rehman et al., 2025; Glöser-Chahoud et al., 2021). To limit the need of virgin materials in cell production, the need to reuse and recycle material from used batteries has been assumed in the present study.

Anticipating increased demand on responsibility and control of material and substances of concern places a high demand on traceability and information (Compagnoni et al., 2025). Data and relevant tracking systems need to be in place to fulfil legal requirements as well as social and ethical demands on the heavy truck manufacturer. The access to battery status and health places demands on information and data over the full lifetime of a battery (Terkes et al., 2024; Hasib et al., 2021). Strengthened producer responsibility, including responsibility for the post-consumer battery, requires extensive battery information. In addition, the battery data are needed to make informed decisions to secure supply of secondary raw materials. Sustainable solutions will be sought to manage batteries both included in and excluded from trucks, aiming to minimize the use of virgin raw materials. Expanded responsibility for the entire value chain needs to be understood, from raw material, cell to built-up product in a vehicle, during the battery lifetime and beyond (Montecchi et al., 2021). Maintaining control, information, and data across the battery value chain is essential to ensure it is used efficiently and in a socially responsible way taking ethical, societal, and environmental perspectives into account. The battery value chain must be transformed to secure solutions fitted for the future, looking beyond the current business logic.

## 1.3 Research motivation and questions

The overall objective of this research is to create an actionable knowledge base intended for use in the transition from linear value chains to circular value chains for heavy truck batteries. The intention is to conceptualize the transformation through a theoretical model, described in the *battery maturity assessment model* in Chapter 2.4, and find pathways to industrialized circularity. Industrialized circularity is referred to as large-scale implementation of circular practices, scalable collection and reverse supply chains and utilizing end-of-life batteries as a supply base for battery cell production. Figure 2 illustrates the foreground of this thesis, circular value chains for heavy truck batteries and provides an overview of the research problem, the distinct parts of this thesis, and their relationships to the research questions and appended papers. The first research question brings the results of the first and second studies together and seeks to map the problem solving capability of mass customization. The second research question broadens the battery journey perspective and connect the findings of the two studies, resulting in the *battery maturity model* described in Chapter 5.2.

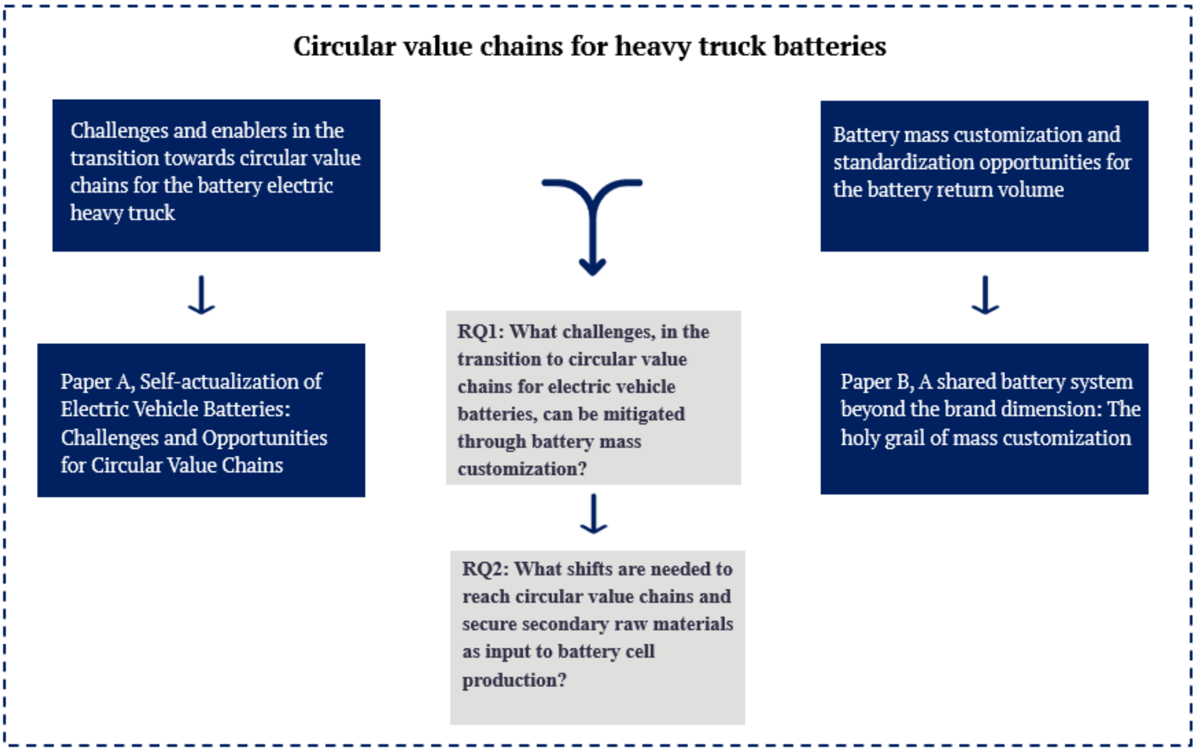


*Figure 2. Overview of research scope and research questions*

The below research questions have been formulated to guide this research.

**Challenge mitigation through mass customization.** The aim of the first study was to set the scene for the research. The focus was on the challenges and opportunities for circular value chains in the context of electric vehicle batteries. The study showed that requirements in the transformation range from internal competence and knowledge in the organization, through physical artefacts such as product design towards and the reverse battery flow. In the second study, the primary focus was to gain an in-depth understanding of the battery diversity and the consequences with a lack of a mass customization building on a standard for heavy truck batteries, creating an understanding of how mass customization can enable the transformation to circular value chains.

RQ1: What challenges, in the transition to circular value chains for electric vehicle batteries, can be mitigated through battery mass customization?

**Shift needed to reach circularity.** The answer to the second research question sheds light on the shift needed to reach industrialized circularity, utilizing installed base of batteries as supply base for battery cell production, presented in the *battery maturity assessment model* and *the battery maturity model*.

RQ2: What shifts are needed to reach circular value chains and secure secondary raw materials as input to battery cell production?

## 1.4 System boundaries

This research focuses on heavy-duty truck batteries, with a particular emphasis on battery materials and their recovery, Figure 3 illustrates the boundary between the battery material and the battery throughout its journey. Achieving circularity and recovering battery raw materials from electric vehicle batteries presents significant industry challenges, and overcoming these obstacles requires substantial shifts. Regarding the transferability of the results, because the case company is an early adopter in the electrification transformation, it is likely that the results are also representative for other large truck manufacturers or automotive players.

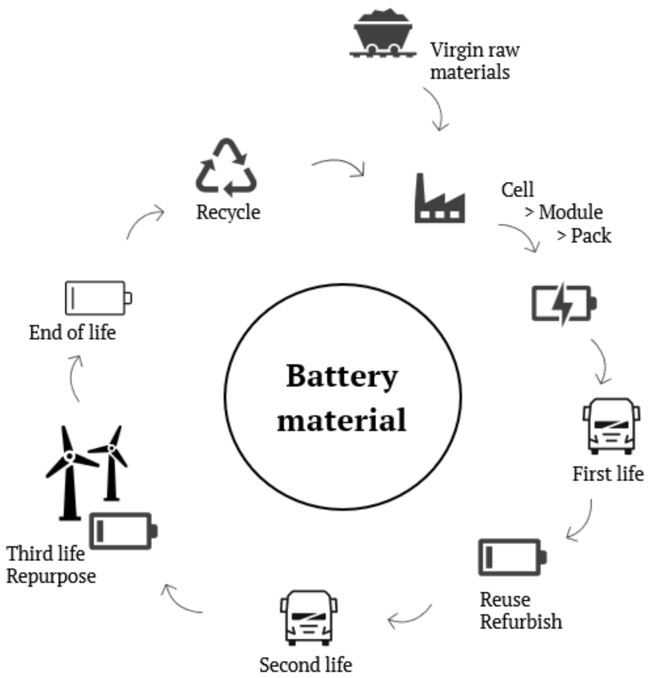


*Figure 3. Circular lifecycle of an electric vehicle battery*

## 2. Frame of reference

This chapter establishes the theoretical perspectives for this research by providing relevant aspects from the existing body of literature to address the purpose and research questions. This thesis contributes to three fields – circular value chains, scalability, and servitization – as illustrated in Figure 4. These fields were chosen because of the relevance of the battery journey through its different lives and beyond the useful life. In this thesis, circular value chains are assumed to be a prerequisite for a sustainable electrification of heavy trucks, where resources are fully used and then circled back by "slowing resource loops through the design of long-life goods and product-life extension, closing resource loops through recycling, and narrowing resource flows aimed at using fewer resources" (Bocken et al., 2016). Scalability was chosen in order to gain insights regarding the ability to establish battery solutions for an electric truck volume at scale "increase in the size of a focal subject that is accompanied by a larger-than-proportional increase in the performance resulting from the said subject" (Palmié et al., 2023). The field of servitization was selected to establish knowledge about the evolving business model opportunities because of heavy truck electrification, "moving from product-focused business models to providing advanced lifecycle services" (Rabetino et al., 2021).

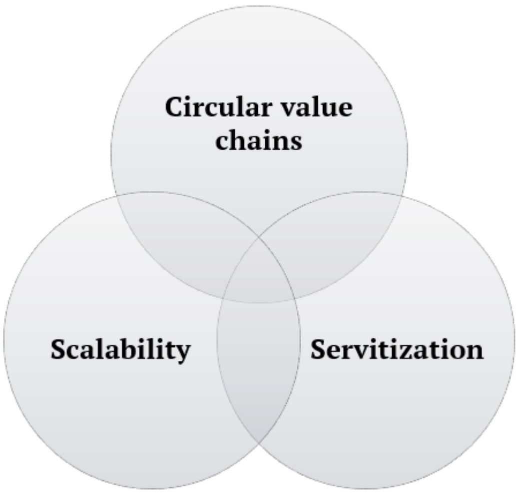


*Figure 4. Identified theoretical pillars underpinning this thesis.*

### 2.1 Circular value chains

In the field of circular value chains, this research focuses on extending battery life through procedures to recover secondary raw materials for battery cell production. Within this area, I look at circular design, product life extension, reverse supply chains, and recycling, as described in Figure 5.

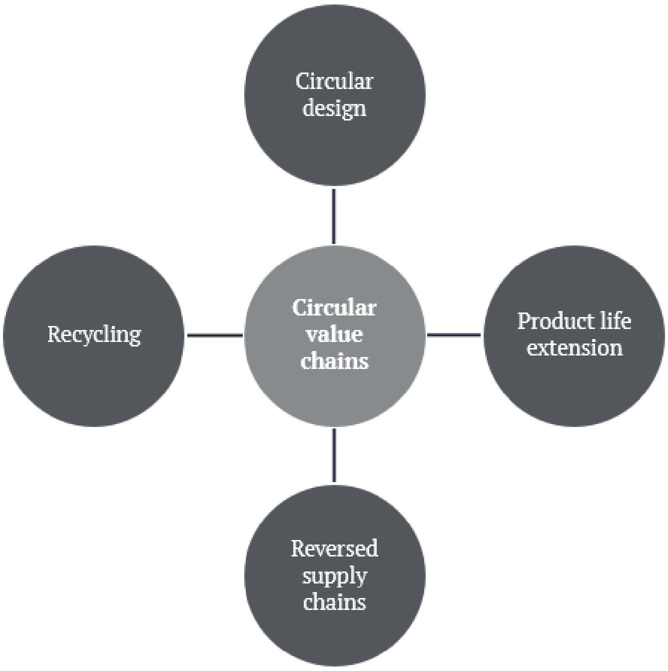


*Figure 5. Circular value chain literature focus*

Circular value chains target the reduced need for primary raw materials and were chosen as the first theoretical component of the framework for this research. The definition of a circular value chain I refer to aligns with the Ellen MacArthur Foundation's definition of a circular economy: "the circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, and recycling" (Ellen MacArthur Foundation, 2025). A circular value chain is an economic model that emphasizes sustainability by designing products and processes to maximize resource efficiency, minimize waste, and encourage the continual reuse and recycling of materials by slowing, closing, and narrowing resource loops (Bocken et al., 2016). Unlike the traditional linear model, where resources are extracted, used, and discarded – "take, make, and dispose" (Farooque, 2017) – a circular value chain aims to establish loops in which products are kept in use for as long as possible and materials are reused for production (Seika et al., 2024). Key principles for circular value chains are designs of products (Bocken et al., 2016) with durability in mind, ensuring that they last longer and can be repaired, refurbished, or repurposed rather than discarded after a particular use. Products need to be designed considering the 9R concept: "Refuse, Rethink, Reduce, Re-use, Repair, Refurbish, Remanufacturing, Repurpose, Recycle and Recover" (Kirchherr et al., 2017, Kazançoğlu et al., 2020). Resource efficiency means that materials are selected and used in ways that minimize waste and energy consumption during production. Recycling, at the end of a product's life cycle, involves recovering and recycling materials into new products, reducing the need for raw materials, and cutting down on waste (Alipanah et al., 2021, Harper et al., 2019). Reverse supply chains are key aspect of circular value chains, considering the system for collecting and returning used products and materials to the manufacturing process. This often requires redesigning supply chains and logistics to manage the reverse flow of goods for reuse, repurpose or recycling. Circular value chains encourage partnerships between industries, suppliers, and customers to ensure that materials flow efficiently through the economy. In respect to circular value chains for electric vehicle batteries, the growing demand for batteries underscores the importance of solutions for battery life extension applications and stresses high volume recycling, enabling material recovery (Rehman et al., 2025; Chirumalla et al., 2024). Not only the forward supply chains but also the reversed supply chains need to be established to secure an efficient and safe return flow of batteries for reuse and recycling, enabling a circular value chain (Altuntas Vural et al., 2024).

