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Towards Web3- and metaverse-enabled decentralisation of electric vehicle battery closed-loop supply chains: insights from advanced text mining techniques[☆]

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ABSTRACT

The rapid transition to electric vehicles has intensified challenges in electric vehicle battery (EVB) closed-loop supply chains (CLSC), particularly regarding material traceability, supply chain transparency, and recycling efficiency. While decentralised technologies, particularly Web3 and Metaverse, offer promising solutions, their integration into EVB CLSC remains fragmented and insufficiently examined. We introduce an Operational Decentralisation Framework enabling a systematic analysis of centralised operations and a critical evaluation of decentralised alternatives as transformational forces. By adopting a holistic perspective, the framework equips firms with strategic guidance for transitioning from centralised structures to decentralised ecosystems. We analyse 588 academic articles and 1,168 industry documents through two advanced text mining techniques – Dynamic Latent Dirichlet Allocation and Burst Detection. Web3 and metaverse can potentially reconfigure the design, manufacturing, end-of-life diagnostics, procurement, waste management, load balancing, capacity planning, inventory management and service operations of two key areas: (1) EVB CLSC operations and (2) EVB circular energy/grid operations. We also found that while blockchain and digital twins show established applications, Web3 and Metaverse applications face significant barriers, including scalability, technology complexity, and expertise gaps, despite their great potentials. Therefore, we propose four visionary models integrating Web3, Metaverse, and AI technologies that have the potential to overcome existing barriers and enable transformative decentralisation. Extending the TOE framework, the study contributes to the theory by developing an integrated framework for evaluating decentralised technology adoption in EVB CLSCs. For practitioners, we provide actionable insights and pathways for technology implementation across different CLSC stages and guidance for addressing key adoption barriers.

1. Introduction

To mitigate carbon emissions and environmental pressures from conventional fossil fuel vehicles, the global automotive industry is

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rapidly transitioning to battery-powered electric vehicles (EVs). According to the International Energy Agency's report, EVs are projected to comprise 60 % of global vehicle sales by 2030 to align with carbon budget targets (Bouckaert et al., 2021). EVs are not only shaping the future of transportation but are also vital to green and sustainable development.

Nevertheless, with the rising popularity of EVs, demand for electric vehicle batteries (EVBs) is increasing, which brings several associated challenges, from the extraction of raw materials such as lithium and nickel to the production, usage, reuse, and eventual disposal of batteries through the closed-loop supply chain (CLSC) (Albertsen et al., 2021; Chirumalla et al., 2024). These challenges include carbon emissions, resource use, and environmental and social damage (Wrålsen et al., 2021). Particularly, EVBs contain metals, toxic, and flammable substances that adversely affect the environment and may pose a risk to human health due to their carcinogenic and mutagenic nature (Banza et al., 2009; Kang et al., 2013). Additionally, the challenges and complexities of managing the lifecycle of EVBs within a CLSC are not limited to production but extend to unethical and untransparent sourcing of raw materials, higher recycling costs and lower returns of retired EVBs, an opaque and imperfect information traceability system (Jia et al., 2024), and lower supervision efficiency by regulators in EVB CLSC (Zhou et al., 2023).

These challenges highlight the urgent need for more efficient, transparent, and intelligent supply chain operating systems. Decentralised technologies offer significant potential in addressing these challenges. Decentralised technologies refer to ecosystems that operate without a central authority or a single entity that controls the data (Davies et al., 2024; Dutta et al., 2020). They distribute authority, control, or data across multiple participants or nodes, eliminating the need for intermediaries by allowing peer-to-peer (P2P) transactions and collaborative, secure data management. Organisations have real-time access to vast amounts of data spanning product logistics, lifecycles, customer-supplier interactions, and market demand (Centobelli et al., 2021), enhancing supply chain visibility and transparency.

