Integration of Circular Value Chains and Digitalization: a Focus on Lithium-Ion Battery Material Value Chain

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October 28, 2023

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Abstract. Circular value chains, driven by sustainability goals and resource efficiency, are now central in industrial strategies. Simultaneously, digital technologies transform business models and accelerate the shift towards circular economies. This paper explores circular material flow for the electrification of the vehicle fleet, focusing on the Lithium-ion battery value chain. In the paper, a conceptual model integrating digitalization is developed and evaluated to enhance efficiency and product innovation. The paper reviews the lithium-ion battery value chain literature and investigates digitalization potentials for circular business models. A conceptual model is presented in this study to represent the intricate relationship between each stage of the value chain and the concept of circularity while considering the carbon footprint and complexities associated with the implementation of digitalization.

Keywords. Circular value chains, Digitalization, Sustainable production, Lithium-ion battery

1. Introduction

Circular value chains are now at the forefront of industrial strategies driven by the pursuit of sustainability and resource-efficient production systems. The concept of the value chain (1) represents a series of activities within a specific industry that a company engages in. In this chain, products move through these activities sequentially, and at each step, they acquire additional value. The value chain concept emphasizes that the combined value generated by these interconnected activities exceeds the sum of their individual values. The value chain is a crucial process that examines each step from procurement to end-users, emphasizing the delivery of superior value, customer perception, and lifetime customer value as essential elements (2).

In recent years, there has been a growing interest in creating circular value chains, emphasizing sustainability and the principles of the circular economy (CE) (3). In a CE, every material is regarded as valuable, aiming to reduce excessive consumption, resource wastage, and production inefficiencies while emphasizing durability, reliability, and value enhancement (4). CE can be realized through maintenance, durable design, repair, reuse, remanufacturing, refurbishment, and recycling (4,5). The core principles of CE include eliminating waste and pollution through design, prolonging product and material lifetimes, and regenerating natural ecosystems (4). Sustainability considerations play a pivotal role in shaping the value chain of lithium-ion batteries (6). Conventional value chains should transform to give precedence to recycling and remanufacturing processes (7). Sustainability is of utmost importance in the electric vehicle (EV) value chain, especially in the context of the circularity of batteries (8). The global push to reduce greenhouse gas emissions and other pollutants, in line with the Paris Agreement, has put road transport and the future of mobility in the spotlight. However, the resource-intensive nature of EV production raises concerns about the availability of resources to meet this growing demand (8).

Simultaneously, digital technologies drive reshaping business models, foster collaboration, and support accelerating CE shifts (9). Since the transportation sector increasingly seeks eco-friendly alternatives, the investigation into establishing circular and fossil-free material flows holds great promise (8). The growth of emerging digital technologies has prompted a structured review, revealing the need for firms to realign their business models with value chain activities, emphasizing the importance of Industry 4.0 and the CE for internalizing knowledge flows among value chain actors and promoting sustainable development in the global economy (10).

This paper addresses the pressing need for sustainable transportation solutions by investigating the feasibility of creating a circular material flow of batteries to foster sustainable vehicle fleet electrification. The focal point of this exploration is the Lithium-ion battery value chain as a critical component of electrification efforts. This endeavor encompasses developing a conceptual model to highlight interconnections among different stages of the material value chain and integrating the catalytic influence of digitalization to enhance efficiency and innovation within the circular value chains of batteries.

2. Review of literature

2.1. Lithium-ion battery traditional and circular value chain

Lithium-ion batteries (LIBs) actors face many challenges throughout their lifecycle, from forecasting materials demand to managing end-of-life batteries (11). For example, there is an increased demand for natural resources such as cobalt, which is a finite resource, and its mining is associated with environmental and social problems (12). Other challenges include environmental impacts (such as the high energy and resource requirements of battery production and the negative environmental impacts of battery disposal), economic challenges (such as the high cost of EV batteries, which can limit their adoption), and social challenges (such as the potential for social and human rights abuses in the mining and processing of EV battery materials) (11,13). CE practices can potentially manage challenges regarding recycling and reusing EV LIBs (14). Adopting a CE approach for the LIBs value chain can help address supply chain vulnerabilities, improve manufacturing efficiency, and promote sustainable end-of-life management, ultimately contributing to a more environmentally friendly and economically viable LIB ecosystem (11).