*Circular design* is a sustainable approach that designs products for durability, allowing products to be reused, repaired, and recycled, thereby extending their life and reducing waste (Bocken et al., 2016). Unlike traditional linear systems, circular design aims to create systems where resources are kept in use for as long as possible (Tan et al., 2024), minimizing the need for virgin raw materials and reducing environmental impact. This approach involves designing products that are modular, easy to disassemble, and built from materials that can be reprocessed at the end of their life. To achieve sustainable solutions, battery product design must account for not only the initial lifespan within a vehicle, but also its second and third lives, as well as end-of-life considerations. The design should encompass the entire lifecycle, including use, reuse, repurposing, and recycling. Creating environmentally friendly electric vehicle batteries presents challenges, which drives the need for improved life cycle design.

*Product life extension* is key to maximizing the lifespan and utility of products, thereby reducing waste and conserving resources. Through practices like repair, refurbishment, remanufacturing, and upgrades, product life extension allows businesses and consumers to use items longer before they reach their end-of-life. By keeping products in circulation and functional for as long as possible, product life extension contributes to a more resilient, resource-efficient economy that is focused on longevity (Etxandi-Santolaya et al., 2024). For electric vehicle batteries, the use in the first life needs to be extended as far as possible; when the battery no longer fits into the first life, it can still be used in a second life in a vehicle with other demands (Tsao et al., 2024, Xu et al., 2024). For heavy truck needs, the battery has reached the end of its first life at a state of health of 70–80 percent (Kang et al., 2025; Glöser-Chahoud et al., 2021), but the battery can still be useful in another truck with different demands on range or power. The lifetime of a vehicle with a combustion engine is significantly longer than the lifetime of the battery vehicle or the battery in the vehicle (Alfaro-Algaba et al., 2020), resulting in higher battery demand than the volume of electric vehicles. To further extend the battery life, the battery can be refurbished, or problematic components can be exchanged or remanufactured to get them back to an “as good as new” performance level (Shaikh et al., 2023). When the battery cannot operate as a power source for the vehicle it can be repurposed into energy storage, contributing to the overall societal need of energy distribution. Battery energy storage systems are technologies that store energy in rechargeable batteries for later use, meaning they play a crucial role in modern energy management. These systems help balance energy supply and demand (Nyamathulla et al., 2024). To extend the battery life and take appropriate actions, data collection, monitoring, and analysis is crucial.

Establishing *reverse supply chains* is essential for creating circular value chains for heavy truck batteries. Collecting and reclaiming used batteries is crucial to ensure battery second life and end-of-life activities. Reverse supply chains focus on the flow of products, materials, or resources back from consumers to manufacturers or recyclers (Sasikumar et al., 2008). This process includes activities such as collection, logistics, and storage to be able to reuse or recycle products (Tsoulfas et al., 2002). By implementing a reverse supply chain, companies can recapture value from used products, reduce waste, and support sustainability efforts by giving materials a second life. It is necessary to minimize cost and secure product recovery and recycling for the battery population reverse supply chains for the return flow (Al-Salem et al., 2016). Open and closed loops are concepts of the reversed supply chain. These are two distinct models for managing the lifecycle of materials and products, especially in the context of sustainability and resource efficiency. They describe how materials are used, circulated, or disposed of within economic systems. In closed-loop systems, products are returned to the original supply chain after use for value extraction; this is often facilitated by manufacturers in collaboration with other actors. Open-loop systems, on the other hand, manage returned products from various actors, creating a diverse range of materials for reprocessing (Berlin et al., 2022). Additionally, a reverse logistics system is necessary to retrieve batteries at the end of their life, ensuring that appropriate actions such as reuse, repurpose or recycling are taken. Transporting end-of-life batteries presents significant challenges due to the potential risks they pose, such as fire, chemical leaks, or explosions (Liu et el., 2023). Proper handling, packaging, and transport procedures are essential to ensure the safety of personnel, the environment, and surrounding infrastructure. Given the growing prevalence of lithium-ion batteries in electric vehicles, safe transport solutions for batteries are essential for ensuring the safety of supply chains, protecting the environment, and facilitating the circular economy for battery reuse and recycling (Meegoda et al., 2024). To guarantee producer responsibility, secure supply chains, and promote sustainable solutions, robust processes for recovering valuable metals and managing the storage, transportation, and recycling of substances must be developed. The identity of a battery must be tracked throughout its entire lifecycle and beyond to monitor its state of health, behavior, and performance (Ghadbane et al., 2024). To make informed decisions about the most suitable value recovery option, and whether reuse, repurposing, or recycling of the battery is optional, the information and data about the battery's condition and health need to be accessible.

Transitioning from a linear value chain to a circular value chain ensures more efficient use of natural resources and generates value from waste by closing the loop on raw materials. To secure a sustained and sustainable supply of materials for battery production, the recovery and *recycling* of batteries at the end of their life is essential. Managing battery returns at scale requires the availability and quality of battery data (Ali et al., 2024), an industrialized reversed supply chain, and a disassembly model to enable efficient recycling and mitigate safety risks. This disassembly system should be systematic and automated, breaking down batteries from pack to module, cell, and material levels to achieve circularity. Considering the expected volume of batteries at end of life, a standardized and automated disassembly is needed to create circular value chains (Glöser-Chahoud et al., 2021, Wegener et al., 2015). Achieving resource-efficient disassembly demands automated processes, which in turn necessitates common battery standards and product designs (Harper et al., 2019). By efficiently recycling used batteries, valuable resources can be returned to the supply chain, which supports the production of new batteries and reduces dependency on virgin mining operations. Advanced recycling techniques, such as hydrometallurgy and pyrometallurgy, are employed to recover high-purity metals that can be directly reintroduced into battery manufacturing (Dong et al., 2024, Panda et al., 2023). These methods not only reduce waste, but also lower the energy consumption and carbon emissions associated with virgin resource extraction. Secondary raw materials are materials recovered from end-of-life products that can be reused in manufacturing processes, serving as alternatives to virgin resources (Hu et al., 2024). Utilizing secondary raw materials is a key strategy in promoting a circular economy, where resources are continually reused rather than discarded, thereby reducing the need to extract finite natural resources. However, the continued evolution of electric vehicle battery technology and design, and significant product variation, meaning that disassembly and recycling pose challenges for safe and automated recycling processes. Battery mass customization based on a battery standard could enable efficient and automatic recycling (Rehman et al., 2025; Dominish et al., 2021; Glöser-Chahoud et al., 2021).

To conclude, circular value chains represent a transformative approach to sustainable business, offering both environmental and economic benefits. By creating a loop on production and consumption, companies can reduce waste, optimize resource use, and drive innovation, while contributing to the long-term health of the planet. In addition, circular value chains promote greater resource independence by reducing reliance on virgin raw materials, which are subject to price volatility and supply chain disruptions and geopolitical dependencies (Ren et al., 2024, Bednarski et al., 2024). Businesses that embrace circularity can also reduce costs by reusing materials and improving operational efficiency. Circular value chains for batteries are essential for reducing the environmental and economic impacts of the growing demand for energy storage and electrification. By designing batteries for longevity, improving recycling technologies, and creating systems for reuse and material recovery, industries can build more sustainable battery supply chains. While challenges remain, such as the need for scalable battery collection, reversed supply chains, recycling infrastructure, and recycling technologies, a circular approach offers a path toward a more resource efficient and environmentally friendly battery journey.

Based on my professional experience, I feel that the structure needed to execute the recommendations in the literature is not evident. A recommendation or potential solution does not mean the solution exist or is possible to implement. Table 1 illustrates the literature around circular value chains and the feasibility of the solutions. The evaluation of the actionability is based on a review evaluating the view of existing solutions or realistic implementation. While automotive batteries are currently collected and recycled to an extremely limited extent, the extant literature gives the impression that this process is already established and fully implemented. As an example, Meegoda wrote, “upon reaching the end of their operational life, either due to aging or due to damage, batteries are replaced at dealerships or body shops. This critical juncture marks the transition to the next phase: transportation to and evaluation at designated collection points. These older batteries are often transported via pallets in trucks, considering their substantial weight and the risks associated with their hazardous nature, so classified due to their thermal, electrical, or chemical properties. At collection points, each battery is assessed for its individual potential path forward: repair, reuse, or recycle. The repair process entails replacing damaged cells within the battery, a process that extends its functional life” (Meegoda et al., 2024). Another example from Kan gives the impression that the processes are established and implemented: “Advancements in various technologies have made it possible to recycle end-of-life batteries from electric vehicles (EV) into a stationary energy storage system (ESS) within residential buildings” (Kan et al., 2025).

| Circular value chains | Key words | Number of articles | Where of Theoretical | Where of Actionable |
|---|---|---|---|---|
| **Circular Design** | Electric Vehicle Battery System, Industrial, Disassembling, Circular Economy, Reuse Remanufacturing, Repurposing, Recycling | 28 | 26 | 2 |
| **Product life extension** | Lithium-ion battery, Aging mechanism Long-life battery design, Degradation modeling, Energy storage system, State of health, State of charge | 11 | 10 | 1 |
| **Reversed supply chain** | Reverse logistics, Inventory management, Warehouse location, Closed loop supply chains, Open loop supply chains | 20 | 18 | 2 |
| **Recycling** | Recycling, Disassembly, Electric vehicles, Traction batteries, Lithium-ion battery | 53 | 50 | 3 |

*Table 1. Circular value chain feasibility in the literature*

## 2.2 Scalability

Scalability the capability of establishing battery solutions for electric truck volume at scale. To provide insight into the complexity of scalable solutions for electric vehicle batteries, I have focused on the area of modularity, mass customization, standardization and battery data, as illustrated in Figure 6.

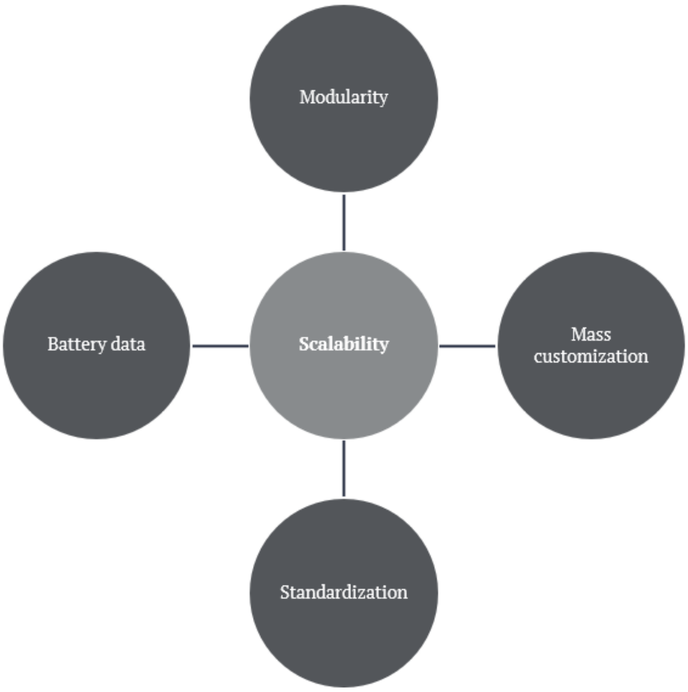


*Figure 6. Scalability literature focus*

Scalability refers to the ability of a system, process, or business to grow and manage an increased demand or workload without compromising performance, efficiency, or quality (Palmié et al., 2023). A scalable system can manage larger volumes or complexity without requiring a complete overhaul of its underlying structure, and can manage increased demand while maintaining performance and cost-effectiveness. As industries continue to evolve, the ability to scale efficiently will be a defining characteristic of resilient and innovative organizations. Reverse supply chains, disassembly, and recycling processes must be designed to meet increasing demand. To ensure a growing return flow of batteries, scalability of future solutions will be critical, which is why scalability is a key theoretical component of the present research.