Nowadays, interest in Web3 and the metaverse is rapidly gaining momentum among both operations and supply chain management (OSCM) scholars and industry practitioners (Dolgui and Ivanov, 2023; PERBOLI et al., 2025; Queiroz et al., 2023). Web3 is the next evolution of the Internet and fuses digital and physical elements. The fundamental idea of Web3 is to create a decentralised internet of open, interconnected, intelligent systems that provide programmable primitives for governance, coordination, and value/ownership (Huang et al., 2023; Mourtzis et al., 2022). Within the Web3 domain, the metaverse, integrated with digital twins, emerges as an immersive, collective virtual shared space and operational interface (Lyu and Fridenfalk, 2024; PERBOLI et al., 2025). It bridges the physical and digital realms based on a 3D representation, and various applications and users can interact, work, trade, and create through immersive digital experiences (Damar, 2021; Davies et al., 2024).

Metaverse may integrate Web3 infrastructure (Mourtzis et al., 2022), involving the use of avatars supported by smart devices, such as smartphones and headsets (PERBOLI et al., 2025), as well as cutting-edge technologies like extended reality, augmented reality, virtual reality, blockchain, artificial intelligence, and digital twins (Dolgui and Ivanov, 2023; Queiroz et al., 2023). Blockchain provides the foundational layer for Web3 ecosystems and metaverse projects as a decentralised infrastructure (Davies et al., 2024), enabling transparent and traceable digital asset trading. Metaverse is an interface layer as the collaboration front-end facilitated by Web3 and digital ecosystems, to combine the digital and physical worlds. Hence, they can be considered a decentralised operating paradigm rather than isolated technologies.

From an OSCM perspective, there is plenty of literature highlighting the decentralised technologies of technology adoption in supply chain operations (Dutta et al., 2020; Queiroz et al., 2023; Wang et al., 2019) or applications in transportation industries, such as parking systems (Wang et al., 2023) and charging stations for EVs (X. Li et al., 2024), EV supply chain (Capocasale et al., 2025). Especially, the metaverse can unlock how goods are produced and traded, and how businesses interact with their customers. Organisations are beginning to evaluate the potential of the metaverse and how it can be integrated into existing business models as a tool and a target (Dwivedi et al., 2022). Emerging real-world EV applications of decentralised technologies also underscore their value for supply chain management. For instance, Volvo Cars, in partnership with its battery suppliers Contemporary Amperex Technology Co., LG New Energy, and blockchain firms, began implementing cobalt traceability in 2019. Additionally, platforms such as Catena-X are being developed in the automotive industry, enabling the creation of digital product passports. Volvo collaborated with Circular to introduce a battery passport using blockchain to trace the origins of raw materials for their EVBs (Khan, 2024; Volvo Cars, 2019). Digital twins, by simulating the lifecycle of EVBs, offer predictive capabilities for monitoring battery health and optimising second-life usage (Alamin et al., 2023; Branco and Fontanela, 2024). These initiatives represent a trend towards decentralised technologies across industries. By reducing dependence on centralised platforms and supporting transparent and automated systems, Web3 and Metaverse technologies can reintegrate digital transformation with sustainable development goals.

Despite such progress, deployment of decentralised technologies in EVB CLSC remains fragmented and mostly confined to isolated use cases (e.g., forward-chain traceability), with limited end-to-end integration across use, second-life and recycling. The rapid development of emerging Web3 and metaverse invites further examination of their state and how they reconfigure operations in the EVB CLSC. This gap presents an opportunity to create a comprehensive framework that integrates various decentralised technologies into the EVB CLSC. Another gap concerns theoretical treatment and feasibility. The Technology-Organisation-Environment (TOE) framework is underused in resource-intensive sectors (Han and Fang, 2024; Kouhizadeh et al., 2021; Yadav et al., 2023) and has not been adapted to multi-actor, decentralised ecosystems where Web3 primitives and metaverse interfaces interact. Consequently, we lack clarity on the capabilities firms need to progress, as well as a staged transition roadmap from centralised to Web3- and metaverse-enabled EVB CLSCs.