Hua et al. (15) concluded the growing importance of handling used LIBs from electric vehicles (EVs) due to their widespread use and the potential shortage of raw materials. A “5R” strategy, including redesign, remanufacture, repurpose, recycle, and reduce is proposed by (15) to maximize the economic, environmental, and resource value of LIBs. Key challenges in this process include technical advancements, cost reduction, regulatory frameworks, and data security. Despite the potential of reusing and recycling LIBs, significant challenges remain in managing the large volume of retired batteries, requiring a comprehensive circular value chain approach.

2.2. Adoption of digitalization to foster CE for LIBs

The rapidly evolving digitalization landscape offers many opportunities to develop a circular value chain (16,17). Digital technologies such as digital twins, AI-driven algorithms, the Internet of Things, Big data, blockchain, and cloud systems can offer opportunities for virtualization, collaboration with stakeholders, and co-creation with customers (18). Piscicelli (19) highlights the need for further research into the multifaceted impacts of digital technologies on CE strategies, emphasizing economic and social benefits, industry-specific variations, and empirical assessments to guide policy interventions.

Regarding LIBs' circular value chain, adopting digital technologies and concepts like Industry 4.0 can provide opportunities to foster CE. Awan et al. (10) highlighted the importance of realigning business models within the battery industry, integrating emerging digital technologies, and embracing concepts like Industry 4.0 and the CE to optimize knowledge flows among value chain actors and foster sustainable development. Zanotto et al. (20) emphasize the critical role of digital technologies, including AI-driven algorithms and digital twins, in advancing battery innovation and manufacturing, ultimately improving performance, safety, and recyclability across the battery's entire lifecycle. Anandavel et al. (21) focus on adopting lithium-ion batteries in electric vehicles and the safety, durability, charging time, and driving range challenges. They propose a digital twin-based framework that enables real-time monitoring and intelligent management across the battery pack lifecycle, offering solutions to critical issues and significantly improving safety and service life. Wang et al. (22) delve into the potential of digital twin technology in addressing complex issues within lithium-ion batteries for new energy vehicles. Wang et al. (22) highlight its development, concepts, key technologies, and propose solutions for digital modelling, state estimation, safety, and control. Digital twins require a robust platform that incorporates big data, AI, IoT, cloud computing, and blockchain. These technologies are interconnected and tightly integrated with digital twins.

Nevertheless, the digitalization journey is not without its challenges (23). The transformation toward smart factories, driven by Industry 4.0 and information technologies, is particularly complex in electrode manufacturing, which plays a pivotal role in battery cell performance (23). These challenges necessitate a tailored digitalization approach that prioritizes parameters based on quality management and complexity, paving the way for smarter and more sustainable battery cell production. The convergence of digitalization and circular value chains in the battery industry promises to reshape the sector in ways that enhance efficiency, sustainability, and environmental impact. Antikainen et al. (18) discuss the potential opportunities for digitalization in the CE, emphasizing the need to address challenges related to business models, data management, collaboration, and competence for successful implementation. They highlight the importance of virtualization, collaboration with stakeholders, and co-creation with customers but also stress the need to overcome data sharing, trust, and security challenges. Piscicelli (19) highlights the need for further research into the multifaceted impacts of digital technologies on CE strategies, emphasizing economic and social benefits, industry-specific variations, and empirical assessments to guide policy interventions.

3. Research method

3.1. Empirical study

The empirical study was conducted during a project aimed at preparing for the electrification of the Swedish vehicle fleet by assessing the feasibility of a circular and fossil-free material supply. Two workshops were organized, involving 17 participants from various professional backgrounds, including engineers, academics, and industry experts in the lithium-ion battery sector. Participants were selected from the extended professional networks of the project team members based on their demonstrated interest in the battery value chain, and invitations were extended via electronic mail. The workshops were designed to be interactive and knowledge-intensive, structured as presentations, discussions, brainstorming sessions, and group activities. The participants were encouraged to actively share their experiential insights and expertise across various facets of the lithium-ion battery value chain, including mining, battery manufacturing, distribution, and considerations regarding end-of-life scenarios. Each workshop lasted three hours, ensuring a comprehensive and in-depth exploration of the subject matter.

Extensive notes were taken during the workshops to capture valuable insights, key points, and discussions. In addition to the group activities and plenary sessions, participants were engaged in individual or paired work focused on specific thematic elements, such as “possibilities for digitalization”, “technological maturity of various phases of value chain”, and “material flow through LIBs’ value chain”. These focused activities were followed by facilitated group discussions to consolidate findings and insights.