End-to-end processes will evolve, and organizations must take initiative-taking steps to secure sustainable solutions, reducing the need for virgin raw materials by extending product lifetime and enabling secondary use. Extending the life of the battery, through reuse and repurpose, presupposes the possibility of decoupling the battery from the truck by battery *modularity* (Cicconi et al., 2023). The vehicle and the battery must be designed to enable modularity, with the possibility for the battery to be easily separated from the truck or third life application. Decoupling the battery from the vehicle is crucial to scale the use of batteries by extending the battery life in multiple applications. Modularity is a design principle that involves dividing a system into distinct, smaller components, or modules, each of which can be independently developed, evaluated, and maintained. These modules can then be integrated into a complete system through standardized interfaces (Langlois, 2002). Modular systems have several defining characteristics: independence, meaning modules can be developed separately and operate independently in both form and function; interchangeability, which allows modules to be replaced or upgraded without affecting the entire system; and reusability, which enables modules to be used across different systems or contexts (Gershenson et al., 2003). To complete the full life cycle modularity, the battery must be decoupled from the vehicle at the end of life of the vehicle or when the battery no longer fulfils the demands of the vehicle; this precedes any reuse, repurpose, or recycling. Realization of the potential of electrification managing end of life batteries is a necessity, the battery needs to be disassembled from the truck in a cost-effective, cost-efficient, and scalable way (Hertel et al., 2024). Modular solutions are key to scale battery recycling. It is essential to address the growing demand for raw materials in the battery industry and mitigate the environmental impacts of battery disposal. As battery usage continues to rise, developing efficient, safe, and economically viable recycling at scale will be key to achieving sustainability in the battery industry and fostering a circular economy. In this chapter, modularity is focused on product modularity; however, modular solutions entail opportunities also for servitization or product as a service and in this context battery as a service (Shi et al., 2022; Jiao et al., 2016), as further elaborated upon in the servitization chapter (Chapter 2.3).

Mass customization is a manufacturing and business strategy that merges the efficiency and low unit costs of mass production with the flexibility and personalization typical of custom-made products. This approach enables companies to produce a large volume of products tailored to specific customer preferences and needs. Customization can occur at various levels, pure, tailored, or standardized, depending on the desired uniqueness of the product (Mintzberg, 1988). In the context of electric vehicles, mass customization with support from a battery standard is key for faster market adoption. Mass customization refers to the capability to produce customized goods for a mass market (Wang et al., 2016). Combining standardization that fosters uniformity and innovation that create agility and customer adaptability mass customized battery systems will be key to achieving economies of scale and scope (Wang et al., 2016).

A standard is a collection of best practices based on consensus among industry experts, academia, and government representatives (Brown et al., 2010). Standardization refers to the process of making something conform and implementing that standard; in this case, the battery for electric trucks. Despite the acknowledged importance of standards for electric vehicle batteries, barriers such as proprietary interests and the complexity of battery design impede their implementation (Tankou et al., 2023; Meng et al., 2022). The lack of a standardized electric vehicle battery designs limits the diffusion and adoption of heavy-duty electric vehicles, which highlights the need for internationally recognized standards (Brown et al., 2010). While battery technology evolves rapidly, standards must promote safety and environmental protection without stifling innovation (Brown et al., 2010). A major barrier to electric vehicle battery standardization is the self-interest of original equipment manufacturers in protecting their proprietary systems (Bhardwaj et al., 2022; Dominish et al., 2021). Enhanced standards are needed for battery reuse, recycling, and transportation, which would reduce costs and increase the incentive for recycling (Thompson et al., 2020).

To transform battery volume at scale into material input, collection, return flow, and recycling solutions must be established. To ensure appropriate actions throughout a battery's life and enable scalable battery solutions, it is essential to have access to data (Ali et al., 2024, Ward et al., 2022) to monitor the battery's condition and determine the most suitable value recovery options at each stage of its lifetime (Reis et al., 2021). For trucks in-use, the geographical location and physical condition of batteries needs to be known. Using the battery in other applications and at end of life puts other dimension to the condition of the battery. Safety considerations, uncertainties about battery history, and handling during initial use also pose challenges (Ahuja et al., 2020). Ensuring battery quality before reuse is crucial to mitigate risks and prevent reputational damage. Ensuring data and traceability of battery condition and heath, along with structured collection, reverse logistics, and sustainable reuse, repurposing, and recycling solutions, will be key to closing the extend the life of batteries and extract raw materials for battery production.

## 2.3 Servitization

The servitization area covers the evolving business model opportunities focusing on service-oriented business models and customer-centric solutions, as illustrated in Figure 7.


*Figure 7. Servitization literature focus*

Unlike traditional linear business models, circular value chains emphasize reducing resources and reusing and recycling products – "slowing, closing, and narrowing loops" – to reduce environmental impact and create economic value (Bocken et al., 2016). For original equipment manufacturers, embracing circularity transforms their business models by promoting service-based offerings, enhancing value creation, and integrating new actors (Ziegler et al., 2022). Business models are expected to evolve as the electrification transition accelerates (Bitencourt et al., 2023), making servitization in focus of this research. Innovative business models can serve as powerful drivers for profitable growth, commercialization, and competitiveness (Ziegler et al., 2022), especially in the context of scaling electric heavy truck fleets.

Innovative business models are key for sustainable growth and competitiveness (Bocken, 2020). New business models evolve as response to unleashing the potential in the electrification transition; one such pathway is servitized customer offerings (Liu et al., 2021). In the context of customers of a heavy truck electric fleet, it can be expected that the ongoing transition from a product-based to *service oriented business models* will create new opportunities for enhanced circularity. In the circular product-as-a-service business model, the logic is to keep the economic value in the product (Scheel et al., 2022) during its useful life and beyond. Circular economy business models prioritize services rather than products, while a transition to the circular economy can be made through a product and service combination, the product-as-a-service business model (Otekenari 2020). To increase market share, profitability, and customer satisfaction, at the same time as reducing the consumption of the product, a product-service system could be a solution. The product-service system offers alternatives for the product use instead of acquiring it (Beuren et al., 2013). Expanding zero-emission heavy truck fleets requires substantial financing, as the upfront cost of battery electric vehicles is significantly higher than that of traditional diesel trucks (Making Zero-emissions Trucking Possible 2022). This, along with the need for specialized maintenance, opens opportunities for new business models, such as truck-as-a-service and battery-as-a-service (Shi et al., 2022). In the latter model, the battery could be leased separately from the truck, with ownership of the truck and battery being divided. The cost of the battery is distributed over its usage, while maintenance and risk remain with the original equipment manufacturers. This not only benefits truck owners by reducing upfront costs, but also provides original equipment manufacturers with opportunities to monitor battery health and optimize value recovery throughout the battery's lifecycle.

*Customer-centric solutions* are business approaches designed to prioritize and address the specific needs and preferences of customers at every point of interaction (Sheth et al., 2023). A customer-centric approach involves tailored products or services, flexible support options, and seamless user experiences. With the shift to electrification, traditional ownership models may be replaced by access-based models, where users pay for services or "pay per use" (Bocken et al., 2018), rather than owning or leasing the vehicles outright. Customer-centric solutions put the customer needs and customer data in focus (Fader 2020) and mean that opportunities for the transport industry needs to be optimized. By addressing the unique demands of trucking, customer-centric solutions build stronger relationships, reduce lifecycle costs, and help fleet operators achieve optimal performance and profitability.

Servitization exemplifies how market forces can converge to create new business models. The aim is not only to sustain competitiveness and meet shifting customer demands, but also to lower the environmental impact. Business models may combine material products with intangible services, offering hybrid solutions that blend product ownership with service-based offering (Rabetino et al., 2021). The rise of servitization is not incidental; it is a response to new opportunities for maintaining competitiveness in the evolving global economy. The market for servitization of batteries is nascent, but the early adopters to the changing environment could gain momentum in the sales development by creating not only a competitive advantage through service, but also maintaining control of critical materials in the various loops of reuse, recycling, and remanufacturing (Lüdeke-Freund et al., 2019).

## 2.4 Theoretical building blocks

This section integrates the theoretical components with the various battery life stages throughout the battery journey, culminating in a battery maturity assessment model. A maturity model is effective for monitoring, assessing, and evaluating a transformation process (Montag et al., 2021) and helps practitioners to create insights and assess the capability to implement strategies (Goh et al., 2015; Grimson et al., 2007). Figure 8 illustrates the *battery maturity assessment model* proposed as an outcome of the theoretical components of this thesis. The battery journey dimension can be evaluated by examining the detailed aspects of process, technology, and stakeholders, providing insights into the actual battery maturity. The vertical dimension of the model states the different lives that the battery undergoes during its journey, from its first life until it reaches its end of life. The model's horizontal dimension represents the diverse options within processes, technology, and involved actors. The intensity and content of the dots determines the stage of maturity. In Chapter 5.2 (Figure 14 and Table 4), the battery maturity assessment model is combined with findings from the empirical studies resulting in a battery maturity model.

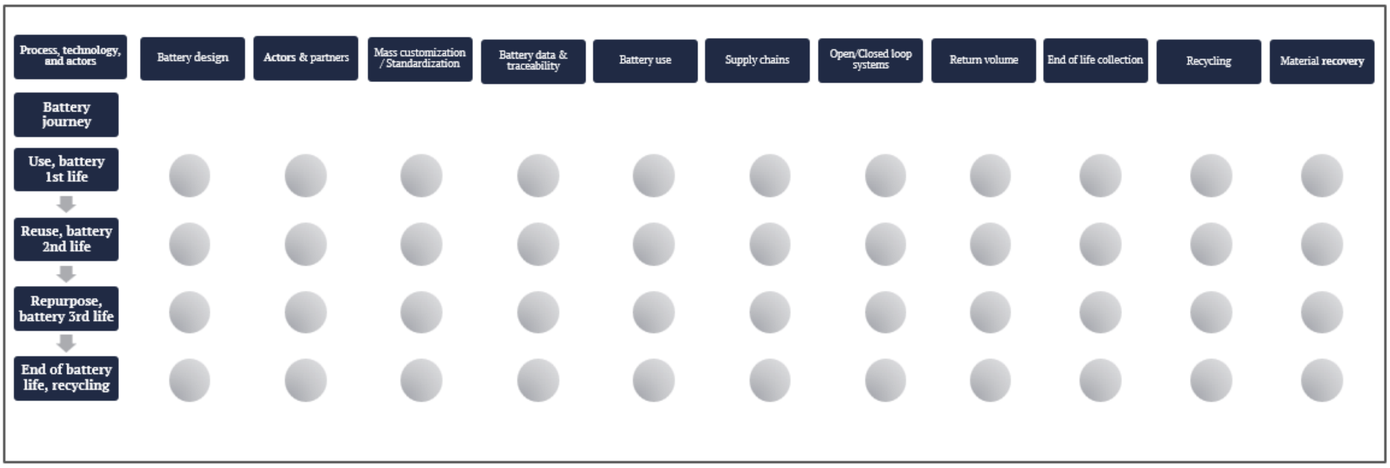


*Figure 8. Battery maturity assessment model*

# 3. Research approach

This chapter presents the research process (as illustrated in Figure 9, followed by the strategy chosen for this research. With the collaborative nature and deep integration with a case company, the chosen research strategy is an interactive research design with an interventional approach. The research conducted during the first half of my doctoral work, like the studies in this thesis, was phenomenon-driven. The climate emergency and urgency to find actionable solutions supporting sustainable zero emission trucking allowed me, as an industrial PhD student, to let the practical problem set the scene for this research. In Section 3.1, the research context is discussed, followed by the research strategy in Section 3.2. Section 3.3 addresses the data collection and sampling process, and Section 3.4 elaborates on the ethical considerations and trustworthiness of the research. Section 3.5 covers the overall theory and Section 3.6 describes the link to the chosen literature.

