UNIVERSITY
OF TURKU
Turku School of
Economics

Artificial intelligence and blockchain as enablers in global circular supply chain traceability

A battery supply chain perspective

International business
Bachelor’s thesis

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16.4.2026
Turku

Student’s statement regarding the use of Artificial Intelligence (AI) for preparing and/or writing this thesis:

☐ **I have not used any AI-based tools.**

☒ **I have used AI-based tools**. Their use is documented in the Appendix. The AI tools were used in a way that complies with academic integrity guidelines.

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Subject: International business
Author: Sohvi Niinistö
Title: Artificial intelligence and blockchain as enablers in global circular supply chain traceability: a battery supply chain perspective
Supervisor: D. Sc. Henna Leino
Number of pages: 40 (+ appendices 1 page)
Date: 16.4.2026

Abstract

In the future, battery supply chains are facing many challenges. Raw critical battery mineral scarcity and their concentration into a handful of locations create geopolitical tensions and might hinder the development towards sustainable energy solutions. Recycling, reuse, and remanufacturing of used batteries along the supply chain through a circular supply chain (CSC) model can be proposed as a solution. CSCs are supply chains based on circular economy principles, where materials can re-enter previous phases instead of being disposed.

A wider industry application of global circular supply chains is hindered by a lack of traceability information among supply chain participants. Existing literature has covered traceability in linear supply chains, but only minimal research has touched upon traceability in circular supply chains especially. The purpose of this thesis is to show how artificial intelligence (AI) and blockchain technology can act as solutions in enabling traceability information sharing and battery tracking along the most critical phases of a circular battery supply chain. The principles and challenges of AI and blockchain are also discussed.

The findings present many applications of blockchain and AI in material sourcing, distribution, and end-of-life phases. Participants within a digital blockchain structure can verify miners and logistics providers and create digital smart contracts between participants to ensure compliance and truthfulness on battery chemistry information and traceability during transportation. Artificial intelligence can be utilized in securing tracking information, automating smart contracts and predicting remaining use-of-life of batteries. Through the tools of these technologies, information can be accessed by participants along the supply chain and opportunities for battery circularity can be harnessed at any point.

This thesis brings new theoretical value to previous literature within supply chain traceability and battery circularity, which has been lacking in covering the circular supply chain model especially. In academia, the focus of traceability for circularity has been on the end-of-life phase rather than enabling it along the whole supply chain that CSCs offer. By also covering sourcing and distribution from manufacturing, the thesis presents a larger picture of possibilities and also the interrelatedness of supply chain phases in enabling traceability in battery CSCs.

The thesis also includes limitations and challenges. Before wider industry application, challenges related to implementation of AI and blockchain should be discussed to ensure privacy, regulative requirements and in the end, functional circularity.

Keywords: circular supply chain, supply chain traceability, artificial intelligence, blockchain technology, battery supply chains

Kanditutkielma

Oppiaine: Kansainvälinen liiketoiminta
Author: Sohvi Niinistö
Otsikko: Tekoäly ja lohkoketjut globaalien kiertotaloustoimitusketjujen jäljitettävyyden mahdollistajina: akkuteollisuuden toimitusketjun näkökulma
Ohjaaja: KTT Henna Leino
Sivumäärä: 40 (+ liitteet 1 sivu)
Päivämäärä: 16.4.2026

Tiivistelmä

Globaalit akkujen toimitusketjut kohtaavat monenlaisia haasteita tulevaisuudessa. Akkujen tuotannossa tarvittavien kriittisten mineraalien niukkuus ja niiden keskittyminen tiettyihin maantieteellisiin sijainteihin aiheuttavat geopoliittisia jännitteitä ja lisäksi materiaalien saatavuus saattaa hidastaa muun muassa kehitystä kohti kestäviä energiaratkaisuja. Käytettyjen akkujen kierrätys, uudelleenkäyttö ja uudelleenvalmistus toimitusketjun eri vaiheissa kiertotaloustoimitusketjujen (eng. circular supply chain) kautta voi olla ratkaisu. Kiertotaloustoimitusketjut ovat toimitusketjuja, jotka perustuvat kiertotalouden periaatteisiin ja joissa materiaalit voivat palata aiempiin vaiheisiin sen sijaan, että ne hävitettäisiin.

Globaalien kiertotaloustoimitusketjujen laajempaa soveltamista hidastaa huono akuista saatavilla oleva jäljitettävyystiedon määrä eri toimitusketjun portailla. Aikaisemmassa kirjallisuudessa on käsitelty jäljitettävyyttä lineaarisissa toimitusketjuissa, mutta vain pieni osa siitä on käsitellyt jäljitettävyyttä, joka tukisi kierrätettävyyttä kiertotaloustoimitusketjuissa. Tutkielman tarkoitus on esitellä tekoälyn ja lohkoketjuteknologian työkaluja, jotka mahdollistavat jäljitettävyystiedon keräämisen ja jakamisen sekä akkujen seurannan kiertotaloustoimitusketjun kriittisimmissä vaiheissa. Lisäksi tutkielma selittää tekoälyn ja lohkoketjujen periaatteet, mutta myös teknologioiden haasteita.

Tutkimustulokset tuovat esille lukuisia lohkoketjujen ja tekoälyn sovelluksia materiaalien hankinnassa, tuotteiden jakelussa ja akkujen elinkaaren loppuvaiheessa. Digitaalisen lohkoketjurakenteen toimijat voivat tarkistaa esimerkiksi kaivoksien ja logistiikkapalvelujen tarjoajien luotettavuuden sekä luoda toimijoiden välille digitaalisia älykkäitä sopimuksia (eng. smart contracts), joilla varmistetaan materiaaleista tai akuista saatavan tiedon oikeellisuus ja kuljetusten turvallisuus. Tekoälyä voidaan hyödyntää seurantatietojen keräämisessä ja hallinnassa, älykkäiden sopimusten automatisoinnissa sekä arvioimaan akkujen jäljellä olevaa käyttöikää. Näiden teknologioiden avulla toimitusketjun osanottajat pääsevät käsiksi tietoihin, ja akkuja voidaan kierrättää missä tahansa vaiheessa.

Tutkielma tuo teoreettista lisäarvoa toimitusketjujen jäljitettävyyttä ja akkujen kiertotaloutta käsittelevään kirjallisuuteen, jossa erityisesti kiertotaloustoimitustketjut ovat jääneet vähemmälle huomiolle. Jäljitettävyyttä käsittelevässä tutkimuksessa on keskitytty kierrätettävyyteen elinkaaren loppuvaiheessa toimitusketjun kokonaistarkastelun sijaan. Käsittelemällä myös hankintaa ja jakelua kuluttajalle, tutkielma esittää laajemman kuvan mahdollisuuksista sekä toimitusketjun vaiheiden keskinäisistä yhteyksistä akkujen kiertotaloustoimitusketjujen jäljitettävyyden mahdollistamisessa.

Ennen laajempaa soveltamista teollisuudessa tulisi kuitenkin keskustella tekoälyn ja lohkoketjujen käyttöönottoon liittyvistä haasteista, jotta voidaan varmistaa datan yksityisyys, mukautuminen alan säännöksiin sekä lopulta, toimiva kiertotalous.

Avainsanat: kiertotaloustoimitusketjut, jäljitettävyys toimitusketjuissa, tekoäly, lohkoketjuteknologia, akkujen toimitusketjut

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1 Introduction

1.1 Context of the thesis

The battery industry is powering cleaner transportation and energy production driven by regulations, environmental crises and shifting consumer preferences. The industry carries the crucial role of producing batteries for electric vehicles (EVs) and for storing renewable energy. However, it faces challenges throughout its supply chains. One of them is the global availability of critical minerals needed to produce batteries. According to UNCTAD (2025, vi), the demand for critical materials widely used in battery technologies such as lithium, cobalt and nickel is predicted to rise sharply in the next centuries. The production based on 2018 levels for graphite, lithium and cobalt needs to rise about 450% to meet demand in 2050 mostly because clean energy technologies have a higher material intensity in comparison to fossil-fuel-based ones. (World Bank Group 2020, 73, 93). This means larger mining projects, creating risks for both the environment and society. However, depending on the direction that future battery chemistry innovations take, manufacturers may be able to detach themselves from using for example cobalt, but will most probably depend on other critical minerals. (Ritchie & Rosado 2024).