To fill the gaps, the study aims to shed light on the adoption of decentralised technologies, particularly Web3 and the metaverse, in EVB CLSC, and develops a holistic transformation framework to guide firms in transitioning from centralised to decentralised systems. Our paper explores the gaps by the following research questions:

- RQ1. How do decentralised technologies, particularly Web3 and Metaverse, fundamentally reconfigure the structure, processes, and stakeholder interactions within EVB CLSC?
- RQ2. What implications might this have for transforming operations practices?
- RQ3. Which pathways should firms take to merge into a fully Web3 and Metaverse enabled EVB CLSC in the future?

To answer these RQs, this study applies a systematic methodology to explore decentralised technologies in the EVB CLSC. We collect and process text data from academic (588 articles) and industry (1,168 documents) sources, then utilise the Dynamic Latent Dirichlet Allocation (D-LDA) and burst detection analysis to identify prominent and emerging topics related to the applications of these technologies. We also assess the feasibility of adopting these technologies across the CLSC stages using the TOE framework. Our identified applications show that blockchain and digital twins are prominently applied, while the applications of smart contracts, Web3, and the metaverse are existing but limited. Notably, we observe that Web3 and the metaverse are beginning to reconfigure: (1) EVB CLSC operations and (2) EVB circular energy/grid operations. These technologies are driving a fundamental shift from centralised to decentralised operational models, impacting key functions such as design, manufacturing, end-of-life (EoL) diagnostics, procurement, waste management, load balancing, capacity planning, inventory control, and service operations. Despite these advancements, significant operational and organisational barriers persist – including integration complexity, lack of data standardisation, scalability challenges, and regulatory uncertainty. To address these challenges, we propose four visionary Web3 and metaverse-based models, integrated with AI. These models aim to alleviate existing barriers and unlock new capabilities for decentralised, intelligent, and resilient supply chain operations.

This study makes several noteworthy contributions. First, this study develops a novel Operational Decentralisation Framework to diagnose the current centralised operations and explore how decentralised technologies can propose novel transformative pathways and offer future research avenues for both academia and practitioners. Second, this study provides a structured feasibility assessment based on the TOE framework, examining the potential and barriers of these technologies in real-world EVB applications, offering potential resolutions for these barriers. This contributes to a forward-looking theoretical discourse by integrating decentralised maturity with dynamic capability development and ecosystem readiness. Finally, the study provides actionable guidance to industry stakeholders on locating themselves and integrating the envisioned Web3/Metaverse end-to-end system to meet sustainability goals and improve efficiency and transparency in the EVB CLSC.

The remainder of this study is organised as follows: [Section 2](#) provides the theoretical foundations of decentralised technologies and EVB CLSC. [Section 3](#) introduces and justifies the research methodology. [Section 4](#) presents and discusses the main results. The theoretical and practical contributions are highlighted in [Section 5](#). [Section 6](#) concludes with a summary of the findings and provides recommendations for future research.

2. Theoretical foundations

2.1. Electric vehicle batteries closed-loop supply chain

A CLSC integrates forward activities with reverse logistics to create circular flows of products and materials ([Savaskan et al., 2004](#); [Thierry et al., 1995](#)). For EVB, a CLSC is vital because production, use and EoL handling entail substantial environmental and economic externalities ([Ahmadi et al., 2017](#)). The core CLSC stages typically include procurement, manufacturing, distribution, use, collection, and recovery. However, EVB supply chains stretch conventional CLSC logics. Owing to hazardous chemistries and safety constraints, EVBs require specialised handling; returned packs exhibit heterogeneous states of health; and multiple recovery pathways exist, such as reuse in vehicles, stationary energy storage, or materials extraction, depending on the residual capacity and condition ([Gu et al., 2017](#)). Consistent with [Bernhart \(2019\)](#) and [Rajaeifar et al. \(2022\)](#), EVB supply chains are characterised by: (i) high technological complexity requiring specialised handling and processing; (ii) significant value retention potential through multiple life cycles; (iii) strict regulatory requirements for safety and environmental protection; (iv) variable quality and condition of returned products; (v) multiple recovery pathways requiring sophisticated sorting and routing decisions. Building on these characteristics, the EVB CLSC exhibits the operational frictions on governance assurance, coordination and collaboration, data sharing and identity, rather than isolated task issues.