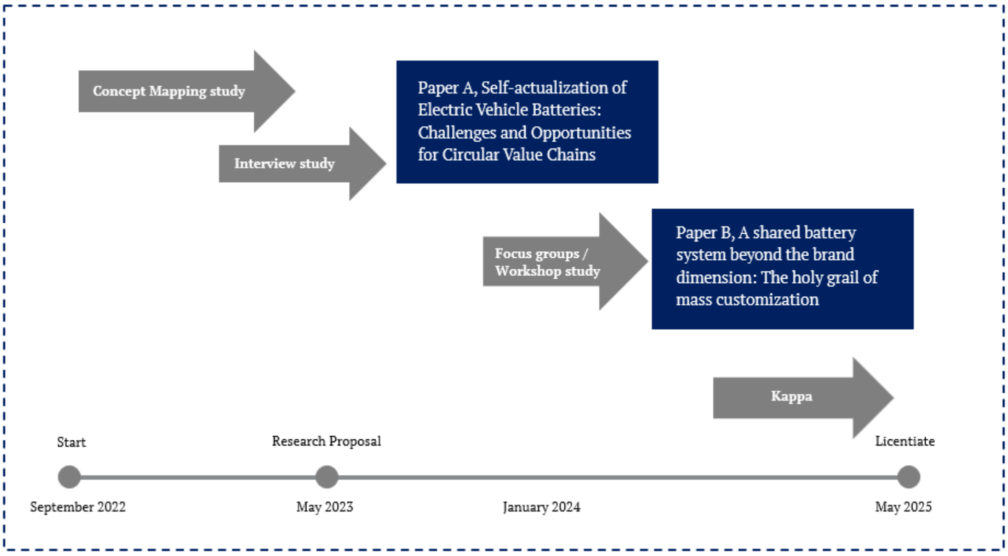


*Figure 9. Timeline of the research process*

## 3.1 Research context

The scientifically interesting and industrially relevant problem investigated in this research is how to move from linear value chains to circular value chains for critical battery materials. The current research object is partly under transformation during the time for the research; therefore, an interactive research method was chosen to create new models and frameworks of *how* to transform from linear value chains to circular value chains, focusing on continuous joint learning processes between the researcher and practitioners (Ellström et al., 2020). The challenge of transforming linear to circular value chains was studied, diagnosed, and treated at the case company with an action, interventional approach (Van de Ven, 2007). The research aims to bridge the theory and practice by connecting findings and learnings at the case company to scientific knowledge on the matter. Different stakeholders in the case company have been involved in the research process to collect data and to validate research results. Studies, tests, and validation to evaluate the hypotheses for current and future demands have been conducted at the case company to design conceptual frameworks and models. The aim is to generate theory based on analysis from data collection and field studies and continuously apply them to the case company through sharing of results, interactions, and presentations.

The collaboration between the case company and the research project has shaped the research problem to reflect the organization's needs. While the involvement of the case company provides access to people and real-world case studies, it may also pose a risk to the external validity of the findings. The context of the empirical data included in this thesis is the Volvo Group, referred to hereafter as the case company. The case company is a leading global manufacturer of commercial vehicles and solutions, with a focus on driving progress through sustainable transport solutions. The company has grown into one of the world's largest producers of trucks, buses, construction equipment, marine and industrial engines, with approximately 100,000 employees globally. With a mission of leading the world towards a more sustainable future, the case company continues to innovate in fields such as electrification, automation, and connectivity. The company has a portfolio that includes a variety of products and brands produced in 18 countries, in addition, there are aftermarket distribution centers and logistic centers all over the world to support customers and operations. The case company is currently in the process of establishing a battery cell plant to support the electrification journey.

## 3.2 Research strategy

Practical involvement provides exclusive access to data and deep insights, making it invaluable for researching the transition from linear value chains to circular value chains for recovering battery materials as inputs for cell production. Validity of findings is strengthened by involvement of practitioners that provides opportunities to evaluate hypothesis and solutions to confirm accuracy. This research is phenomenon-driven, where the primary motivation for research is to understand and explain what is needed in order for the transformation towards circular value chains for electric vehicle batteries to take place. The phenomenon has steered the studies both in terms of data collection and the literature studies. An inductive research approach is appropriate to use when the theory needs to be developed (Bell 2019) or, as in this case, to help develop a theoretical understanding of the phenomenon. In my view, implementing circular practices for electric vehicle batteries requires complementing existing research with actionable knowledge and theoretical models.

An interactive approach was selected as the primary method for this research due to the nature of the problem. This approach is highly effective for fostering collaboration among various stakeholders throughout the research process (Ellström et al., 2020). Table 2 summarizes the major components of the studies connected to the papers, research focus, area of literature, and chosen methods for data collection as well as results. The research conducted during the first half of my doctoral work has had an internal case company focus. The studies have been phenomenon-driven and the selected participants in the data collection has been experts and persons who are knowledgeable about the topic. The results of the two studies have been shared with reference teams and technical expert groups at the case company during the time of the research process. In addition, multiple interactions and discussions with subject matter experts related to findings have occurred during the process, while open discussions fostered feedback, enhancing insights and knowledge. Presenting the study results at the case company has been a crucial step to create intervention and transform research insights into practical applications. The interactive, interventional process included communicated findings, highlighting implications for the company, and providing actionable recommendations.

Considering the industrial urgency of the matter and access to the studied company, an action design methodology could have been used to secure implementation of results and recommendations; however, while the actionable results were shared and discussed at the case company, the results of the intervention were not measured.

| Study | Focus | Key Concepts | Sampling strategy | Data | Method of data collection | Results |
|---|---|---|---|---|---|---|
| Paper 1 | Challenges and enablers in the transition towards circular value chains for the battery electric heavy truck | Circular value chains, Servitization, Scalability, Self-actualization | Collecting data at the case company. The interviewees were selected using purposive sampling, focusing on individuals with a high level of expertise and extensive knowledge. Each person holds a key position at the case company, allowing them to influence and guide the development of sustainable processes. | Collection of the unsteered view on the topic at the case company | Concept Mapping at the case company, getting answers to the question: "In the transition to resilient and effective circular value chains for materials critical to our products, we need to..." | Identified challenges and enablers in the transition from linear to circular value chains at the case company regarding electrification of heavy trucks |
| Paper 2 | Battery mass customization and standardization opportunities for the battery return volume | Electric vehicle batteries, Product variety, Modularization, Circular economy, Mass customization | Collecting data at the case company. Non-probability sampling was used, the participants were selected based on specific criteria, their expertise in electric vehicle batteries. An interactive approach was chosen; stakeholders from the case company participated in data collection and validation of results. | Collection of deep insights from knowledge able persons for the topic. | Workshop format was chosen for the data collection due to the innovative nature of the subject. In addition, an online form was sent out to the participants after the workshops with the topics discussed to get additional reflections on the topic. | Clear view of problems caused by battery diversity as well as the potential of mass customization and standardization on different levels of the battery. |

*Table 2. Research approach*

## 3.3 Data collection and sampling

In this section the methods for gathering data for the research in this thesis are presented and motivated.

Since this research is phenomenon-driven the data collection for the first study started with a broad data collection, the aim was to create actionable knowledge of the challenges and opportunities in respect to circular value chains for heavy truck batteries. An action-oriented and interactive research design (Van de Ven, 2007) was chosen. To involve practitioners at various stages of the research process, the concept mapping method was employed (Vaughn & McLinden, 2016). This mixed-method approach integrates qualitative and exploratory phases of idea generation and sorting with quantitative hierarchical analysis. A group of individuals at the case company was invited to contribute to the concept mapping study. Due to the cross-functional nature of the task, respondents were selected through purposive sampling, prioritizing those with extensive experience (Van de Ven, 2007) among internal stakeholders at the case company. The participants represented diverse functional areas within the organization, including senior industrial project managers in manufacturing and executive leaders in environmental sustainability. To further enhance understanding and deepen insights from the concept mapping study, a qualitative, structured interview methodology was employed to ensure the study's trustworthiness and objectivity (Kallio et al., 2016). For this interview study, subject matter experts at the case company were selected to contribute. The results of the study were presented and discussed with company representatives, both those who were included in the data collection and those who were new to the study to secure correct understanding and sharing of results.

The second study adopted an interactive approach, facilitating multiple engagements between the researcher and practitioners. The objective was to bridge theory and practice by connecting insights from a case company to existing scientific knowledge. Stakeholders from the case company played an active role in both data collection and the validation of research findings. To gain a deeper understanding of participants' perspectives and explore under-researched topics, qualitative research methods were utilized (Bell, 2019). Rather than aiming to confirm existing theories, the study sought to provide new insights into the emerging field of mass customization of heavy truck batteries. Data collection primarily involved literature reviews and workshops conducted within the case company, in collaboration with master's students working on their theses. This study employed a non-probability sampling method, selecting participants based on specific criteria rather than random selection (Bell, 2019). The researcher strategically identified individuals relevant to the research questions, ensuring a diverse group with varied expertise and perspectives essential to the study. Using generic purposive sampling, insights were gathered from various positions within the organization to gain a comprehensive understanding (Bell, 2019). Participants were chosen based on their expertise in electric vehicle batteries and environmental matters, particularly their roles in shaping battery development at the case company. The analyzed result of the data collection was validated together with case company experts.

## 3.4 Validation approach

Evaluating a study's trustworthiness involves four key aspects: credibility, transferability, dependability, and confirmability (Bell 2019), as summarized in Table 3.

| | | |
|---|---|---|
| Credibility/Validity | Demonstrate correlation | Data coding and analysis<br><br>Review of findings with involved and uninvolved professionals at the case company |
| Transferability | Results applicable to other settings | Concepts and models applicable for other areas or products |
| Dependability | Repeatability | Use of research protocol through presentations to participants and through online forms |
| Confirmability | Objectivity and neutrality of findings | Participants articulation of responses, quotes were transcribed, data validation, presentation of findings to participants |

*Table 3. Data analysis reliability*

*Credibility*, which is essential for assessing result trustworthiness, was reinforced in the studies through several means. In the first study, the data collected through the concept mapping study were analyzed and grouped by individuals at the case company and further validated through interviews and by experts from the case company to ensure alignment with participant perspectives. In the second study, the diverse range of knowledge and experiences among workshop participants ensured a comprehensive perspective, allowing participants to articulate their responses minimized the risk of misinterpretation. In addition, the responses were transcribed and the results were further analyzed together with a selection of participants.

*Transferability* ensures the findings' applicability across different contexts or times. The transferability of the studies is uncertain as the studies use the input from the one organization while the input comes from various parts of the organization; however, the findings may not be transferable to another context. The studies improve transferability by exploring broader themes such as the circular economy, variety complexity, and standardization, relevant beyond electric truck batteries.

*Dependability*, the third consideration, involves assessing the likelihood of results holding true over time and circumstances. The data collection methods are clearly documented and based on well-defined rationales, making it possible to replicate the study for similar purposes.

*Confirmability*, the final aspect, involves demonstrating that personal values did not unduly influence outcomes. While it is difficult to achieve complete objectivity, measures were taken to mitigate bias. Allowing participants to articulate responses and incorporating quotes from transcripts minimized researcher influence. Participants' involvement in the validation of the data analysis process further enhanced confirmability.

## 3.5 Theory building

As illustrated in Figure 10, this research situates itself between theories and empirical observations, aiming to develop practical frameworks on *how* to move from linear value chains to circular value chains for critical battery materials for heavy trucks. The interactive, interventional approach aligns with middle-range theory's emphasis on testing and refining theories through empirical research. By combining literature reviews with empirical data collection, the study seeks to bridge theoretical constructs with real world applications, ensuring that insights are both conceptually grounded and applicable. Middle-range theory provides a structured yet flexible approach to studying complex, evolving phenomena such as the transition to circular value chains for electric vehicle batteries. Middle-range theories develop testable frameworks that link theoretical concepts with empirical observations, making them highly relevant for phenomenon-driven research (Tate et al., 2022). Rather than starting with established theories, middle-range theory begins by exploring emerging patterns, behaviors, and industry shifts, such as the increasing demand for circular solutions in electric vehicle batteries. By applying middle-range theory within phenomenon-driven research, actionable knowledge can be created; this approach ensures that research remains both theoretically robust and relevant. In addition, the knowledge can be transferred to other sectors. The findings of this research highlight both the broader concept of circular transformation and the specific potential for circular value chains for automotive batteries.

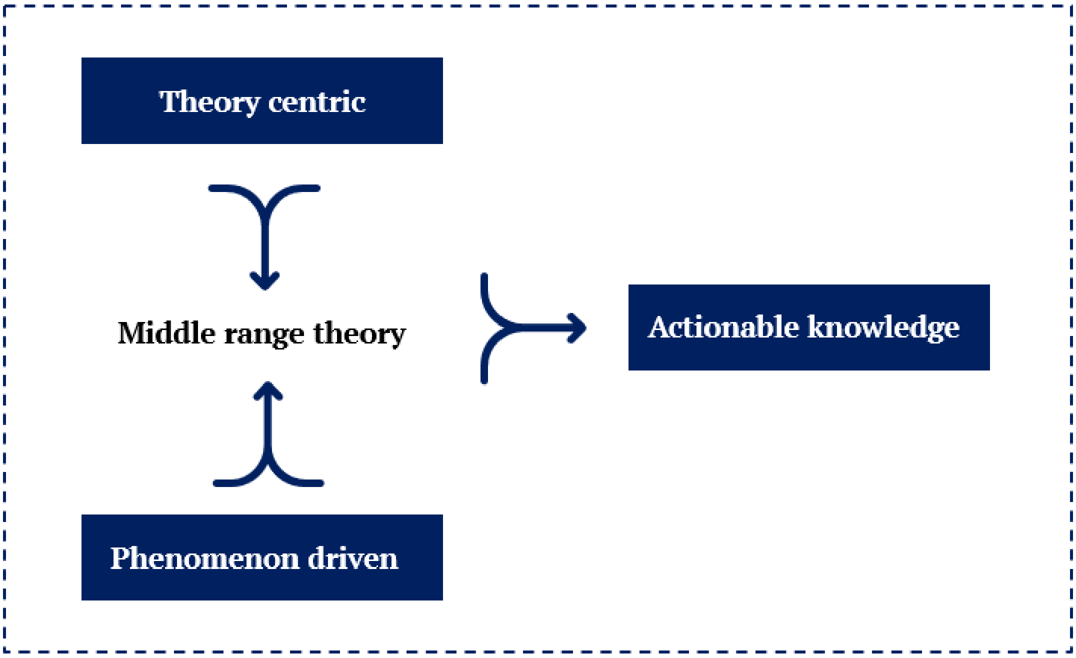


*Figure 10. Middle-range theory*

## 3.6 Literature analysis

The studies included in thesis were initiated by literature reviews that were conducted to build on previous research and ideas. As stated in the frame of reference chapter, a literature review is conducted in the concerned fields of theory. The focus is on reaching an understanding of previous research and findings related to circular value chains, scalability, and servitization to reach sustainable and, circular, solutions for materials in heavy truck batteries. The approach to finding relevant literature involved formulating suitable search strings. Once relevant literature was identified, additional academic works were uncovered using snowballing techniques.