The future global supply of these materials is also shaped by geopolitics. Firstly, the nature of many critical minerals is that there is often one single country dominating the export of virgin material. For example, 75% of global cobalt in 2024 came from the Democratic Republic of Congo and 76% of refined cobalt from China. With the case of nickel, Indonesia is the largest producer with a share of 59% leaving the next largest producer Philippines with only 9%. (Ritchie & Rosado 2024.) This concentration creates geopolitical tensions and supply disruptions when a crucial region is hit by a crisis or when trade restrictions are put in place. The dependency leads in supply volatility and price fluctuation driving overall uncertainty among firms and in the broader economy (IEA 2025). And if a company wanted to pursue virgin resources coming from alternative or more sustainable suppliers, the lack of traceability of critical materials is still not standardized and reliable.

The logical solution to this dependency would be to diversify the mining of critical minerals but it is hindered by clashing motives. Some mineral-concentrated developing economies will see growth due to increased mineral demand (World Bank Group 2020, 93). At the same time, the transition has to be made ethically and at a reasonable cost. Although the way towards cleaner transportation and energy is desperately needed, there seems to be too much disagreement on how it should be achieved. Recent discussions have centred around the poor traceability of minerals and how it conceals the use of child labour and violations of environmental standards. Most recently in February 2026, media reported on a mineral mine collapsing in the Democratic Republic of Congo with over 200 deaths, including women and children (BBC 2026). This lack of traceability and standards create an environment, where motivations towards safe mining are minimal (Schöneich et al. 2023, 954, 961). It can be concluded that the rising demand of critical minerals globally and the exploitation of human rights in the process do not support moving forward sustainably with only the traditional linear supply chain model.

The World Bank Group (2020, 95) predicts that in the future, extraction of minerals will still be needed but that recycling could play a significant role in supporting the low-carbon transition. In addition to enhancing traceability in the start of the supply chain to ensure sustainability, promoting traceability in the end of the supply chain enables recycling and makes reusing critical minerals more lucrative. Regulations enforced by for example the European Union are driving the role of end-of-life recycling of batteries and the manufacturer’s role in it. (European Commission 2023). Navigating minimum recycling rates for critical metals while also balancing the economic viability of recycling requires battery manufacturers to consider new product cycles. This is where circular supply chains come to offer a solution.

The concept of a circular supply chain (CSC) builds on the idea of a circular economy (CE) and supply chains. A circular economy can be defined as an economic system where instead of following a linear product lifecycle, materials are recovered, reused, and recycled along the lifecycle in production, consumption, and end-of-life phase (Kirchherr et al. 2017, 229). A supply chain can be defined as “the flow of products, information and money through a network of partners from raw material suppliers to end users” (ASCM 2025, 187). What makes supply chains circular is that materials are recovered from various parts of the supply chain and optimally are put back to other parts of the chain to be used again. The term circular supply chain is covered in more detail in chapter 2.

However, CSCs alone do not solve the critical mineral sourcing and recycling dilemmas in the battery industry. Combining traceability with CSCs ensure the circularity, sustainability, and ethical aspects in battery industry supply chains. While sourcing and delivery networks are becoming more complex and are pressured by regulations, they are filling firms’ information systems with data that cannot be managed efficiently without additional help. There is a growing interest for artificial intelligence and blockchain solutions in enabling traceability and supply chain transparency. With its many definitions, artificial intelligence (AI) can be said to mean “systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals" (AI HLEG 2018, 1). Blockchain technology can be classified as a distributed data structure shared among participants of a system, where every transaction is first accepted by a majority of participants and then digitally documented (Crosby et al. 2016, 7). When it comes to enhancing traceability of circular supply chains in the battery industry, AI together with blockchain can offer a lot of opportunities, which are further discussed in the thesis.

1.2 The thesis in the light of previous literature

The thesis combines research efforts from the fields of circular economy, supply chain, artificial intelligence and blockchain technology. While still emerging, circular supply chains have been studied as the solution to promote circular economy principles both in theory and practice (e.g. Amir et al. 2022; Batista et al. 2018; Das 2024; De Angelis et al. 2018). Supply chain management literature has focused on supply chain traceability to both promote supply chain transparency and sustainability (e.g. Garcia-Torres et al. 2019; Hoang et al. 2023; Shaëfer et al. 2025). Lastly, artificial intelligence and blockchain technology have been comprehensively studied separately but also their possibilities in circular supply chains have been touched upon (e.g. da Silva et al. 2023; Centobelli et al. 2022; Mankar et al. 2024). From the two technologies, AI has received relatively less attention. Figure 1 presents the cross-sections of relevant topics of literature used in the thesis and the context that the thesis is discussing. In the middle, the research gap is visualized.

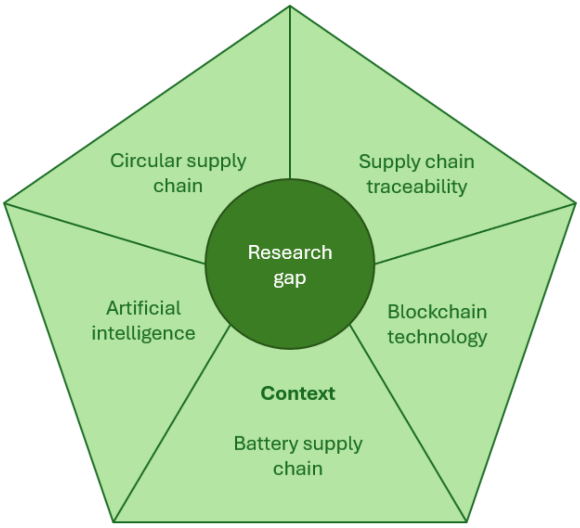


Figure 1 Theoretical context of the thesis and research gap

Combining the three very current and important themes: circular supply chain traceability, artificial intelligence and blockchain with an industry that is constantly shaped by regulative requirements regarding circularity and sustainability offers a research gap worth studying. The still young academic research on the topic of traceability in circular supply chains also presents a valuable research gap. The thesis offers new academic insights but also acts as a launchpad for actors in the battery supply chain to harness circularity and collaboration. The thesis does not aim to propose a framework to fit for every kind of industry and focuses solely on circular supply chain traceability, rather than presenting a framework for implementing overall circular economy principles and CSCs in industries.

1.3 Purpose and structure of the thesis

With the help of previous research, this thesis aims to uncover ***how AI and blockchain can support traceability in various parts of the circular supply chain and further promote circularity of critical mineral use in the battery industry***. Regulations and an evolving competitive landscape are drivers for enhancing supply chain traceability and technologies can support battery manufacturers in navigating these changes. In this thesis, supply chain traceability is defined as the capacity to trace information about a product and its supply chain. This information can for example include the product’s origin and chain of custody. (IEA & OECD 2025, 15.) The thesis contributes to international business research by offering a review on the possibilities of harnessing technologies in promoting circularity in globally operating businesses. It also shares executable solutions to moving towards sustainable global supply chain practices, which are at the heart of international business.

To answer the main research question, the thesis will discuss the following sub-questions:

- What are the phases of a CSC and how does traceability manifest in them?
- What is artificial intelligence and how is it employed in supply chains?
- What is blockchain and how is it employed in supply chains?

First, the thesis covers the overall concept and phases of a circular supply chain. In chapter 3, the working principles of AI and blockchain are presented and how they are currently implemented in supply chains. Lastly, the concepts are brought together with traceability to show how these technologies can promote circular supply chain traceability in the most critical phases of a battery industry’s supply chain.

2 Global circular supply chains

The term circular supply chain (CSC) is often used interchangeably in academic literature with terms like sustainable supply chain, green supply chain, environmental supply chain, reverse supply chain, and closed-loop supply chain (Gurtu et al. 2015, 167; Montag 2023, 36). A fragmented and young research base on the topic of CSC has yet to agree on one specific definition (Montag 2023, 36). Prior research has rather tried to form a framework to understand CSCs, but the aforementioned terms are still used to describe a similar topic. Farooque et al. (2019, 883) argue that these concepts integrate different levels of sustainability thinking into supply chains and thus differ from each other. After all, CSCs emerge from circular economy principles, which differentiates them from other terms. According to Batista et al. (2018, 445), reverse and closed-loop supply chains are the greatest reference points for describing the restorative and regenerative processes that circular supply chains entail. On the other hand, Farooque et al. (2019, 884) argue that the terms fail in including the nature of regenerative cycles and the vision of a zero-waste circular economy that CSCs build upon. Although academia is torn on terminology, most of the principles of circular supply chains are agreed upon.