These challenges motivate more innovative approaches to CLSC management. Circular economy extensions such as the 9R principles (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover) further emphasise sorting, diagnostics and routing decisions across competing options. Data-driven approaches and digital integration have been demonstrated to enhance visibility and operational efficiency in circular operation systems ([Tao et al., 2018](#)). Meanwhile, conventional centralised operating systems, built around siloed enterprise databases and hub-and-spoke electronic data interchange (EDI) integration, struggle to deliver real-time verifiability, flexible multi-party coordination and auditable settlement ([Babich and Hilary, 2020](#); [Saberli et al., 2019](#)). By contrast, decentralised technologies enable transparent, secure, and efficient data management across the firms. Following prior lifecycle studies ([Alamerew and Brissaud, 2020](#); [Reinhardt et al., 2019](#); [Wrålsen et al., 2021](#)), we operationalise the EVB CLSC into six stages used throughout this study: (1) raw and active material production, (2) EV and battery design and manufacturing, (3) EV in-use phase (1st life), (4) EoL diagnostics, (5) the second-life phase involving battery reuse, and (6) disassembly, recycling, and disposal. These stage-specific challenges set up our later analysis of how decentralised technologies like Web3 and metaverse can deliver verifiable governance, flexible coordination and auditable value allocation.

2.2. Technology-organisation-environment framework

We use the TOE framework as the central lens for analysing decentralised technologies in EVB CLSC. The TOE conceptualises the adoptions through three interacting contexts: (i) technological context, focusing on the characteristics and availability of technologies relevant to the firm; (ii) organisational context, addressing the firm's resources and capabilities; and (iii) environmental context, considering external industry and regulatory pressures (Baker, 2012).

Prior supply chain studies show TOE's suitability for technology adoption. For example, the TOE dimensions have been shown to influence the adoption of electronic supply chain management systems and to highlight the interplay between organisational capabilities and competitive market (Lin, 2014). In EVB CLSC, decentralised technologies require coordinated, multi-actor adoption across the battery lifecycle, from forward to reverse flows (J. Li et al., 2024), making TOE particularly suitable. TOE captures the technological capabilities needed for interoperability and performance tracking; the technological context must address specific challenges like battery monitoring systems integration and performance tracking (Kumar et al., 2020; Saberi et al., 2019). The organisational capacity is also captured to implement and operate such systems, and the environmental pressures that drive or constrain adoption. However, the TOE framework is largely static and may underplay dynamic interdependencies between supply chain actors and underrepresent the sociotechnical and lifecycle-wide coordination challenges in EVB CLSC. Thus, we extend TOE with a Layered Modular Architecture (LMA) for the technological dimension in the EVB CLSC context.

2.2.1. Technological perspective with layered modular architecture

Within the technological domain, firms must assess not only the emergence of new tools but also their fit with existing systems. As Lin (2014) notes, organisations operating in supply chain environments should possess strong capabilities for technology integration and maintain a foundational level of digital infrastructure readiness. We therefore operationalise the technological context using the LMA of digital innovation proposed by Yoo et al. (2010), which views digital innovations as loosely coupled modular layers: **device, network, service, and content**, that can evolve independently yet interoperate. Yoo et al. (2010) highlight that digital innovation thrives when platforms attract diverse contributors to build components across layers. Hylving and Schultze (2020) further posit that such hierarchical, layered modularity supports extensibility across organisational and ecosystem boundaries. This openness enhances generativity, the capacity to produce unanticipated innovations, though it is constrained by organisational and institutional limitations.

Decentralised technologies align naturally with this logic: P2P, ledger-based architectures enable protocol-level trust and cross-boundary coordination. LMA lens not only helps us understand the landscape and interconnections of Web3, metaverse and their infrastructure, but also shows how these technologies replace or restructure legacy enterprise systems in operations. For example, distributed ledger technology can replace centralised traceability from enterprise resource planning (ERP) (Saberi et al., 2019) and shift from point-to-point EDI via value-added networks to verifiable, permissioned inter-firm data (Babich and Hilary, 2020). This is particularly important for EVB CLSC, where modular innovation across layers is essential for systemic-wide coordination and value creation.