# 4. Results

This chapter presents results from the conducted research, which are used to answer the research questions. Section 4.1 is dedicated to summarizing the appended papers and the following sections go through the results in detail.

## 4.1 Summary of appended papers

The main contribution of this thesis are papers currently under review for publication, appended in the second part of this thesis.

The aim of the first paper, entitled “Self-actualization of Electric Vehicle Batteries: Challenges and Opportunities for Circular Value Chains,” was to gain an understanding of the challenges and opportunities for circular value chains for heavy truck batteries. The study investigated the potential requirements on “batteries as a service” and “circular value chain” and, derived from this, propose actionable principles for a scalable working model. This was done through a concept mapping data collection in conjunction with interviews to deepen and confirm the understanding of the results. The conclusion of Paper A is that challenges need to be bridged to reach circularity and that they range from internal competence and knowledge in the organization, through physical artefacts such as product design towards external partners and the reverse battery flow.

The second paper, entitled “A shared battery system beyond the brand dimension: The holy grail of mass customization,” focused on gaining an understanding of the issues arising from the diversity of heavy truck batteries from different battery producers, brands, and markets. It also explored the opportunities and challenges associated with battery mass customization. Additionally, the study examined various aspects and degrees of battery standardization. The paper explains that the variety and diversity of batteries are hindering a sustainable growth of batteries and that there are opportunities in mass customization, both for original equipment manufacturers and for truck customers, second-use actors, and recycling actors. Secondly, the results show that, to manage a high volume of end-of-life batteries, an open loop supply chain would benefit the environment and future access to secondary raw materials by handling batteries from diverse applications. Lastly, the study shows that a sustainable electrification of heavy trucks and battery energy storage at scale demands a certain level of battery mass customization, particularly at the cell level, building on a standard.

## 4.2 Paper A. Self-actualization of electric vehicle batteries: Challenges and opportunities for circular value chains

The purpose of this study was to investigate potential requirements on “batteries as a service” and “circular value chain” and, derived from this, propose actionable principles for a scalable working model.

The data collection from the concept mapping study, as shown in figure 11, illustrates that the that requirements in the transformation range from internal competence and knowledge in the organization, through physical artefacts such as product design towards external partners and the reverse battery flow. The eight clusters from the concept mapping study were grouped into four guiding principles – circular value chains, servitized customer offerings, scalability, and self-actualization – combining literature and empirical findings from the data collection. Interviews were conducted to gain a deeper understanding of the eight clusters and four areas. The interviews started from the eight clusters and four areas as outcomes of the concept mapping study and gave extensive insights building to the results from the study.


*Figure 11. Eight clusters of requirements for circular value chains*

The study of the challenges in transitioning from linear to circular value chains identified eight categories of requirements. From these, four sets of guiding principles emerge for managers to consider when designing a scalable working model. The first set focuses on the circular value chain as an organizational structure, emphasizing change management throughout the battery life cycle as a key feature. The second set extends current principles of servitization to support circularity by incorporating through-life management, where technology-enabled traceability and customer incentives play a vital role. The third highlights scalability, not just in terms of managing the volume and variety of physical items within the value chain, but also ensuring the circular solution itself is highly replicable. Lastly, the principle of self-actualization, often applied to people, is used here to reflect the unique characteristics of a battery, such as its health and location, in determining the appropriate circular value chain activity.

To conclude, viewing products as unique entities with evolving needs, health, and development requirements can be a valuable approach for organizations to identify business opportunities in a changing environment. The concept of self-actualization and the battery maturity model could be transferable to other physical products and contexts. However, empirical research is necessary to develop and validate a maturity model that would be useful for practitioners in diverse settings.

## 4.3 Paper B. A shared battery system beyond the brand dimension: The holy grail of mass customization

The aim of Paper B was to shed light on the issues arising from the diversity of heavy truck batteries from different battery producers, brands, and markets. The paper also explored the opportunities and challenges associated with battery mass customization and examined various aspects and degrees of battery standardization and their impact on stakeholders.

For this study, workshops with relevant stakeholders at the case company were conducted to collect data. The data was grouped and analyzed in the following categories: *variety problems*, *mass customization opportunities*, *mass customization challenges*, and *standardization requirements.*

The data related to battery variety problems show that the variety and diverse technology are causing problems for truck manufacturers as well as for other stakeholders during the battery lifetime and beyond. The data show that mass customized batteries, building on a high degree of standardization, entails opportunities but also challenges.

In relation to the potential of standardization on distinct levels of the battery, the study shows that a standard on module level does not give the benefits of standardization; standardizing on the battery cell level entails the highest potential in terms of reclaiming raw materials. However, standardizing the battery on the pack level provides opportunities for battery use in terms of reuse, recycling and repurpose of the battery, as illustrated in Figure 12.

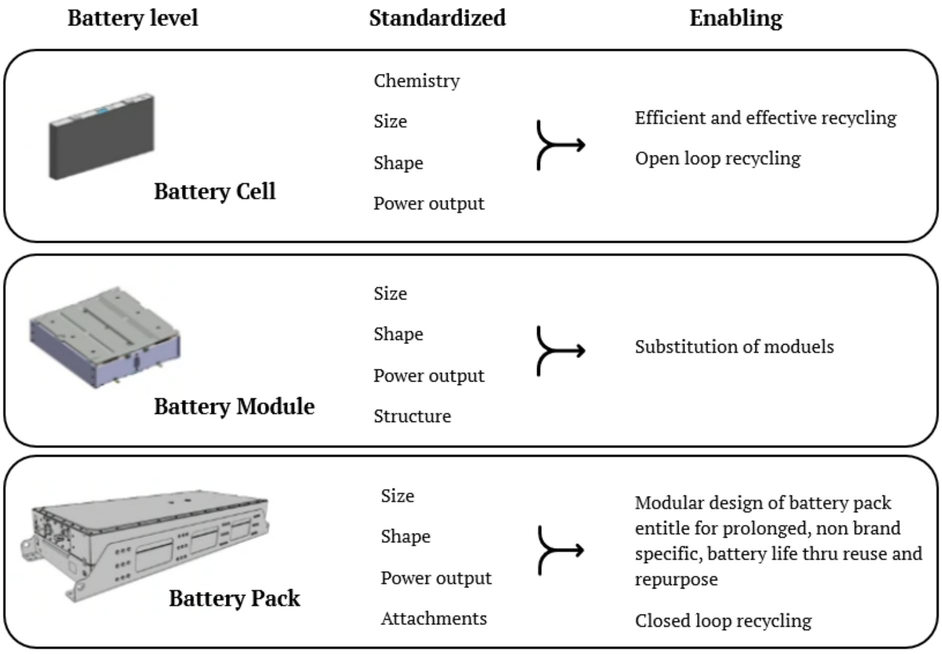


*Figure 12. Beyond brand mass customized batteries*

To conclude, the study highlights three key points. First, the wide variety and diversity of batteries are currently limiting sustainable growth in the battery sector. However, there are significant opportunities in mass customization for original equipment manufacturers, truck customers, second-use actors, and recycling companies. Second, to manage the large volume of end-of-life batteries, the study demonstrates that an open-loop supply chain could benefit both the environment and future access to secondary raw materials by efficiently processing batteries from various applications. Finally, the study emphasizes that the sustainable electrification of heavy trucks and large-scale battery energy storage requires a certain level of mass customization, particularly at the cell level, built on standardized approaches.

# 5. Analysis – answering research questions

In this chapter, the research questions formulated in Section 1.3 will be discussed and answered.

## 5.1 Attaining circular value chains

*What challenges in the transition to circular value chains for electric vehicle batteries can be mitigated through battery mass customization?*

The strong societal drive and regulations stemming from environmental concerns will push for the continuation of electrification that will lead to expansion and development of technical solutions (Lehtimäki et al., 2024). The results show that the challenges and enablers range from change management, knowledge, and organization to technical challenges such as recycling and manufacturing. Extending the battery life through reuse and repurpose is challenging from different perspectives. Challenges to overcome include technical solutions under development, diversity of batteries, contradiction in lifetime of products, and novel business models.

The value chains need to be set up differently from the traditional, linear value chains in order to reach circularity for battery materials. The reversed supply chains need to be established, including collection of used and end-of-life batteries (Sasikumar et al., 2008). The various conditions of used, end-of-life, or damaged batteries makes the reversed supply chain complex. The batteries are an asset and need to be treated with care due to their hazardous nature, which makes the collection and transportation complex (Liu et al., 2023). Decisions need to be made in relation to the loops of the reversed value chain, open or closed, which means that collection actors and recycling actors manage all batteries or only take back only the batteries from the respective original equipment manufacturer (Berlin et al., 2022).

The variety of batteries is causing complexity for manufacturing, reuse, repurpose and reversed supply chains and specifically for the recycling of batteries (Tankou et al., 2023). The lack of standardization makes the battery recycling process manual, inefficient, insecure, and problematic to scale.

The variety and diversity of heavy truck batteries creates various problems for different actors in the battery value chain. For the original equipment manufacturers, aftermarket, and workshop actors, the diversity is causing production and handling complexity. Reusing used batteries is difficult, even in the same brand with different generations of batteries. Currently, the diversity between brands makes reuse impossible. In the repurpose area, focusing on battery energy storage systems, the diversity makes the solution brand-specific and dependent on current technology. It is not a plug-and-play battery energy storage; each installation is unique and dependent on brand specific batteries and connectors. The diversity makes the collection, storage, and transportation of used batteries complex and unsafe, not to mention the recycling. The batteries at end of life that are returned or collected for recycling are in different health conditions and have different shapes, sizes, and chemistries. This diversity means that disassembly is a manual process and the crushing is inefficient and involves safety concerns (Hertel et al., 2024). Since the chemistry varies between brands, producers, and battery intra brand generations, different recycling methods will be used to recover secondary raw materials for cell production.

If mass customized solutions were in place or there was standardization of battery packs, including power, size, shape, and/or attachments, truck customers would benefit from the reduced lock-in effect, with customer solutions enabling the replacement and comparison of batteries between brands and simplified access to batteries.

Battery life extension through reuse in other trucks that are fit for different usage would benefit from a mass customized battery. The original equipment manufacturer can remanufacture or refurbish the battery and create business opportunities for second-life vehicles for second-life batteries. Having a common shape, size, power output and attachments would enable the expansion of battery energy storage systems. Energy storage holds promises for societal expansion, supporting electricity balancing of supply and demand.

A standardized battery cell would benefit the recycling actors, who could process cells from multiple brands creating a large scale, automated recycling. Optimized recycling methodologies would benefit recycling actors, and the environment, by recovering secondary raw materials for battery cell production.

To summarize, mass customization with standardized content on a pack level would benefit most of the stakeholders during the battery life. However, adding a standardized battery cell in terms of chemistry would give the highest environmental benefit, enabling efficient and automated recycling and recovery of secondary raw materials.