To the best of the author’s understanding, the biggest difference between the similarly used terms is that while closed-loop and reverse supply chains have waste or material flows exiting the supply chain cycle at multiple points, circular supply chains minimize them to the greatest extent so that the material can enter the other phases of the same cycle (closed loop) or a different cycle (open loop) to be used again, optimally forever (Farooque et al. 2019, 885). Rather than seeing used products and biproducts as waste, they can be recovered and reused in the production of secondary products (Genovese 2017, 353). Nasir et al. (2017, 444) support the idea that the implementation of circular economy practices pushes for the creation of CSCs in which products re-enter the supply chain as input for production through remanufacturing or recycling.

2.1 The phases of a global circular supply chain

When comparing the phases of a linear, a closed-loop and a circular supply chain, many differences can be observed. The three varying models are presented in Figure 1. While the agents and phases in the supply chains seem to be the same, the final phase is not. Rather than disposing waste and products, circular supply chains aim to minimize waste and even reach for a zero-waste economy. The circular supply chain manages this through regenerative cycles between the echelons, where materials and biproducts from later phases re-enter previous phases. (Farooque et al. 2019, 885.)

This is enabled by reverse logistics, which includes the planning and controlling of materials from the point of consumption to recycling or disposal in a cost-efficient way and to recapture value (Bressanelli et al. 2021, 8).

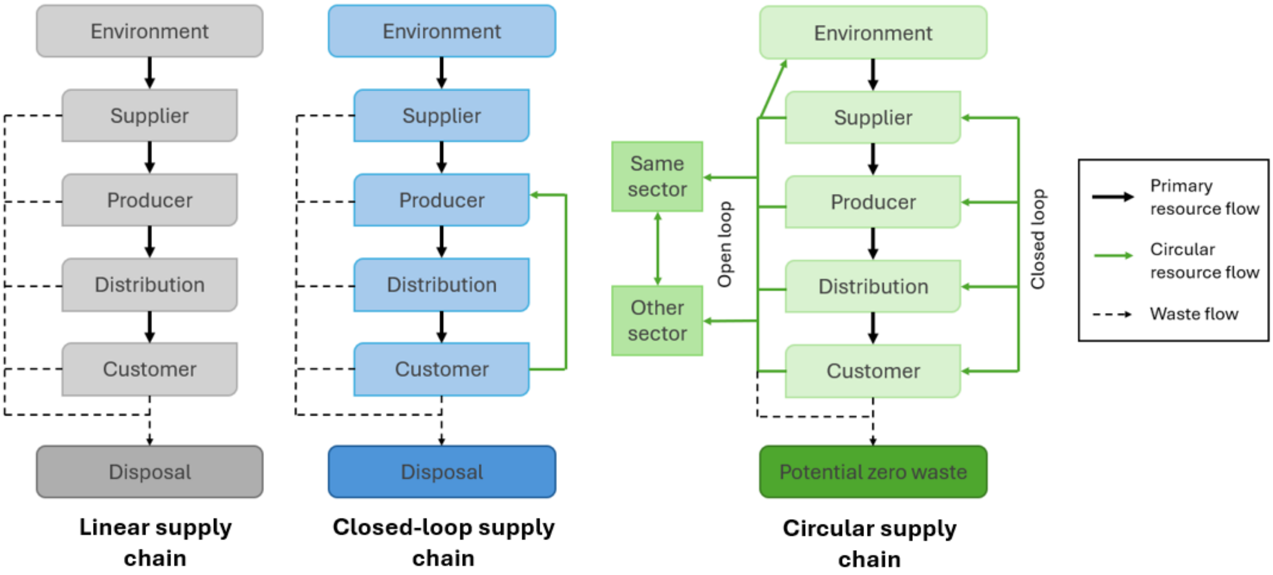


Figure 2 A linear, a closed-loop and a circular supply chain (adapted from Farooque et al. 2019, 885).

In Figure 2, the key difference between the closed-loop and circular supply chain is that not only can resources be exchanged between multiple echelons via a closed-loop cycle, they can also enter supply chains within the same sector or other sectors via an open loop cycle (Farooque et al. 2019, 885). The difference to a closed-loop supply chain becomes therefore clear. A close-loop supply chain (CLSC) is defined as a supply chain where postconsumer products are brought back to initial manufacturers via reverse flows (Souza 2012, 7). The materials do not enter other phases or even other cycles in the same sector. A circular supply chain is the most sustainable of the three, but it also requires more shared infrastructure, planning, and cooperation between firms. The management of a circular supply chain is motivated by innovating business models and supply chain functions, involving all stakeholders within a product’s lifecycle (Farooque et al. 2019, 884). Of course, Figure 2 presents the most optimal form of a circular supply chain, and it requires all stakeholders to collaborate. But a circular supply chain does not necessarily require no waste since it is often inevitable in most industries.

2.2 Current state of global circular supply chains

The global economy strongly continues relying on linear supply chains and the market for recycled materials is still small despite challenges that traditional supply chains entail. When considering the implementation of CE principles on supply chains, it has proven to be much more complicated on a global level than on a local one. Since points of sourcing, manufacturing and use are geographically distant from each other, recovery of materials becomes complicated. (De Angelis et al. 2018, 431.) This is most often the case in battery supply chains where the economic interest and market for used materials is thus not large, especially in the case of low-cost battery raw materials (Neumann 2022, 2). Implementing circular supply chains on a global level also requires high levels of collaboration between buyers and suppliers, which may raise challenges regarding coopetition and sharing sensitive information on manufacturing processes. However, this collaboration at the start of the supply chain can offer the most value since recycling materials takes the form of down-cycling rather than up-cycling. (De Angelis et al. 2018, 429, 431.) Up-cycling is meant by the creation of a new and more valuable product from used materials (McDonough & Braungart 2013). Down-cycling means the opposite: products made from used materials are of lower quality relative to their original quality (Helbig et al. 1164). Designing products so that their life cycle is long and quality is preserved is in the heart of CSCs.

Although CSC implementation faces challenges, it has been successful in some forms. A pioneer in circular economy advocacy Ellen Macarthur Foundation (2026) has published case studies in great implementation of CSCs in the battery industry, automotive sector and textile industry. The options of circular flows between phases in CSCs allow for various levels of implementation. The importance of CSCs is also estimated to grow in the future. In a survey by the World Economic Forum (2025, 4) 95% of 491 executives stated that circularity will become important in the next three years, and 71% answered “very important”.

2.3 Traceability in global circular supply chains

In chapter 1.2 traceability was defined as the ability to verify detailed information about a product’s life cycle and across its supply chain (ISO 2000; IEA & OECD 2025, 15). Traceability and transparency are not equivalent, since traceability only enables transparency, which means that firms know the happenings in their supply chain and their impacts on the environment and society (United Nations ECE 2023, 11). In the case of circular supply chains, traceability is sometimes limited in literature to traceability for sustainability. United Nations (2014, 6) defines it as the ability to trace the history of products and to ensure the reliability of environmental and societal sustainability claims. In the time of many drivers towards requiring traceability in supply chains like the recent ISO 590004 standard for circular economy (ISO 2024) and EU-level regulation on batteries and waste batteries (European Commission 2023), functional traceability is crucial in

CSCs. According to da Silva et al. (2023, 4) there is still a lack of global standardisation on traceability information and data transparency, which are hindering the creation of a second-life market of for example electric vehicle batteries. Information available on battery design characteristics is also not cohesive and challenges recycling.