3.2. Review of the literature

A literature review was conducted to identify the latest research on circular value chains, digitalization, and lithium-ion batteries. The following databases were used: Web of Science, Google Scholar. The following keywords were used: “Circular business model and lithium-ion battery”, “digitalization and circularity”, “Industry 4.0 and lithium-ion battery”, “digitalization and lithium-ion battery”, “Circular economy and Lithium-ion battery”, “Circular value chain and Lithium-ion battery”, “Carbon footprint and lithium-ion battery”, “sustainability and lithium-ion battery”, “Sustainable value chain and lithium-ion battery”.

Table 1- Review Protocol

Item	Description
Keywords	“Circular business model and lithium-ion battery”, “digitalization and circularity”, “Industry 4.0 and lithium-ion battery”, “digitalization and lithium-ion battery”, “Circular economy and Lithium-ion battery”, “Circular value chain and Lithium-ion battery”, “Carbon footprint and

	lithium-ion battery", "sustainability and lithium-ion battery", "Sustainable value chain and lithium-ion battery".
Databases	Web of Science and Google Scholar
Search fields	Title; Abstract; Keywords
Language	English
Publication type	Journal and conference proceeding articles.
Time window	2000 to 2023

This review of 40 relevant papers highlights the complex interplay between CE, digitalization, Industry 4.0, carbon footprint, and sustainability in the lithium-ion battery industry. The authors of the paper draw on these insights to explore the challenges and opportunities for a more sustainable and circular approach to lithium-ion battery production and usage.

4. Findings

In this section, the findings from the literature review and empirical study are summarized to discuss each stage of the value chain regarding the impact on circularity, carbon footprint level, and technological maturity and potential for adoption of digitalization.

4.1. Impact on circularity

The impacts on the circularity of each phase of LIBs' value chain are shown in Figure 1. The collection and recycling of LIBs are the two most important stages for circularity, as they allow the valuable materials in the batteries to be recovered and reused. Recycling end-of-life electric vehicle batteries could meet 60%, 53%, 57%, and 53% of the global demand for cobalt, lithium, manganese, and nickel in 2040 (8). Waste management is a major challenge in collecting and recycling LIBs due to the risk of fires and hazardous contamination, and their recycling requires sustainable processes (8).

Design is critical in fostering circularity among the various stages of LIBs' value chain. Batteries designed to be easy to disassemble and recycle are more likely to be recycled at the end of their life (14). There is a need to design LIBs to facilitate repair, disassembly, and recycling (13). Reuse is also an important strategy for circularity, as it extends the life of the batteries and reduces the need to produce new ones. A hierarchy of reuse strategies can be used to extend the life of electric vehicle batteries and optimize their lifecycle value. These strategies include intensified use, repair, repurposing, refurbishment, and remanufacturing (13). Repurposing batteries in energy storage systems is a viable market opportunity (8).

However, to facilitate the CE strategy for LIBs to improve the design for circularity and improve reuse policies, there is a need to shift the responsibility for end-of-life management from the consumer to the producer. In the Extended Producer

Responsibility (EPR) policy, the battery manufacturers are responsible for taking back their batteries for reuse, refurbishing, recycling, or remanufacturing (8,13). However, further research is needed to examine the challenges of balancing producer incentives for design for recycling, durability, and repurposing under the EPR policy.

In the circularity literature of LIBs, less attention has been paid to processing and mining. However, these stages are still important to consider. Mining raw materials for LIBs batteries can have a significant environmental impact, including water pollution and ecosystem destruction (24). Minimizing the environmental impact of mining can be done by using renewable energy sources to power mining operations and recycling mining waste (25). Despite promising prognoses about recycling lithium-ion batteries to reduce reliance on natural resources by up to 50% (25), mining and exploration will remain important because not all materials are recyclable.

4.2. Carbon footprint level

The most carbon-intensive stages of the LIBs' lifecycle are extraction, processing, and production. These stages account for a significant portion of the total carbon footprint of LIBs (25,26). Extracting lithium from brine deposits requires a lot of energy, as the brine needs to be pumped to the surface and then evaporated to extract the lithium. Mining cobalt can also be energy-intensive, as the cobalt ore needs to be crushed and processed to extract the cobalt. Furthermore, refining raw materials into battery-grade materials can be a complex and energy-intensive process.