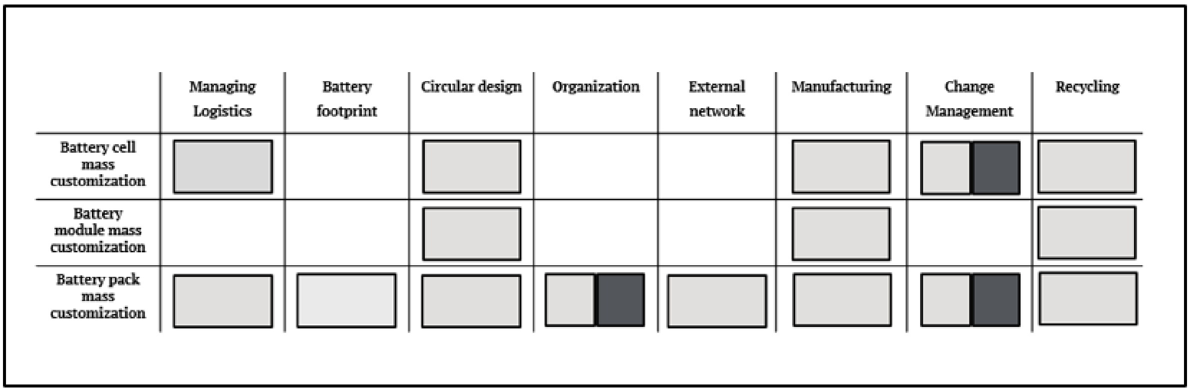


*Figure 13. Mass customization as enabler to overcome circular challenges*

Battery diversity is causing challenges in many of the areas identified as important for the transformation to an industrialized circularity, and the potential in mass customized batteries is evident. However, in the change management and organization area there could be benefits that conflict with drawbacks, such as business model advantages and competitive edge of the battery diversity. Figure 13 illustrates the challenges that can be mitigated through a mass customized battery. The challenges were identified in the first study of this research and presented in paper A, entitled "Self-actualization of Electric Vehicle Batteries: Challenges and Opportunities for Circular Value Chains". The preferred level of battery mass customization originates from the findings in the second study, presented in Paper B, entitled "A shared battery system beyond the brand dimension: The holy grail of mass customization".

## 5.2 Shifts needed to reach battery circularity

*What shifts are needed to reach circular value chains and secure secondary raw materials as input to battery cell production?*

Throughout the battery journey, in the different lives of the battery, the capability to reach circularity depends on the level of maturity in the broken-down perimeters of process, technology, and actors. The lowest level of battery maturity – denial – is distinguished by design for use in the first life only and not designed for separation of the battery from the truck. The data is unstructured and incomplete and the reuse and repurpose of batteries are non-existing. The return volume of batteries is low; collection and recycling are ad hoc, manual, and inefficient; the supply chain is forward and no battery loops are developed; and the interface between actors is based on the traditional linear set-up. Throughout the process of maturity until reaching the self-actualized maturity level, the technology, process, set-up, and interface with actors have developed.

By borrowing from the field of psychology and healthcare management, *self-actualization* envisages batteries as "individuals." A full utilization of the battery materials value recovery potential would mean reaching *self-actualization* in the sense of managing the "health" and "personality" of the battery to align with the ideal state and to decide what value recovery options are the most suited at various stages of the battery lifetime. The life of a battery can be compared with the process that an individual undergoes through life (Maslow 1965). A self-actualized battery is designed to enhance every stage of its lifecycle while providing control and opportunities to manage the battery value chain. The circular battery design enables disassembly and breakdown of the battery at end of life, enabling recovery of raw materials as input to cell production (Bocken et al., 2016). The battery is used to its full extent during all lives, use, reuse and repurpose (Etxandi-Santolaya et al., 2024). The battery return volume is significant and the reverse supply chain is set up with, preferably, an open loop system enabling full collection. The open loop supply chain demands a level of mass customization building on a standard. The recycling process is automated and secure, enabling recovery of raw materials as input to cell production (Glöser-Chahoud et al., 2021). There is traceability, access, and control of battery data throughout the battery journey. Interfaces with actors, partners and customers are established to ensure profitable business models, access to raw materials, and sustainable solutions. The battery maturity levels are illustrated in Figure 14 and further described in the battery maturity model (Table 4). The maturity model derives from the theoretical building blocks presented in Chapter 2.4, combined with the findings from the empirical studies. When the battery reaches its highest level of maturity, self-actualization, industrialized circularity is achieved, enabling large-scale implementation of circular practices.

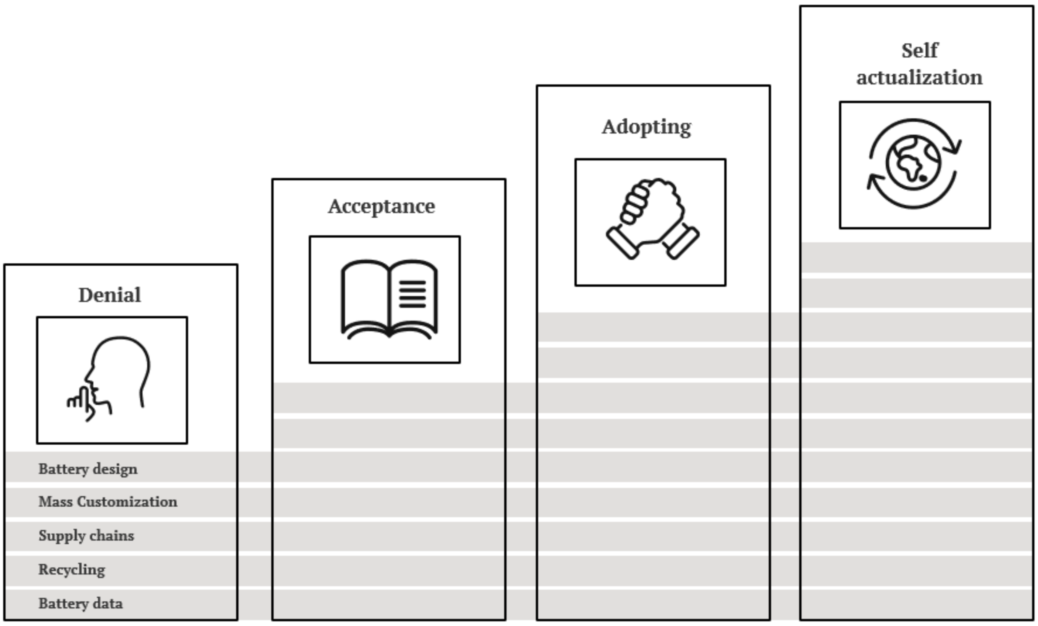


*Figure 14. Battery maturity model*

| Maturity | Characteristics | Processes | Technical solutions | Actors |
|---|---|---|---|---|
| **Denial** | Battery design for first life.<br>Battery used in its first life.<br>None or low rate of collection of used batteries.<br>No recycling of battery materials. | Forward supply chains.<br>Ad hoc return flow for collection.<br>Low return volume | Solution for batteries in the first life application. | Original equipment manufacturer to first life customer. |
| **Acceptance** | Battery design for first life, second life and third life.<br>Reuse, second life, and repurpose, third life, to limited extent.<br>Manual disassembly, of returned batteries.<br>Low return volume.<br>Low recycling rate. | Forward supply chains.<br>Ad hoc return flow for collection. | Solution for batteries in the first life application.<br>Development of solutions for reuse of batteries and repurpose to Battery Energy Storage System. | Original equipment manufacturer to first life customer.<br>Trial of reuse and repurpose customer solutions. |
| **Adopting** | Battery design for first life, second life and third life.<br>Battery utilization in the first life, second life and third life. (Reuse and repurpose of most batteries).<br>Partly automated disassembly.<br>Recycling of most materials.<br>Access to battery data, control of the battery health and battery condition throughout the battery life. | Forward and reverse supply chains in place.<br>Structured end of life battery collection. | Solution for batteries in the first life application. Solutions for reuse of batteries and repurpose to Battery Energy Storage System.<br>Mix of manual and automated disassembly. | Original equipment manufacturer to first life, second life, and third life customer.<br>Collection actors and recycling actors in place. |
| **Self-actualization** | Mass Customized battery design.<br>Circular battery design, including modular battery and modular truck solutions.<br>Extended first battery life.<br>Implemented second life use after R actions.<br>Third life, repurpose, solutions in place.<br>Full control of battery data, health and condition throughout the battery life.<br>Automated disassembly, safety regulations are fulfilled.<br>Urban mining in place, raw materials recycled, recovered, and reused to full extent for battery cell production, need of virgin materials only for volume increase. | Forward and reverse supply chains in place.<br>Control, access and collection of all used batteries from the original equipment manufacturer.<br>Automated disassembly and recycling process in place. | Solution for batteries in the first life application. Solutions for reuse of batteries and repurpose to Battery Energy Storage System.<br>Automated disassembly and recycling. | Original equipment manufacturer to first life, second life and third life customer.<br>Transportation set up in place for collection and distribution.<br>Inhouse or external automated recycling. |

*Table 4. Battery maturity model*

# 6. Discussion

In this chapter, the findings are further evaluated and reflected on regarding the battery journey.

## 6.1 The battery journey

In the first study, eight clusters of challenges and enablers were identified. Challenges that need to be bridged to reach circularity range from change management, knowledge, and organization to physical artefacts such as battery footprint, product design and the set-up of reversed supply chains. The second study explained that the design needs to be not only for the complete life of the battery, but also modular and mass-customized to move towards circularity (Hertel et al., 2024). The possibility of decoupling the battery from the truck is an enabler for the reuse, repurpose, and recycling of batteries, thus extending the life and enabling material recovery (Cicconi et al., 2023). The establishment of a reversed supply chain, including collection and return flow will impact the organization and battery footprint. Considering future access to raw material, geopolitical dependencies, and characteristics of used batteries in different conditions, the move towards regional set-ups for the battery footprint is likely. During the battery journey – that is, the complete life of the battery, from the first use phase until the materials are recovered for cell production – the battery will face different actors and touchpoints, so it is reasonable to assume that business models and interface with partners and actors will evolve to meet the needs surrounding the battery (Zhou et al., 2025). To move towards circularity, many of the identified challenges would be mitigated by a mass customized battery (Thompson et al., 2020). As referred to in the battery maturity model, there are a set of areas that determines the choices for the lives of the battery journey; however, the battery design sets the direction and will steer many of the following decision points (Bocken et al., 2016).

## 6.2 The battery maturity

The first maturity level of the battery is when the process of the battery is in the denial phase; design, processes, and technology are immature; data is lacking or incomplete; and the battery has an excessive cost. The status in the denial phase is acceptable since the volume is low; however, the process needs to get out of denial mode until the volume starts to take off, the organization needs to change, solutions for extended life need to be up and running, the battery footprint needs to be set to secure collection, take-back, and recycling. Batteries need to be taken care of, independent of their condition and in a secure manner, due to their hazardous nature. With volume comes demand for automation, efficiency, and accurate battery data (Rehman et al., 2025; Ali et al., 2024; Terkes et al., 2024). The higher volume, the greater the need for mass customization and standardization to secure sustainable and profitable solutions, production efficiency, and reduced customer lock-in effect (Wang et al., 2016).

When the battery has reached the level of self-actualization, virgin raw materials are only required in case of a volume increase; the supply of raw materials for battery production comes from the battery at end of life. The battery is designed to extend the life including after-life considerations; data are available to make the best-suited decisions at every stage during the battery's journey (Tan et al., 2024). The footprint, collection, reversed supply chains, and recycling need to be set up securing geopolitical independence, avoiding price fluctuations, and securing access to critical materials to recover secondary raw materials as an alternative to virgin materials (Hu et al., 2024). To conclude, when the battery is self-actualized, industrialized circular value chains are implemented meaning large scale, implemented circular practices with consistency, predictability, and efficiency.

# 7. Contribution to knowledge and implications

In this chapter, the contribution to research and contribution to practice are presented in Sections 7.1 and 7.2, respectively. The primary contribution is to bridge academia and industry in the transition to circular value chains, addressing the need to ensure raw material supply, cost efficiency, and sustainable solutions for scaling the battery-electric heavy truck industry.

## 7.1 Contribution to research

The contribution to research is to complement the present literature with *how* the transition from linear to circular value chains will take place. The purpose and the scientific contribution are not only to illustrate the barriers and enablers in the transformation, but how to overcome or benefit from them and to create knowledge in relation to the need for circularity and prerequisites for sustainable battery value chains. The battery maturity assessment model, as presented in Chapter 2.4, is a theoretical model that aims to conceptualize the transformation from linear value chains to circular value chains for electric truck batteries. Combining the battery maturity assessment model with the empirical finings resulting in the battery maturity model provides a testable framework.

## 7.2 Contribution to practice

The circular value chains for the battery life cycle are conceptualized with a focus on efficient use of materials, recycling, and recovery of materials. A transition from a linear to circular value chain is assumed to have a significant impact on the full chain of materials used in the battery for heavy trucks. The research contributes to bringing actionable knowledge and illustrates expected impact on practice, and shifts needed, by a maturity model for self-actualized batteries, as presented in Chapter 5.2.

Vision, willingness, and technical know-how are key to creating a circular mindset for battery production, use, and beyond use. The research brings awareness and provides guidance by illustrating the potential models and pathways towards circularity and how to overcome the barriers and utilize the potential in the electrification journey for heavy trucks.