Many propositions have been made to solve this traceability issue in CSCs and many of them are emerging from circular economy principles or current supply chain management technologies. According to the survey done by the World Economic Forum (2025, 22) digital traceability systems will be the most instrumental factor in scaling circular initiatives. Bonsu (2020, 6) propose the use of technologies like blockchain in mining raw minerals ethically. Horn (2025, 4331) bring examples from the plastics industry, where RFIDs, communication and big data and cloud computing technologies could enable traceability. The European Union is also implementing Digital Product Passports, which require every product sold within the EU to include information about the product’s whole lifecycle and therefore enhance traceability (European Union 2024). However, academic literature has not yet agreed upon on a consistent and realistic framework for implementing circular supply chain traceability especially in complicated supply networks.

3 Overview on artificial intelligence and blockchain technology

As global supply chains become more complex and harder to predict, multiple technologies have been harnessed and comprehensively covered in supply chain management literature. Industry 4.0 technologies such as Internet of Things, AI and blockchain add various positive benefits to CSC management such as operational efficiency, data management, and waste reduction (De Lima & Seuring 2023, 14). On the other hand, Jabbour et al. (2018, 281–282) argue that firms lack technological knowledge of industry 4.0 implementation and there is lack of trust when integrating IT systems between supply chain partners. When firms first understand the principles of artificial intelligence and blockchain, they are easier to implement into CSCs.

3.1 Artificial intelligence

3.1.1 Definition and working principles of AI

Although academia is still torn on an exact definition for artificial intelligence (AI), the European Commission's AI HLEG team (2018, 1) defines AI as "systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals". This definition encompasses AI's ability to search data, learn from it and make conclusions. The concept of artificial intelligence was presented in the late 1950s by John McCarthy and since then, research into AI has covered for example pattern recognition, problem-solving, expert systems and much more (Jiang et al. 2021). Machine learning (ML) is a subfield of AI where systems are fed data and algorithm techniques are developed to independently analyse and interpret data but also to evolve when new data is presented (Gourisaria et al. 2021, 66). AI is also generally divided into artificial narrow intelligence (ANI) and artificial general intelligence (AGI) (Sharma et al. 2022, 7528). ANI is designed to perform one or a few specific tasks, when AGI could perform most activities that humans do. There are many challenges with achieving AGI such as the ability for a computer to have self-awareness and thus most current success regarding AI is limited to ANI (AI HLEG 2018, 6; Jiang et al. 2021, 2). Because of this, the thesis focuses on the possibilities and implementations of ANI.

Since current artificial intelligence cannot reach human-like thinking yet, it relies on data that is fed to it to take action. Machine learning (ML) is at the centre of AI-systems since ML provides them the ability to learn from experience. These ML algorithms analyse data and implement the findings into real-world applications based on rules given to them. (Sarker 2021, 1–2.) When data sizes grow, deep learning (DL) technologies are utilized. DL models can learn more complex functions through having multiple models, which process the data to a more abstract level every time. (LeCun et al. 2015, 436.) This dependency on vast amounts of data is both a benefit and a challenge in implementing AI into for example expert systems. Most of real-world data is unstructured, meaning that there is no specific format which makes the data harder to process (Sarker 2021, 3). Data can also be biased, dirty or too small to train the algorithms with. AI can even hallucinate answers or think that a company document most recently opened in 2024 but created in 2020 is more relevant than an actual document created in 2024 (Forbes 26.6.2025). A shift from developing the algorithms behind models to cleaning data before it is fed to them has proven to be crucial in future successful implementation of AI. Whang et al. (2023, 791–792) present a name for it: data-centric AI. Figure 3 presents the phases of building a ML model to support data-centric AI.

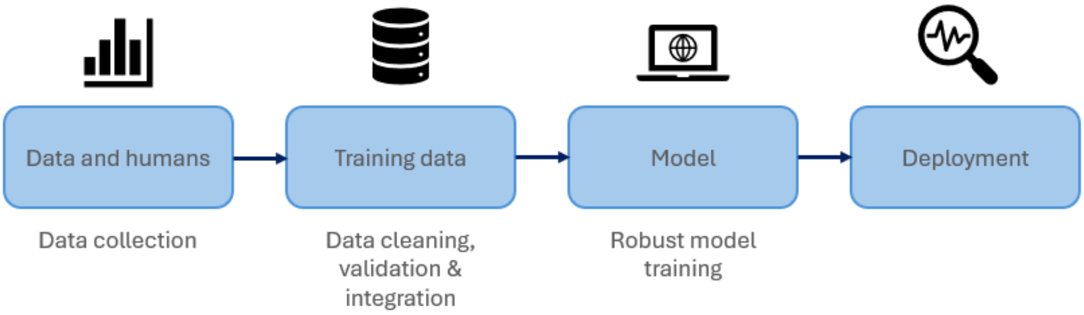


Figure 3 The phases of building a machine learning model while supporting data-centric AI (adapted from Whang et al. 2023, 792).

In Figure 3, data can be cleaned and expanded in the first two phases. In robust model training, the data usually is still partially dirty. The model is then purposefully given adversary inputs to expand coverage of data so that the model can combat against attacks. (Zhang et al. 2022, 2.) Preferably, the data is clean and processable when fed to the model especially when AI is embedded into a firm’s IT system for example to support supply chain management (SCM) activities. Research on opportunities of AI tools in SCM is flourishing, but implementation has proven to be more challenging due to a lack of trust and privacy issues (Wellbrock et al. 2025, 7).

3.1.2 Adoption of AI in supply chain activities

According to IBM (2025) implementing AI into supply chain operations can lower operating costs, cut down waste, improve sustainability, and control inventory levels. Since AI is often great on repetitive tasks and work requiring going through large data amounts, firm executives can concentrate on high-value work (Nishant et al. 2020, 1). Other drivers for AI adoption include faster delivery times, better product quality, and overall efficiency (Hangl et al. 2023). AI has already been effectively harnessed in many parts of the supply chain and it can help with forecasting demand, automating manufacturing processes and optimizing logistics and deliveries (Dash et al. 2019; Danach et al. 2024, 1–2). In the case of the battery supply chains in particular, Wang et al. (2024) have presented an AI-powered optimal supplier selection model, that compares raw lithium supplier sustainability performances and supports decisions towards a more sustainable supply chain.

However, AI adoption is often neither simple nor cheap. A survey and an interview process for experts in AI and SC conducted by Hangl et al. (2023, 4–5) brought up multiple challenges that experts face in adopting AI into SC operations. Firstly, optimal decision-making is not possible since data is often not easily accessible. Also, integrating data from both up and downstream within the supply chain has proven to be time-consuming. Other challenges included a lack of trust in technology and minimal understanding on how AI should be integrated into current processes. These challenges hinder the adoption of AI as a tool when moving towards supply chain transparency and in the end, circularity.

3.2 Blockchain technology

3.2.1 Definition and working principles of blockchain

Originally developed by an unknown person/team behind the cryptocurrency Bitcoin in 2008, blockchain technology can be defined as a distributed and decentralised ledger (database) that documents all transactions or digital events conducted between the participants sharing the system. Transactions must be approved by a majority of the participants, and a digital mark of the transaction can never be erased. (Casino et al. 2019, 55–56; Crosby et al. 2016, 7.) Figure 4 presents the phases of a financial transaction between parties within a network using blockchain.

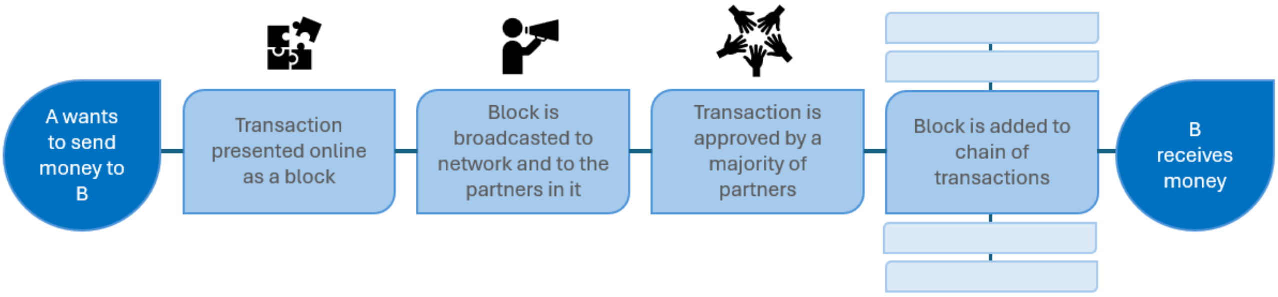


Figure 4 The phases of using blockchain technology in financial transactions (adapted from Crosby et al. 2016, 10).