The production of LIBs requires the use of energy to assemble the batteries and ensure that they meet quality standards. The production of cathode materials contributes significantly, accounting for around 50% of the total battery production emissions (27). These emissions primarily arise from upstream processes involved in nickel, cobalt, lithium extraction, and mineral extraction. Recycling methods, such as hydrometallurgy, direct physical recycling, and remanufacturing using recycled materials, result in a 51.8% lower carbon footprint than battery production with raw materials (26). Furthermore, it is projected that substantial carbon emissions reductions (up to 84.9%) in battery production by 2060 will be achieved primarily through a transition to greener electricity sources (26). While there are several ways to reduce the carbon footprint of LIBs, it is important to note that the technology is still in its early stages of development. Further research is needed to develop more efficient and sustainable manufacturing processes and to identify new ways to reuse and recycle LIBs.

4.3. Technological maturity and potential for adoption of digitalization

Empirical findings indicate that the battery design phase holds significant promise for embracing digitalization, driven by its advanced level of technological maturity. Nonetheless, it is noteworthy that the review of the available literature on the application of Industry 4.0 or digitalization in LIBs' value chain did not yield any discussions pertaining to the technologies implemented during the design phase. The significance of battery design in the realm of EV manufacturing cannot be overstated, as it serves as a cornerstone of technological development. Intriguingly, there appears to be a reluctance among EV manufacturers to divulge pertinent information related to this phase to recycling firms, as observed in the study conducted by (28). Based on empirical findings, production is also a relatively mature stage, with several mature manufacturing processes. However, there is still room for improvement in the production process, such as automation, digital twins, and artificial intelligence, which can be used to optimize the production process and reduce costs (29).

Low △
Medium ○
Strong ◉

Themes	Exploration	Mining	Processing	Design	Production	Use	Reuse	Collection	Recycling
Impact on circularity	△	△	△	◉	○	△	◉	◉	◉
Level of difficulty for circularity practices	◉	◉	○	△	△	△	◉	◉	◉
Carbon footprint level	◉	◉	◉	△	◉	△	△	△	○
Technological maturity	△	△	△	◉	◉	○	△	△	△
Level of difficulty for adopting digitalization	○	○	○	△	△	△	○	◉	◉

Figure 1- matrix of circularity impact, carbon footprint, technological maturity, and difficulties of circularity practices and digitalization adaptation in the lithium-ion battery value chain.

Based on the empirical findings, the use phase of LIBs has reached a level of notable maturity, marked by their extensive deployment across a diverse range of applications, including electric vehicles, consumer electronics, and energy storage systems. This widespread adoption has fostered a comprehensive understanding of the safe and efficient use of LIBs, thanks to accumulated knowledge and experience gained from their extensive integration into these various sectors. Based on the empirical findings, the processing stage within the LIBs' lifecycle can be less mature due to its inherent complexity and significant challenges, necessitating the development of more efficient and sustainable processing methodologies. Similarly, the reuse stage is also in a less mature state, primarily attributable to its relatively recent conceptualization, with several attendant challenges remaining unresolved, including the establishment of standardized practices for reused batteries and the cultivation of a viable market for such products. The exploration, mining, collection, and recycling stages represent the least technologically mature facets of the LIBs battery lifecycle, primarily because of their intricate nature and formidable challenges, thereby underscoring the imperative to advance the adoption of digitalization within these stages.

4.4. Possibilities to adopt digitalization to foster circularity

The model, presented in Figure 2, offers a conceptual framework that illustrates the interplay between each value chain stage and circularity, considering the intricacies of implementing digitalization. This visual representation provides a comprehensive overview of the intensity of influence for each stage of a circular LIBs' value chain while indicating the significance of each stage from a carbon footprint perspective. The y-axis in the figure shows the impact of each phase of the value chain on circularity ranging from low to high. The size of each phase indicates the intensity of the carbon footprint level. Moreover, the model acknowledges and addresses the level of difficulties that stakeholders might encounter when adopting digital technologies within the value chain.

As depicted in Figure 2, the design and production phases have the greatest potential impact on circularity and the highest likelihood of seamlessly adopting digital technologies, largely owing to their low associated difficulty. Product innovation plays a pivotal role in enhancing the circularity of LIBs by extending their lifespan, improving recyclability, and reducing resource consumption. As sustainability and CE principles continue to prominence, innovation in LIB design will be essential in achieving more environmentally friendly and economically viable battery solutions.