This thesis focuses on heavy truck batteries from the case company perspective and sheds light on the transformation from linear to circular value chains for batteries. The results can be used to illustrate a circular transformation in general, as well as the potential for circular value chains for automotive batteries specifically.

# 8. Conclusions

This chapter presents the conclusions from the studies as well as the need for further research in the area.

Circular value chains for heavy truck batteries are a necessity to secure supply of critical raw materials for cell production and have environmentally sustainable systems in place. For the battery-producing original equipment manufacturer, it is crucial to secure supply and avoid exposure to price volatility, supply chain disturbances, and geopolitical dependencies through circularity.

RQ1: What challenges, in the transition to circular value chains for electric vehicle batteries, can be mitigated through battery mass customization?

The findings demonstrate that the challenges and enablers to reach circularity for battery materials are not solely related to technology and practical solutions; the results show that change management and organizational structures play an important part in developing circular flows for battery materials. Circular solutions for electric vehicle batteries need to be scalable, the battery needs to be self-actualized, and the electrification of heavy trucks will impact the future business models. The findings highlight that the wide variety and diversity of batteries currently hinder sustainable growth in the battery sector, presenting significant opportunities for mass customization that would benefit original equipment manufacturers, truck customers, secondary users, and recycling stakeholders. The findings suggest that, to effectively manage a high volume of end-of-life batteries, an open-loop supply chain could positively impact the environment and ensure future access to secondary raw materials by processing batteries from various applications. In addition, achieving sustainable electrification for heavy trucks and scalable battery energy storage requires a degree of mass customization, particularly at the cell level, built upon standardized designs. A significant amount of identified challenges in the transition towards circularity would be mitigated by a mass customized battery, building on a standard. Most of the identified challenges related to managing logistics, battery footprint, circular design, external network, manufacturing, and recycling could be overcome by a mass customized battery pack. On the other hand, a mass customized battery cell would give the biggest environmental impact, but not mitigate the same number of challenges.

RQ2: What shifts are needed to reach circular value chains and secure secondary raw materials as input to battery cell production?

In conclusion, achieving circularity for heavy truck batteries requires several key shifts. First, regarding battery design, circularity starts by designing batteries for extended use in multiple applications and material recovery for cell production. Secondly, for mass customization, building on a standard is essential to ensure efficiency for manufacturers, provide customers with choices, and facilitate safe battery returns, recycling, and large-scale energy storage. Thirdly, organizations must establish an effective reverse supply chain to collect used batteries efficiently and make decisions regarding open or closed supply chains. Given future access to raw materials, geopolitical dependencies, and the varying conditions of used batteries, the shift toward establishing regional setups, both for battery use and the return process, is likely. The fourth shift needed is the recycling process: the recycling system must be safe, efficient, and automated to enable effective material recovery. Finally, access and control of comprehensive battery data throughout the battery life cycle supports optimal decision-making for use, reuse, repurposing, and recycling.

## 8.1 Further research

To further explore the potential and challenges in the transformation from linear value chains to circular value chains for batteries, the scope should be broadened to include diverse perspectives in the reversed supply chain, including collection actors, transportation of end-of-life batteries, and recycling actors. This inclusive approach would yield comprehensive and reliable insights into the feasibility and potential benefits of circular supply chains and the potential in the material recovery as input to battery cell production for electric heavy truck batteries. As the global demand for batteries grows, so does the challenge of managing the waste generated when they reach the end of their life (Dong et al., 2024). Waste treatment of batteries is crucial from an environmental perspective, as well as from a material supply perspective. The focus of having the installed base of batteries, the urban mine, as the source of raw materials for battery production is key to support sustainable growth of green technologies and reducing supply chain vulnerabilities (Chirumalla et al., 2024; Tang et al., 2023). The concepts of open loop supply chains and closed loop supply chains need to be further elaborated upon; in the current literature, the closed loop supply chain is used carelessly. The closed loop supply chain is often used as taking back resources in general, not considering the closed loop supply chain definition, that products are returned to the original supply chain after use for value creation (Govindan et al., 2015). In terms of the battery return flow, the impact and selection of open loop supply chain or closed loop supply chain is significant. Furthermore, the impact of regulations on the battery supply chain, transparency, traceability, and battery data should be investigated. The impact of digitalization for battery data and the potential in data driven-decision making is significant and needs to be further understood and developed (Nyamathulla et al., 2024). In addition, further research is needed around circular design and understanding the needs enabling decoupling of the battery from the vehicle (Glöser-Chahoud et al., 2021); modularization will be a prerequisite for full utilization of batteries throughout the battery lifetime.

# 9. References


Ahuja, J., Dawson, L., Lee, R. (2020), A circular economy for electric vehicle batteries: Driving the change. Journal of Property, *Planning and Environmental Law*, Vol. 12, No. 3, pp. 235–250.

Alfaro-Algaba, M., Ramirez F., J. (2020), Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing, *Resources, Conservation and Recycling*, Vol. 154, pp. 1–14.

Ali, A-R., Bartie, N., Husmann, J., Cerdas, F., Schröder, D., Herrmann, C. (2024), Simulation-based life cycle assessment of secondary materials from recycling of lithium-ion batteries, *Resources, Conservation and Recycling*, Vol. 202, pp. 1–13.

Alipanah, M., Saha, A. K., Vahidi, E., Jin H. (2021), Value recovery from spent lithium-ion batteries: A review on technologies, environmental impacts, economics, and supply chain, *Clean Technologies and Recycling*, Vol. 1, No. 2, pp. 152–184.

Al-Salem, M., Diabat, A., Dalalah, D., Alrefaei, M., (2016), A closed-loop supply chain management problem: Reformulation and piecewise linearization, *Journal of Manufacturing Systems*, Vol. 40, pp. 1–8.

Altuntas Vural, C., Van Loon, P., Halldórsson, Á., Fransson, J., Josefsson, F. (2024), Life after use: circular supply chains for second-life of electric vehicle batteries, *Production Planning & Control*, pp. 1–18.

Bednarski, L., Roscoe, S., Blome, C., Schleper, M. C. (2024), Geopolitical disruptions in global supply chains: a state-of-the-art literature review, *Production Planning & Control*, pp. 1–17

Bell, E., Bryman, A., Harley, B. (2019), Business research methods (5th ed.), Oxford University Press.

Berlin, D., Feldmann, A., Nuur, C. (2022), The relatedness of open- and closed-loop supply chains in the context of the circular economy; Framing a continuum, *Cleaner Logistics and Supply Chain*, Vol. 4, pp. 1–10.

Beuren, F. H., Gomes Ferreira, M., Cauchick Miguel, P. A. (2013), Product-service systems: a literature review on integrated products and services, *Journal of Cleaner Production*, Vol. 47, pp. 222–231.

Bhardwaj, S., Mostofi, H. (2022), Technical and Business Aspects of Battery Electric Trucks – A Systematic Review, *Future Transportation*, Vol. 2, No. 2, pp. 382–401.

Bitencourt, L., Dias, B., Soares, T., Borba, B., Quirós-Tortós, J., Costa, V. (2023), Understanding Business Models for the Adoption of Electric Vehicles and Charging Stations: Challenges and Opportunities in Brazil, *IEEE Access*, Vol. 11, pp. 63149–63166.

Bocken, N. M. P., De Pauw, I., Bakker, C., Van Der Grinten, B. (2016), Product design and business model strategies for a circular economy, *Journal of Industrial and Production Engineering*, Vol. 33, No. 5, pp. 308–320.

Bocken N. M. P., Geradts, T. H. J. (2020), Barriers and drivers to sustainable business model innovation: Organization design and dynamic capabilities, *Long Range Planning*, Vol. 53, No. 4, pp. 1–23.

Bocken, N. M. P., Mugge, R., Bom, C. A., Lemstra, H-J. (2018), Pay-per-use business models as a driver for sustainable consumption: Evidence from the case of HOMIE, *Journal of Cleaner Production,* Vol. 198, pp. 498–510.

Brown, S., Pyke, D., Steenhof, P. (2010), Electric vehicles: The role and importance of standards in an emerging market, *Energy Policy*, Vol. 38, No. 7, pp. 3797–3806.

Centobelli, P., Cerchione, R., Del Vecchio, P., Oropallo, E., Secundo, G., (2021), Blockchain technology for bridging trust, traceability and transparency in circular supply chain, *Information and Management,* Vol. 59, pp. 1–14.

Chirumalla, K., Kulkov, I., Dahlquist, E., Stefan, I., Parida, V., Johansson, G. (2024), Enabling battery circularity: Unlocking circular business model archetypes and collaboration forms in the electric vehicle battery ecosystem, *Technological Forecasting and Social Change*, Vol. 199, pp 1–19.

Chordia, M., Nordelöf, A., Ager-Wick Ellingsen, L. (2021), Environmental life cycle implications of upscaling lithium-ion battery production, *The International Journal of Life Cycle Assessment,* Vol. 26, pp. 2024–2039.

Cicconi, P., Kumar, P. (2023), Design approaches for Li-ion battery packs: A review, *Journal of Energy Storage,* Vol. 73, pp. 1–18.

Compagnoni, M., Grazzi, M., Pieri, F., Tomasi, C. (2025), Extended Producer Responsibility and Trade Flows in Waste: The Case of Batteries, *Environmental and Resource Economics*, Vol. 88, No. 1, pp. 43–76.

Dominish, E., Florin, N., Wakefield-Rann, R. (2021), Reducing new mining for electric vehicle battery metals: Responsible sourcing through demand reduction strategies and recycling, *Sustainable Futures, University of Technology Sydney*, pp. 1–49.

Dong, C., Liu, C., Qin, Z., Deng, J., Zhu, Y. (2024), A comprehensive overview of decommissioned lithium-ion battery recycling: Towards green and economical, *Separation and Purification Technology*, Vol. 354, pp. 1–14.

Ellen MacArthur Foundation, (2024), Rethink the future. Available online at: http://www.ellen macarthurfoundation.org/ (accessed March 2025).

Ellström, P-E., Elg. M., Wallo, A., Berglund, M., Kock, H., (2020), Interactive research: concepts, contributions and challenges, *Journal of Manufacturing Technology Management*, Vol. 31, No. 8, pp. 1517–1537.

Etxandi-Santolaya, M., Casals, L. C., Corchero, C. (2024), Extending the electric vehicle battery first life, *Heliyon*, Vol. 10, No. 4, pp. 1–18.

European Commission, (2024), The future of European competitiveness: Report by Mario Draghi, pp.1–70. https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

Fader P, (2020), Customer centricity: Focus on the right customers for strategic advantage, The Warthon School, University of Pennsylvania, ISBN:978-1-61363-102-7.

Farooque, M., Zhang, A., Thürer, M., Qu, T., Huisingh, D. (2017), Circular supply chain management: A definition and structured literature review, *Journal of Cleaner Production*, Vol. 228, pp. 882–900.

Feng, J., Liu, W., Chen, F. (2025), Moving towards a circular economy: A systematic review of barriers to electric vehicle battery recycling, *Sustainable Production and Consumption*, Vol. 54, pp. 241–260.

Gershenson, J. K., Prasad, G. J., Zhang, Y. (2003), Product modularity: Definitions and benefits, *Journal of Engineering Design,* Vol. 14, No. 3, pp. 295–313.

Ghadbane, H. E., Rezk, H., Ferahtia, S., Barkat, S., Al-Dhaifallah, M. (2024), Optimal parameter identification strategy applied to lithium-ion battery model for electric vehicles using drive cycle data, *Energy Reports*, Vol. 11, pp. 2049–2058.

Glöser-Chahoud, S., Huster, S., Rosenbera, S., Baazouzi, S., Kiemel, S., Singh, S., Schneider, C., Weeber, M., Miehe, R., Schultmann, F. (2021), Industrial disassembling as a key enabler of circular economy solutions for obsolete electric vehicle battery systems, *Resources, Conservation & Recycling*, Vol. 174, pp. 1–15.

Goh, S. H., Eldridge, S. (2015), New product introduction and supplier integration in sales and operations planning: Evidence from the Asia Pacific region, *International Journal of Physical Distribution & Logistics Management*, Vol. 45, pp. 861–886.

Govindan, K., Soleimani, H., & Kannan, D. (2015), Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, Vol. 240, No. 3, pp. 603–626.

Grimson, J. A., Pyke, D. F. (2007), Sales and operations planning: an exploratory study and framework, *The International Journal of Logistics Management*, Vol. 18, No. 3, pp. 322–346.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P. (2019), Recycling lithium-ion batteries from electric vehicles, *Nature*, Vol. 575, No. 7781, pp. 75–86.

Hasib, S. A., Islam, S., Chakrabortty, R. K., Ryan, M. J., Saha, D. K., Ahamed, Md H., Moyeen, S. I., Das, S. K., Ali, Md F., Islam, R., Tasneem, Z., Badal, F. R. (2021), A Comprehensive Review of Available Battery Datasets, RUL Prediction Approaches, and Advanced Battery Management, *IEEE Access*, Vol. 9, pp. 86166–86193.