Figure 4 presents a financial transaction, but the transaction done within a network does not necessarily have to be financial. The phases of the transaction build upon the main principles of blockchains: decentralized authority, transparency, and privacy when needed (Böckel et al. 2021, 526). Transactions are transparent because they are both broadcasted and later approved by the parties involved in the larger network. Since blockchains were originally developed to prevent the double-spending problem in trading cryptocurrencies, blocks are unerasable, which also promotes traceability of transactions. After all, a blockchain is supposed to validate and safeguard entries and transactions while also preserving them for historic records for any participant to see (Crosby et al. 2016, 9). Blockchains can be classified into public and private networks, which control the participants' ability to submit, read, and validate transactions. In a public blockchain, all participants can read and submit transactions, but only authorized participants can validate them. In the case of a private blockchain, only authorized participants can submit, read, and validate transactions. (Beck et al. 2018, 1022.)

While there is still some governance in blockchains, the technology brings more openness and efficiency into current digital transactions. Today's digital economy and traditional business environment are reliant on third-party authorities to confirm transactions and communication, while the parties within a blockchain can make transactions without even fully trusting each other. (Casino et al. 2019, 55; Crosby et al. 2016, 8; Christidis et al. 2016, 1.) These kinds of business relationships are further supported by smart contracts, which were presented in 1994 by Nick Szabo and are tightly knitted to efficient blockchains today. They can be defined as computer protocols, which automatically facilitate, confirm and enforce digital contracts without a third-party authority such as banks or courts. (Wang et al. 2019, 2266; Crosby et al. 2016, 13.) According to Khan et al. (2021, 2901) they can also minimize human error and disputes regarding contracts.

3.2.2 Adoption of blockchain in supply chain activities

Blockchain application into supply chains has been covered in academic literature, and industries are starting to see its value in meeting key objectives in supply chain management. Traditional supply chain information systems include data silos, meaning some data is accessible, but some is isolated. Sharing this information requires trust between participants or a central third-party. (Westerkamp et al. 2020, 168.) Blockchains solve these challenges by enabling supply chain participants to know what, where, and when actions are taking place. As a result of blockchain's nature of immutability, suppliers can track progress and shipments in real time and from anywhere. The technology can also be used to "super-audit" suppliers on sustainability or product quality data, speed up contract processes, improve traceability, and provide data for regulatory institutions. (Kshetri 2018, 80–85.)

Although blockchains have high potential, their application also includes challenges. For example, smart contracts have been attacked maliciously on many occasions, resulting in hundreds of millions of dollars in losses (Casino et al. 2019, 71). Several studies have also pointed out the blockchain trilemma, which means that the main properties of a blockchain – decentralization, security, and scalability – cannot co-exist perfectly. For example, having a centralized authority to accept transactions may enable scalability and efficiency in the network but also reduce privacy. (Zhou et al. 2020, 16440–16441; Quattrocchi et al. 2024, 102.)

4 Artificial intelligence and blockchain as tools for traceability in circular battery supply chains

Many of the opportunities presented by AI and blockchain in CSC traceability stem from a comprehensive research pool on linear supply chain traceability. Technologies such as blockchain and AI have been brought up as solutions for example in agri-food and drug supply chain traceability (e.g. Moysiadis et al. 2022; Musamih et al. 2021). Traceability for circularity and traceability in battery supply chains are still much emerging. In more recent years, traceability to enhance circularity has been considered in electric vehicle battery supply chains (e.g. Agrawal et al. 2021; Mathiyalagan & Kandasamy 2026; da Silva et al. 2023), although they have not comprehensively studied CSC models in particular. This could be because of a lack of circular supply chain models in industry or unfamiliarity with circularity opportunities regarding batteries. Much of the coverage on battery supply chain circularity has also focused on blockchain (e.g. Kumar et al. 2023; Moavad et al. 2025) and AI has received minimal interest or has been often grouped together with blockchain applications (e.g. Mankar et al. 2024; Saidu et al. 2025). Building on existing theories within supply chain traceability and their many industry contexts, the thesis aims to shed light on traceability opportunities in battery CSCs. The following chapters contribute to previous literature by bridging the research gap between blockchain, AI and CSC traceability.

4.1 Overview of circularity and traceability in battery supply chain phases

The typical battery supply chain phases include material sourcing (mining), refining, manufacturing, distribution, use, collection, and recycling (Sun et al. 2019, 4; Hendrickson et al. 2015, 2). To make CSCs in the battery industry a reality, traceability within the supply chain phases has to be ensured first. Traceability in, for example, the material sourcing, distribution, and end-of-life phases is crucial to create trusted supply chain data for companies, regulatory bodies, and consumers (Trace4EU 2026). Figure 5 presents a typical linear battery supply chain and its material flows, opportunities for circularity and information flows needed to promote traceability and circularity.

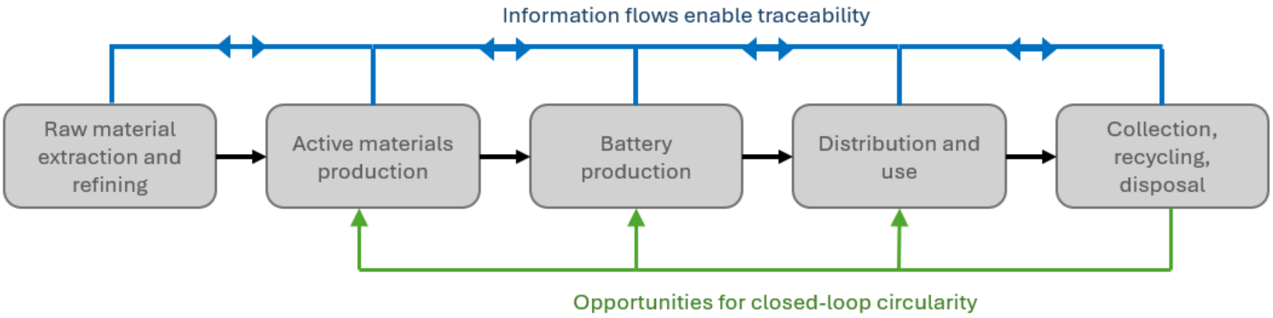


Figure 5 The phases of a typical battery supply chain, opportunities for closed-loop circularity and information flows between participants to enhance traceability and circularity.

Figure 5 was constructed by the writer from information from Gebhardt et al. (2022, 204) and Bals et al. (2024, 8) to gain an understanding of the battery supply chain phases and their circularity opportunities. However, the information flows between supply chain participants were independently added by the writer to highlight how information and traceability needs are crucial in improving linear and circular material flows. Figure 5 presents how information does not share a specific direction between participants. This is because downstream supply chain parties require information such as battery chemistry and recycling instructions from upstream, and producers want information on recycled product quality from recyclers and users. (Bals et al. 2024, 7–8.) The information flows first down the supply chain when products are initially manufactured. Later when products reach their end-of-life, reverse information flows are needed to climb back up the supply chain to enable circularity and an efficient collection and reuse of critical battery materials. This means that every participant has a role in providing information. Through a shared infrastructure, information flows can be established while upholding privacy between supply chain participants (Peng et al. 2023, 4511).

This infrastructure and culture of information sharing can be supported with blockchain and AI. As shown in Figure 5, all steps are crucial within the supply chain, but the chosen phases of focus for the thesis are material sourcing, distribution and end-of-life phase. These phases are also often the ones that are the most complicated from a circularity standpoint and involve environmental and ethical challenges that need to be addressed as well (Rajaeifar et al. 2022, 3, 5–6). Firstly, virgin material mining has issues regarding its environmental impacts and human rights violations and there is a growing need for transparency and traceability of materials (UN Environment Programme 2026). Also, traceability is especially crucial in the distribution phase, which makes it possible for also the consumer to be aware of the battery’s origin and manufacturing details (Trace4EU 2026). Lastly, in the end-of-life phase, adopting AI and blockchain closes the loop and materials can be extracted from products and fed back into the supply chain. Analysing the chosen phases aims at showing the most impactful points of implementing AI and blockchain so that future supply chains can be designed for traceability and circularity in mind.