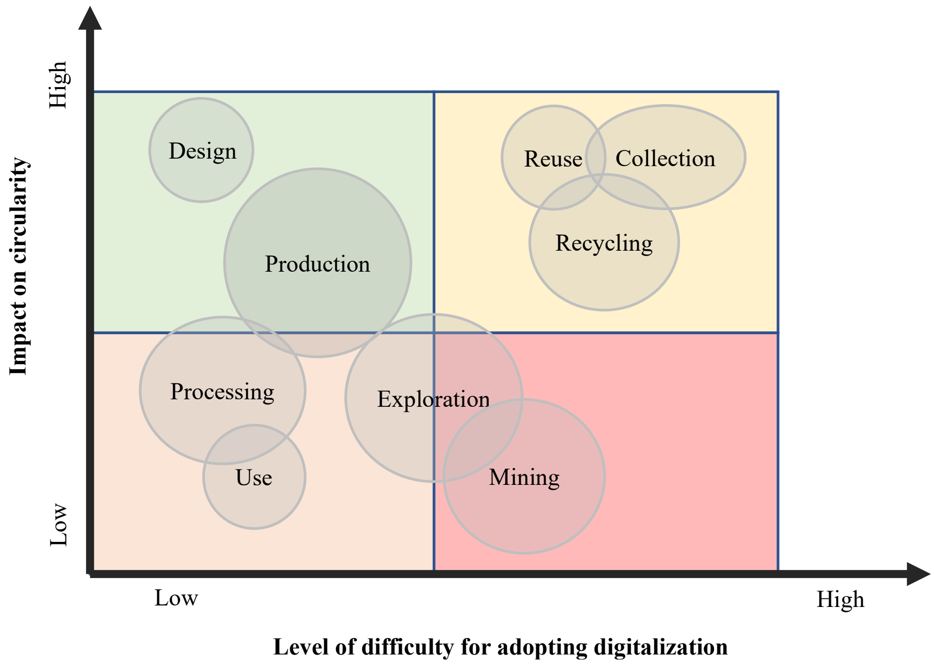

Figure 2- A conceptual representation of the intricate relationship between each stage of the LIBs value chain and the concept of circularity, considering the complexities associated with the implementation of digitalization.

Notably, the production phase plays a pivotal role in shaping the carbon footprint of the entire battery value chain. In the next level, reuse, collection, and recycling of LIBs have high importance due to their high effect of circularity. However, adopting digital technologies in these phases might face challenges due to the low maturity of methods and technologies. Overall, digital technologies have the potential to play a significant role in improving the circularity of LIBs. However, more work is needed to develop and mature these technologies. The stages that exert the least influence on circularity are processing, exploration, mining, and usage. Within this group, the processing stage encounters fewer adoption challenges for digital technologies despite substantially contributing to the carbon footprint.

Conclusion

The findings presented in this paper underscore the potential for digitalization within the LIBs value chain, with the design and production phases showing the most promise. These stages benefit from technological maturity. Yet, a noticeable absence of literature discussions about technology in the design phase suggests a knowledge gap worth addressing, considering its pivotal role in electric vehicle manufacturing. The production phase, while relatively mature, offers room for further enhancement through automation, digital twin technology, and artificial intelligence, with the potential to bolster circularity within LIBs.

Conversely, the usage phase has matured through widespread deployment, providing invaluable insights for safe and efficient LIB utilization. On the other hand, the processing and reuse stages lag in technological maturity, necessitating the development of more efficient and sustainable approaches. Similarly, the exploration, mining, collection, and recycling stages are among the least technologically mature, mainly due to their complexity and challenges.

The proposed conceptual model in this study not only highlights the areas where digitalization can augment circularity but also underscores the practical difficulties that organizations may confront throughout this transformative process. It can be used by decision-makers, equipping them with a holistic perspective and actionable insights to guide investments in technology, process enhancement, and sustainable practices, all of which contribute to a more circular and environmentally responsible value chain.

For future studies, further data collection methods, such as conducting interviews with various stakeholders of LIBs' value chain, can be included to improve the validity of the results. Moreover, investigating the role of collaboration among various stakeholders in facilitating the adoption of digitalization and circularity in LIBs' value chain can be further investigated.

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