Hertel, D., Bräunig, G., Thürer, M. (2024), Towards a green electromobility transition: A systematic review of the state of the art on electric vehicle battery systems disassembly, *Journal of Manufacturing Systems*, Vol. 74, pp. 387–396.

Hu, Z., Yu, B., Daigo, I., Tan, J., Sun, F., Zhang, S. (2024), Circular economy strategies for mitigating metals shortages in electric vehicle batteries under China's carbon-neutral target, *Journal of Environmental Management*, Vol. 352, pp. 1–14.

Jiao, N., Evans, S. (2016), Business models for sustainability: the case of second-life electric vehicle batteries, *13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use*, Vol. 40, pp. 250–255.

Jiang, R., Wu, C., Feng, W., You, K., Liu, J., Zhou, G., Liu, L., Cheng, H-M. (2025), Impact of electric vehicle battery recycling on reducing raw material demand and battery life-cycle carbon emissions in China, *Scientific Reports*, Vol. 15, No. 1, pp. 1–13.

Kallio, H., Pietil, A-M., Johnson, M., Kangasniemi, K. (2016), Systematic methodological review: developing a framework for a qualitative semi-structured interview guide, John Wiley & Sons Ltd. pp. 1–12.

Kang, H., Jung, S., Kim, H., An, J., Hong, J., Yeom, S., Hong, T. (2025), Life-cycle environmental impacts of reused batteries of electric vehicles in buildings considering battery uncertainty, *Renewable and Sustainable Energy Reviews*, Vol. 207, pp. 1–13.

Kazançoğlu, İ., Kazançoğlu, Y., Yarimoglu, E., Kahraman, A. (2020), A conceptual framework for barriers of circular supply chains for sustainability in the textile industry, *Sustainable Development*, Vol. 28, No. 5, pp. 1477–1492.

Kirchherr, J., Reike, D., Hekkert, M. (2017), Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, Vol. 127, pp. 221–232.

Koech, A. K., Mwandila, G., Mulolani, F., Mwaanga, P. (2024), Lithium-ion battery fundamentals and exploration of cathode materials: A review, *South African Journal of Chemical Engineering*, Vol. 50, pp. 321–339.

Langlois, R. (2002), Modularity in technology and organization, *Journal of Economic Behavior & Organization*, Vol. 49, pp. 19–37.

Li, E., Bieker, G., Sen, A. (2024), Electrifying road transportation with less mining; a global and regional battery material outlook, *International Council on Clean Transportation*, https://theicct.org/publication/ev-battery-materials-demand-supply-dec24/

Li, J., Liu, F., Zhang, J. Z., Li, L., Ferreira, J. (2024), Forward–reverse blockchain traceability: promoting electric vehicles with battery recycling in the presence of subsidy, *Annals of Operations Research*, pp. 1–18.

Liu, D., Wang H., Zhong, B., Ding L., (2021), Servitization in Construction and its Transformation Pathway: A Value-Adding Perspective, *Engineering* Vol. 19, pp. 166–179.

Liu, P., Wang, C., Sun, S., Zhao, G., Yu, X., Hu, Y., Mei, W., Jin, K., Wang, Q. (2023), Understanding the influence of the confined cabinet on thermal runaway of large format batteries with different chemistries: A comparison and safety assessment study, *Journal of Energy Storage*, Vol. 74, pp. 1–18.

Lüdeke-Freund, F., Gold, S., Bocken, N.M.P. (2019), A Review and Typology of Circular Economy Business Model Patterns. *Journal of Industrial Ecology*, Vol. 23, No. 1, pp. 36–61.

Maslow A. (1965), Self-actualization and beyond, New England Board of Higher Education, Winchester, Massachusetts, pp. 108–131.

Meegoda, J., Charbel, G., Watts, D. (2024), Second Life of Used Lithium-Ion Batteries from Electric Vehicles in the USA, *Environments*, Vol. 11, No.5, pp. 1–28.

Meng, K., Xu, G., Peng, X., Youcef-Toumi, K., Li, J. (2022), Intelligent disassembly of electric-vehicle batteries: A forward-looking overview, *Resources, Conservation and Recycling*, Vol. 182, pp. 1–26.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., Zacharia, Z. G. (2001), Defining Supply Chain Management, *Journal of Business Logistics*, Vol. 22, No. 2, pp. 1–25.

Mintzberg, H., (1988), Generic strategies: toward a comprehensive framework, *Advances in Strategic Management*, Vol. 5, pp. 1–67.

Mission Possible Partnership (2022), Making Zero-Emissions Trucking Possible – Energy Transitions Commission (energy-transitions.org) 2023-04-18.

Montag, L., Klünder, T., Steven, M. (2021), Paving the Way for Circular Supply Chains: Conceptualization of a Circular Supply Chain Maturity Framework, *Frontiers in Sustainability*, Vol. 2, pp. 1–27.

Montecchi, M., Plangger, K., West, D. C. (2021), Supply chain transparency: A bibliometric review and research agenda, *International Journal of Production Economics*, Vol. 238, pp. 1–15.

Niri, Jannesar, A., Poelzer, G. A., Zhang, S. E., Rosenkranz, J., Pettersson, M., Ghorbani, Y. (2024), Sustainability challenges throughout the electric vehicle battery value chain, *Renewable and Sustainable Energy Reviews*, Vol. 191, pp. 1–15.

Nyamathulla, S., Dhanamjayulu. C. (2024), A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations, *Journal of Energy Storage*, Vol. 86, pp. 1–27.

Otekenari, D. E. (2020), Moving Beyond Take-Make-Dispose to Take-Make-Use for Sustainable Economy, *International Journal of Scientific Research in Education*, Vol. 13, pp. 497–516.

Panda, N., Cueva-Sola, A. B., Dzulqornain, A. M., Thenepalli, T., Lee, J-Y., Yoon, H-S., Jyothi, R. K. (2023), Review on lithium ion battery recycling: challenges and possibilities, *Geosystem Engineering*, Vol. 26, No. 4, pp. 101–119.

Palmié, M., Parida, V., Mader, A., Wincent, J. (2023), Clarifying the scaling concept: A review, definition, and measure of scaling performance and an elaborate agenda for future research, *Journal of Business Research*, Vol. 158, pp. 1–15.

Petzold, M., Flamme, S. (2024), Recycling Strategies for Spent Consumer Lithium-Ion Batteries, *Metals*, Vol. 14, No.2, pp. 1–23.

Rabetino, R., Kohtamäki, M., Brax, S. A., Sihvonen, J. (2021), The tribes in the field of servitization: Discovering latent streams across 30 years of research, *Industrial Marketing Management*, Vol. 95, pp. 70–84.

Reis, G., Strange, C., Yadav, M., Li, S. (2021), Lithium-ion battery data and where to find it, *Energy and AI*, Vol. 5, pp. 1–15.

Rehman, S., Al-greer, M., Burn, A. S., Short, M., Cui, X. (2025), High-Volume Battery Recycling: Technical Review of Challenges and Future Directions, *Preprints.org*, pp. 1–27. DOI: 10.20944/preprints202501.1483.v1

Ren, H., Mu, D., Wang, C., Yue, X., Li, Z., Du, J., Zhao, L., Lim, M. K. (2024), Vulnerability to geopolitical disruptions of the global electric vehicle lithium-ion battery supply chain network, *Computers & Industrial Engineering*, Vol. 188, pp. 1–17.

Sasikumar, P., Kannan, G. (2008), Issues in reverse supply chains, part II: reverse distribution issues – an overview, *International Journal of Sustainable Engineering*, Vol. 1, No. 4, pp. 234–249.

Scheel, C., Bello, B. (2022), "Transforming Linear Production Chains into Circular Value Extended Systems", *Sustainability*, Vol. 14, No. 7, pp. 1–17.

Seika, J., Kubli, M. (2024), Repurpose or recycle? Simulating end-of-life scenarios for electric vehicle batteries under the EU battery regulation, *Sustainable Production and Consumption*, Vol. 51, pp. 644–656.

Shaikh, W. A., Kalwar, M. A., Khan, M. A., Wassan, A. N., Wadho, M. H., Shahzad, M. F. (2023), A System Dynamics Costing Model for The Refurbishment of Electric Vehicle Batteries, *Jordan Journal of Mechanical and Industrial Engineering*, Vol. 17, No. 1, pp. 15–32.

Sheth, J. N., Jain, V., Ambika, A. (2023), The growing importance of customer-centric support services for improving customer experience, *Journal of Business Research*, Vol. 164, pp. 1–11.

Shi, L., Hu, B. (2022), Battery as a Service: Flexible Electric Vehicle Battery Leasing, *SSRN Electronic Journal*, pp. 1-43, https://www.ssrn.com/abstract=4082272

Tan, E. S., Lee, A. W. L., Shekar, Y. C., Tan, Y. S., (2024), Design for Circularity: A Framework for Sustainable Product Redesign, *Procedia CIRP*, Vol. 122, pp. 479–484.

Tang, Y., Tao, Y., Tao, Y. (2023), Collection policy analysis for retired electric vehicle batteries through agent-based simulation, *Journal of Cleaner Production*, Vol. 382, pp. 1–14.

Tankou, A., Bieker, G., Hall, D. (2023), Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches. *International Council on Clean Transportation*. https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf

Tate, W., Ellram, L., Bals, L. (2022), Handbook of Theories for Purchasing, Supply Chain and Management Research, *Cheltenham, UK: Edward Elgar Publishing*.

Terkes, M., Demirci, A., Gokalp, E., Cali, E. (2024), Battery Passport for Second-Life Batteries: Potential Applications and Challenges, *IEEE Access*, Vol. 12, pp. 128424–128467.

Thompson, D. L., Hartley, J. M., Lambert, S. M., Shiref, M., Harper, G. D. J., Kendrick, E., Anderson, P., Ryder, K. S., Gaines, L., & Abbott, A. P. (2020), The importance of design in lithium ion battery recycling – a critical review, *Green Chemistry*, Vol. 22, No. 22, pp. 7585–7603.

Tsoulfas, G., Pappis, C., Minner, S. (2002), An environmental analysis of the reverse supply chain of SLI batteries, *Resources, Conservation and Recycling*, Vol. 36 pp. 135–154.

Tsao, Y-C., Ai, H. T. T. (2024), Remanufacturing electric vehicle battery supply chain under government subsidies and carbon trading: Optimal pricing and return policy, *Applied Energy*, Vol. 375, pp. 1–14.

Van de Ven, A.H. (2007), Engaged scholarship: A guide for organizational and social research, Oxford University Press, Oxford.

Vaughn, L.M., McLinden, D. (2016), "Concept mapping", In: Jason, L., Glenwick, D. (Eds.), Handbook of Methodological Approaches to Community-Based Research: Qualitative, Quantitative, and Mixed Methods, (Oxford, New York, NY).

Walters, D., Lancaster, G. (2000), Implementing value strategy through the value chain, *Management Decision*, Vol. 38, No.3, pp. 160–178.

Wang, L., Wang, X., Yang, W. (2020), Optimal design of electric vehicle battery recycling network – From the perspective of electric vehicle manufacturers, *Applied Energy*, Vol. 275, pp. 1–11.

Ward, L., Babinec, S., Dufek, E. J., Howey, D. A., Viswanathan, V., Aykol, M., Beck, D. A. C., Blaiszik, B., Chen, B-R., Crabtree, G., Clark, S., De Angelis, V., Dechent, P., Dubarry, M., Eggleton, E. E., Finegan, D. P., Foster, I., Gopal, C. B., Herring, P. K., Hu, V. W., Paulson, N. H., Preger, Y, Preger, D., Smith, K., Snyder, S. W., Sripad, S., Tanim, T. R., Teo, L. (2022), Principles of the Battery Data Genome, *Joule*, Vol. 6, No. 10, pp. 2253–2271.

Wegener, K., Chen, W. H., Dietrich, F., Dröder, K., Kara, S. (2015), Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries, *The 22nd CIRP conference on Life Cycle Engineering*, Vol. 29, pp. 716–721.

Xu, X., Han, X., Lu, L., Wang, F., Yang, M., Liu, X, Wy, Y., Tang, S., Hou, Y., Hou, J., Yu, C., Ouyang, M., (2024), Challenges and opportunities toward long-life lithium-ion batteries, *Journal of Power Sources*, Vol. 603, pp. 1–28.

Zhou, X., Pang, B., Tang, R. (2025), As a service or a product? A comparison of electric vehicle battery supply models, *Omega*, Vol. 130, pp. 1–14.

Ziegler, D., Abdelkafi, N. (2022), Business models for electric vehicles: Literature review and key insights, *Journal of Cleaner Production*, Vol. 330, pp. 1–16.