4.2 AI and blockchain traceability tools in material sourcing, distribution and end-of-life phase

4.2.1 Material sourcing

Circular economy literature has historically focused heavily on downstream industries in the supply chain but a growing interest towards circularity also in the critical mineral mining phase has emerged (Born 2024, 31). Adequate traceability information starts at the source of the minerals needed to produce batteries. It plays a huge role in battery circularity and second-life opportunities since traceability all the way from the start of the supply chain enables recycling facilities to classify used batteries into different levels of quality and also to authenticate them in the cases of counterfeit, tampering and false battery chemistry information (Antônio Rufino Júnior et al. 2022, 2). A further reason traceability in the material sourcing phase is crucial for enabling CSCs is that correct data on the battery chemistry and quality of minerals helps with forecasting the battery life cycle and when and with which methods it can be recycled (Matos et al. 2022, 1270). However, often the data on raw materials is dispersed among multiple actors since for example the location of mineral mining and refining is not the same (European Commission RMIS 2026).

Blockchain has been presented to assist in many of the challenges regarding dispersed data and the authenticity of battery chemistry information. The Responsible Minerals Initiative (RMI 2018) has created guidelines for implementing blockchain to enhance transparency and traceability of minerals. Firstly, each upstream supply chain participant (e.g. mine, smelter, manufacturer) that possesses the mineral at any point should have a unique identifier that they are identified within the blockchain. Each transaction made by a participant is linked to their unique identifier with information about who the transaction was with, what metal was in question and other required documentation. However, the guidelines are just a framework for future collaboration and are not yet required to implement. Calvão & Archer (2021, 6) point out that current applications of blockchains in the mining industry are private and are heavily managed by for-profit corporations rather than public or multi-stakeholder actors. This poses a challenge to material traceability, since private blockchains cannot be accessed by governmental actors or outsiders to authenticate data on where and what minerals were extracted.

When considering applications of AI to enable traceability in the mining phase of materials, Khiari et al. (2025) propose a functional solution combining sensors, AI and blockchain. Their solution is especially designed for the context of Africa’s artisanal small-scale mining, which is often left out for opportunities of innovation. A small battery-powered sensor collects data on anomalies such as tampering and improper handling during shipment. Then a machine learning model detects those abnormalities and when materials reach their destination, the information is configured to an app, and the transaction is secured to the blockchain. According to Khiari et al. (2025, 100516), the framework was created to promote traceability but to also support EU’s Circular Economy Action Plan. Africa is a large producer of many critical battery metals such as cobalt, copper and manganese (Ritchie & Rosado 2024) and often storing conditions may not be suitable for battery materials. Applying AI solutions to detect abnormalities decreases contamination risk and ensures the quality of the final battery later in its life cycle.

Since the mining and sourcing phase of materials includes many challenges, the EU has also become interested in enhancing battery material traceability. TRACE4EU is a project that aims to promote blockchain as the solution for battery manufacturers to gather reliable data on their suppliers’ practices and to ensure sustainability. Manufacturers request a responsible mining certification and product carbon footprint report from their supplier, which are then logged to the individual battery’s product passport. (TRACE4EU 2026.) The project is a part of the EU’s Digital Product Passport (DPP) program (European Union 2024). By utilizing a blockchain-based platform, actors downstream in the supply chain can be sure about the battery’s composition and sustainability. This information is crucial in remanufacturing and recycling.

4.2.2 Distribution from manufacturing

After manufacturing raw materials to battery cells and later to battery modules and packs, products are transported often far from their original manufacturing sites to other firms or directly to consumers. In a case of a successful circular battery supply chain, for example contaminated batteries should be able to be recovered from distribution at any point after they leave the manufacturer. This kind of recall requires sufficient traceability data, which can be supported by smart contracts stored in the blockchain (Diallo et al. 2014, 160; Chen et al. 2022, 2678). The smart contracts store information on the product batch, the sender and the receiver and the previous transfer if there is one (Wang et al. 2019, 115126). The ability to trace products to their manufacturer via a chain of smart contracts can also encourage towards better durability and therefore a longer product life cycle, since manufacturers are then better held responsible and cannot hide behind complex supply networks. Through the system presented by Moawad et al. (2025, 5) traceability is ensured through a distribution smart contract, which logs transactions made by logistics participants. The contracts are often written in programming languages which hinders their introduction due to insufficient knowledge within firms. Luckily, they can be automated with artificial intelligence. According to Song et al. (2024, 468) machine learning models like natural language (NLP) processing can create, optimise, and verify smart contracts by going through contract code and details more efficiently than humans. Through smart contract automation, blockchain can become more accessible to for example partners within battery distribution, which promotes traceability.

Although blockchain is built upon privacy and a decentralised authority, in the supply chain context often a certifier or a registrar is necessary. A certifier implements a registration process in which new participants wanting to join the blockchain have to prove their truthfulness. Once a new user is added to the network, a certifier authenticates them based on historical business behaviour and a smart contract including the principles of the chain is created. (Provenance 2023; Centobelli et al. 2022, 3.) In the battery industry, products enter a complex distribution chain with many local logistics operators. By having a certification process to join the blockchain, participants can be sure that the information provided by participants is truthful. The AI-Blockchain enabled framework proposed by Khiari et al. (2025) to track products with sensors could also work in the case of distributing to consumers and firms by detecting abnormalities during shipment and preventing counterfeit products from entering the supply chain. Balancing privacy with participant reliability enables traceability and that the next phase in the battery supply chain can trust the product information and history provided.

4.2.3 End-of-life phase

The end-of-life phase and recycling close the final loop of the circular supply chain. Used batteries are first collected, their quality is diagnosed and they are redistributed to be repurposed or recycled. The core issue of closing of this loop is the challenge to trace where the products are located and how they can be transported to a recycling facility and eventually to the manufacturer or as raw materials to other companies. Since products can be returned at various stages, their quality and quantity can vary. (Guide et al. 2003, 3.) Reverse logistics and secondary raw material markets play a huge role in achieving a functional structure for closing the loop and at the same time, providing traceability. Reverse logistics is defined by Tosarkani & Amin (2018, 662) as all the activities concerned with product recovery such as collection, repairing, and recycling. Bressanelli et al.

(2021, 8) define it as the planning of material from the point of consumption back to its original point through recycling and remanufacturing or directing the material to disposal. The current state of the secondary raw material market of used batteries is still emerging together with reverse logistics. Wolf & Lüken (2024, 115) point out that current battery recycling technologies require substantial amounts of energy and toxic chemicals. The process involves high costs and a low material recovery rate, which do not motivate manufacturers to shift from much cheaper raw minerals. This trend might be shifted by the future scarcity of materials when the role of recycling becomes vital.

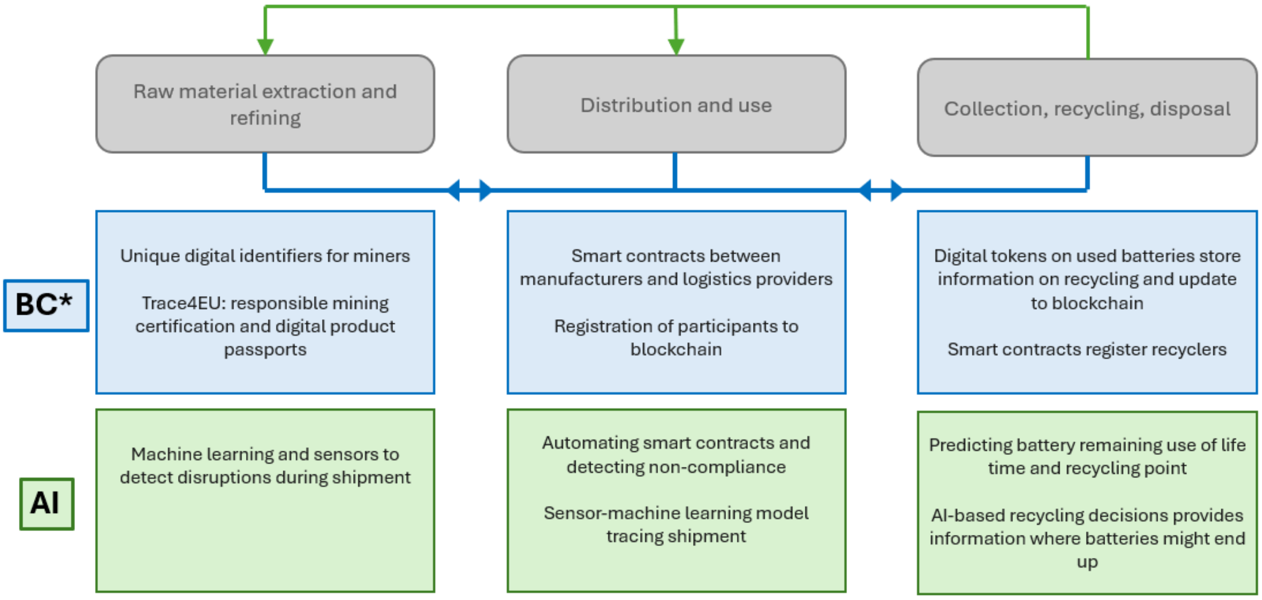
One of the challenges of closing the loop of a battery CSC is the inability to track products after they have been distributed down the supply chain. AI and blockchain have been proposed as solutions to better track the end-of-life phase (Dongare-Jadhav & Deshmukh 2025, 872). Firstly, predicting the time when batteries will no longer be usable can be supported with AI. Samanta & Williamson (2023, 563–564) present a machine learning model, that based on battery data such as temperature, voltage and time can predict degradation and the remaining useful life. For traceability, this means that recycling facilities can estimate the point when a batch of batteries will enter collection. This information enables the planning of capacity and estimation of recycled material availability. After a battery has been considered useless by the end-user, artificial intelligence can support the creation of a reverse logistics network, which includes collection points, sorting, and processing facilities. In addition, it can optimize vehicle routing and make decisions on whether products should be disposed or transported to be remanufactured. (Wilson et al. 2022, 15–16.) By having AI involved in making sorting and transportation decisions, it is known what products will end up where and via which route both in the case of consumer to recycler and recycler to manufacturer. Again, utilizing sensors combined with AI during transportation offers reliable data but requires a shared infrastructure (Khiari et al. 2025).

Although AI has many great applications within traceability, it does not function without sufficient data from crucial actors within the end-of-life and recycling phases. The European Union has been building a framework for recyclers to document and calculate battery material recover rates and recycling efficiency. It also includes documentation of all the recycling facilities involved in treating a specific batch of batteries. Waste management operators and waste battery collectors are obligated to provide information to the first recycler, meaning the actor that starts the actual recycling process. (European Union 2025.) This information is crucial for both AI and blockchain traceability infrastructures. There currently is not a shared blockchain structure to directly combine with EU’s requirements on recycling information, but viable solutions have been presented.

Moawad et al. (2025, 4–6) propose a blockchain & NFT system for lithium-ion battery end-of-life where battery patches are presented as NFTs which are tokens storing ownership, transaction, and composition details. In the system, each participant is tied to their role and tasks by a smart contract. For example, the inspection smart contract is applied when batteries are analysed for their second life opportunities and when a decision is made, the status is updated to the blockchain. Batteries can then be assigned to the correct recycler or actor, and their status is updated on their token. This enables the remanufacturer to know adequate information about the quality and previous use of the materials and product.

4.3 Considerations of AI and blockchain tools in circular supply chain traceability

Figure 6 summarizes the artificial intelligence and blockchain tools that can be used in enhancing traceability within the discussed circular battery supply chain phases. In the upper part of the figure, the key phases, their opportunities for circularity (green) and the nature of traceability information flows (blue) are visualized.



*BC = Blockchain

Figure 6 Blockchain and artificial intelligence traceability tools in the three studied phases of a circular battery supply chain

Figure 6 shows that the tools of AI and blockchain can certainly support CSC traceability in some forms. They can be implemented individually but also function simultaneously and complement each other. Artificial intelligence can for example automate smart contracts but also provide tracking information to be updated to the blockchain. This means that to create functional and cost-effective circular supply chains, benefits from both technologies should be utilized.

Although the named tools were named under in the highlighted phases of the circular supply chain, their working principles can be utilized in all phases by both upstream and downstream participants. By highlighting not only specific tools but the bigger solutions that the technologies offer when brought together, the findings of the thesis can be implemented on a wider scale and can also be brought on a more theoretical level. Figure 7 presents the central working principles of the traceability tools discussed in the thesis and their interrelatedness. The figure shows how the combination of the tools can be the solution to promoting traceability for circularity in any phase of the circular supply chain.

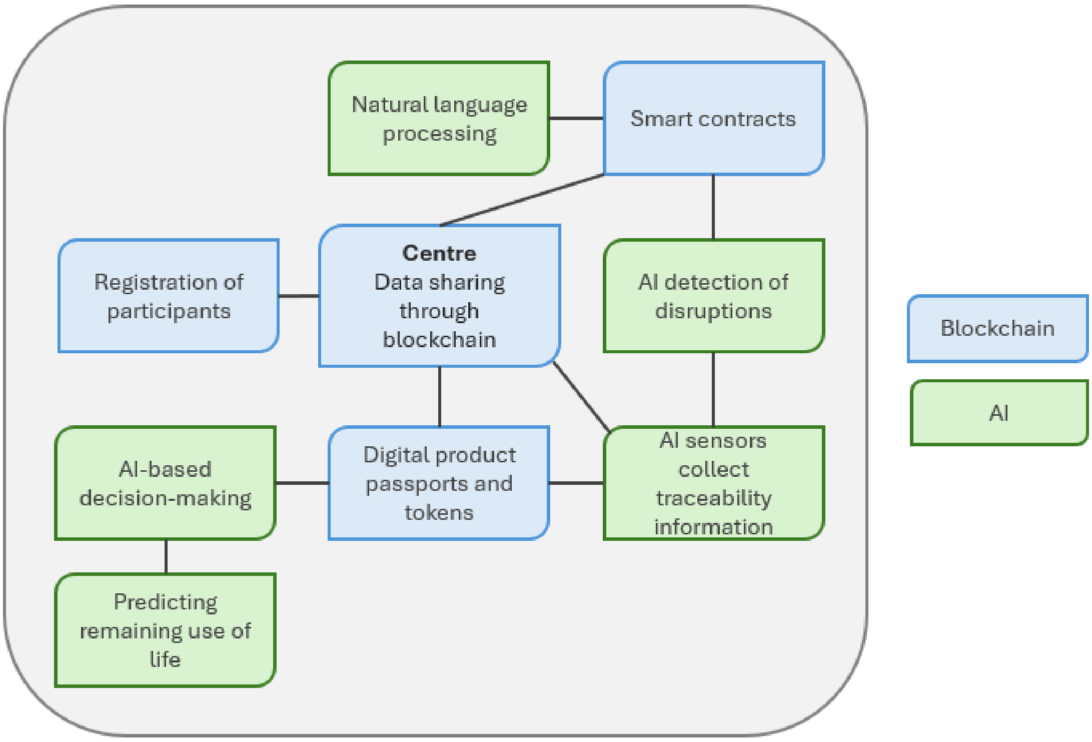


Figure 7 The core principles of blockchain and AI-based traceability tools, their interrelatedness and how they support traceability for circularity together.

Figure 7 shows how the core principle of blockchain – its data sharing ability among supply chain participants – acts as a supporting pillar for other complementary tools. Without it, the traceability data would not be accessible within the network. In the upright corner, AI supports blockchain-based smart contracts in two ways. Natural language processing helps to read complex code languages, that the contracts are often written in (Song et al. 2024, 468). Additionally, AI can detect abnormalities both in the contracts themselves but also in their implementation, for example during shipments. In the lower part of Figure 7, AI supports digital product passports by collecting and updating data with its sensors to be stored in the passports. AI can also make logical decisions about the next best location for a product for example in recycling (Moawad et al. 2025, 4–6), which is also updated to the passport and later the whole blockchain. To conclude, the figure highlights how the tools outside the centre cannot complete enough traceability information to promote circularity but that they need the blockchain framework (or other similar supply chain wide shared database) to store and analyse the collected information in. This is not to conclude the redundancy of the tools but to show how traceability in circular supply chains is multi-faceted and cannot be solved by an individual tool. The tools presented are important for further literature in linear supply chain traceability, offer new opportunities for research and serve as a guide for building a shared framework in building traceability systems in global battery CSCs.

4.4 Challenges of AI and blockchain tools in circular supply chain traceability

Although the tools presented in the thesis can be helpful and improve the transfer of traceability information and therefore support circularity, they are not comprehensive enough to cover the often complex and global supply chains or are in some cases too challenging to implement. When considering blockchain as a tool for circular supply chain traceability, one of the challenges that arises is blockchain’s nature of privacy and even anonymity. Participants are hesitant on sharing information due to a potential loss of competitive advantage and disruption of their anonymity. (Bischoff & Seuring 2021, 237.) Since adequate traceability information can only be achieved through truthful participants, a central certificate authority must be named (Centobelli et al. 2022, 3). Bischoff & Seuring (2021, 235) state that at the end of the day partners within a supply chain have to give up their anonymity, since producers and retailers have to validate content continuously. In the case of a circular supply chain, this central certifier could be interested in recycling efficiency, possible counterfeit goods, or false battery chemistry information. By having a central certifier, it can also create a lack of trust among stakeholders going through traceability information (Saidu et al. 2025, 16839). Hence the choice for a central admin is crucial for bridging trust. Blockchain is also a decentralized technology, that creates traceability information efficiently, but its validation can cause delays. This means that downstream and upstream participants will not be able to access information as quickly as they would like. (Bischoff & Seuring 2021, 236.) Because of this nature of decentralization to reach a functional circular battery supply chain model participants should all have a shared infrastructure. However, there is currently no one standardized model for a blockchain that would be cost-effective for everyone along the supply chain to implement (Saxena et al. 2023, 113). Since battery supply chains are oftentimes complex and involve changing participants, it seems challenging to require every party to invest in a blockchain structure.

At the same time, AI also requires adequate infrastructure, technical knowledge and considerations for security, data privacy, and ethical standards (Perçin 2026, 2). Challenges regarding data availability and quality are also common (Jan et al. 2023, 18). Comprehensive AI-supported traceability along a circular supply chain requires that data is clean and easily accessible to anyone that needs it. When supply chain participant numbers rise and complexity increases, it becomes increasingly hard to manage data in an organized way. AI implementation also faces the same challenge as blockchain: cost and return on investment. Larger corporations may be more willing to implement the technology, but for smaller and medium-sized firms the incentives are slim. (Jan et al. 2023, 18). To reach traceability with AI and blockchain, the movement has to start from the multinational corporations and regulative institutions. For a successful adoption of the aforementioned tools in circular battery supply chain traceability, larger structural challenges have to be conquered first.

5 Conclusions

In this thesis it has been examined ***how artificial intelligence and blockchain technology can enhance global circular supply chain traceability in the battery industry***. Traceability is covered in the three critical phases of a battery supply chain: material sourcing, distribution from manufacturing and end-of-life phase. The thesis also aims to answer the set sub-questions through explaining the working principles of CSCs, AI and blockchain and their current implementations in supply chain activities. The thesis builds upon research in the fields of circular economy, circular supply chains and supply chain traceability while bringing together two disruptive technologies to promote battery circularity on a global level. Hence, the thesis aims to cover the research gap regarding the combination of the two technologies within circular supply chain traceability, since previous research has most times only considered overall traceability for circularity, not necessarily CSCs. The main challenges of implementing AI and blockchain tools in CSCs are also covered. The thesis' theoretical contributions therefore include bridging the gap between the two technologies in the context of the battery industry but also bringing up critical challenges that need to be solved before scalable implementation.

The findings of the thesis show that artificial intelligence can be a beneficial tool in promoting the collection and management of traceability data during all the circular battery supply chain phases discussed in the thesis. AI can be used to detect abnormalities during shipment, automate smart contracts between supply chain participants, and predict the remaining useful life of batteries. All these applications improve material traceability and circularity. Blockchain as a decentralized ledger promotes the sharing of data between circular supply chain participants. Material and product transactions are documented in a chain that all participants have access to, but the information documented will remain tamper-proof indefinitely. Traceability is promoted by certifying blockchain participants both up and downstream the supply chain and tokenising materials and products to track them efficiently.

These findings both support and challenge existing literature. The academia has yet to present a comprehensive framework to show how the integration of the two technologies could promote traceability in CSCs and has instead focused on certain phases in a linear supply chain context (e.g. Khiari et al. 2025; RMI 2018; Moawad et al. 2025). However, the solutions presented previously are also applicable in the context of CSCs and often do stem from linear supply chain literature. This is mostly due to the lack of functioning global circular supply chains and the still emerging research field in them. The two technologies are also often researched separately and previous literature has only minimally considered the interrelationship of blockchain and AI in building traceability and supply chain transparency (e.g. Saidu et al. 2025; Khiari et al. 2025). Hence, the thesis brings the solutions together to support future literature but also challenges the current impression that the technologies are better to be applied individually rather than understanding how their working principles can support each other.

Due to the lack of a shared theoretical framework and the emerging nature of the research field in battery circular supply chains, the managerial implications of the thesis thus remain more as a presentation of the tools of artificial intelligence and blockchain rather than forming a framework suited for every industry. And since artificial intelligence and blockchain themselves involve challenges, they should be solved first before wider implementation. However, it can be said that opportunities for traceability to promote circularity exist in every part of the battery supply chain. While a fully circular supply chain might seem unattainable or even impossible, the technologies can pave the way for making circularity possible in some supply chain phases.

The thesis also inevitably includes limitations. First, the applications and subfields of AI and blockchain are vast. The applications discussed in this thesis were chosen based on what was suitable to cover only on a surface level and that the applications were strictly AI or blockchain applications. Academia has also been covering many more opportunities within AI and blockchain, and the thesis does not give a comprehensive review on every application. The context of a battery supply chain also limits the scope of coverage, although some applications such as tracking during logistics can be applied to similar industries. The chosen phases also limit the coverage on the topic. Academia has for example gained interest in circular design for batteries and extending their lifespan, which are also circular economy principles.

Lastly, further research in the field of circular supply chain traceability is needed to first cover the whole circular supply chain and AI’s and blockchain’s opportunities in them. Blockchain and AI are costly investments, that also require knowledge to implement successfully and this future research can support later industry implementation. The theme should be covered especially in industries where materials face the same scarcity problem and have the same environmental and societal impacts as current battery supply chains.

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Appendices

Appendix 1 Declaration of use of artificial intelligence

Artificial intelligence has been used in this thesis in the ideation of topics to discuss within chapters and as well as looking for suitable sources. I recognize the biases and shortcomings that AI might have so ultimately, I chose what was discussed in the thesis and what sources I deemed reliable. I used critical thinking towards the summaries and points AI tools gave me and recognized that the sources it gives might not be real. The following tools and prompts were utilized in the ideation and writing process.

1. Scopus AI

Several prompts were used in the beginning of the writing process during January and February to get a view of the existing literature. The prompts included “What are circular supply chains?”, “How can AI and blockchain be used to enhance supply chain traceability?”, “Explain the subfields of AI and blockchain”, “Give me multiple definitions for AI and blockchain”, “What are the dimensions of circular economy?”. Using Scopus AI helped me to grasp the bigger picture of the thesis and what it should discuss. Going through literature also showed a research gap. I did not use the summaries that the tool gave me but utilized the sources it provided as a starting point for looking for relevant literature.

2. Microsoft Copilot

Microsoft Copilot was used in the ideation process. Prompts included “What are the main challenges regarding AI?”, “Name industries where circularity is most important in the future”, “What are the main regulations requiring traceability information?”. During the writing process, Copilot was used to ideate the structuring of subchapters for example with prompts such as “How is blockchain utilized in supply chains?” and “What are the main traceability challenges regarding critical mineral mining?”. From these prompts I picked some points and collected more from relevant literature. All the points given by Copilot were later researched and backed up by existing literature that were not given by Copilot.