At the device layer, digital twin technologies are closely tied to physical-digital interfaces. They depend on IoT-enabled sensors and devices embedded in physical assets (the physical sublayer) to capture real-time data, while the logical sublayer (e.g., operating system) leverages edge computing and real-time analytics to process and synchronise this data with dynamic digital replicas of the physical system (Ivanov et al., 2019; Nguyen et al., 2022). This real-time operating system becomes especially powerful as it can connect with blockchain at the network layer, which securely records, verifies, and shares these data streams across decentralised peer-to-peer systems (Queiroz et al., 2019; Yoo et al., 2010). The network layer also contains two sublayers. Physical transport sublayer (1) comprises cables, radio spectrum, and transmission infrastructure, which can be viewed as the main structure of the concept of physical internet in the global logistics domain (Pan et al., 2017), and underpins the connectivity necessary for P2P communication among distributed nodes. This sublayer enables the decentralised data exchange that forms the foundation of blockchain networks, facilitating continuous synchronisation across geographically dispersed supply chain stakeholders. Local transmission sublayer (2) encompasses the communication protocols such as TCP/IP, P2P networking standards, and consensus mechanisms that govern how information is encoded, validated, and transmitted across the blockchain. Blockchain ensures the traceability, tracking, transparency, and trust of these records among multiple stakeholders (Büyükoçkan and Göçer, 2018). Together, they support robust coordination in supply chain management, where real-time condition monitoring must align with verifiable tracking of materials and transactions. However, blockchain alone faces limitations in handling the complex data requirements of product lifecycle management, particularly regarding real-time performance monitoring and predictive analytics (Kumar et al., 2020). For instance, blockchain technologies have shown promise in enhancing traceability and transparency in supply chains, but their scalability and energy demands remain critical concerns (Chen et al., 2023). This reflects the fundamental "blockchain scalability trilemma", that is, the challenge of simultaneously achieving decentralisation, security, and scalability (Zhou et al., 2020).

Since smart contracts depend on blockchain P2P protocols and consensus mechanism to build their automatic, decentralised systems that govern how terms and actions are negotiated (Dolgui et al., 2020), they bridge the logical transmission sublayer (where they rely on P2P and blockchain protocols for propagation and consensus) and the service layer (where they deliver user-facing functionality as programmable agents). At the service layer, they autonomously execute predefined logic in response to on-chain transactions/events, enabling user interactions without intermediaries (Centobelli et al., 2021). As programmable services, they underpin a wide array of decentralised applications (dApps), including supply chain automation, asset transfers, and digital identity verification.

On top of the decentralisation evolution, Web3 infrastructure, built on blockchain, smart contracts and a decentralised storage

network (Ghosh et al., 2024), can situate predominantly at both network and service layers, enabling decentralised data management and autonomous coordination mechanisms. Web3 can serve as a virtual platform for users to create and store data, such as the Decentraland platform (Park et al., 2023). Nevertheless, the implementation of Web3 technologies in EVB supply chains remains challenging due to interoperability issues and the need for standardised protocols (Dolgui and Ivanov, 2023; Kouhizadeh et al., 2021). Metaverse can span both the service and content layers. As a service, it offers immersive digital environments through which users can interact, transact, and collaborate in real time, further enhancing supply chain visualisation and collaboration capabilities (Kumar et al., 2020). However, it also heavily engages the content layer, where rich multimedia assets such as 3D models, avatars, digital twins, virtual goods, and environmental data are generated, shared, and continuously updated. This layer also handles metadata such as ownership, provenance, and access rights, often encoded via NFTs or other digital tokens. The metaverse is fundamentally enabled by the decentralised technologies operating across all aforementioned layers of the digital architecture. As Ritala et al. (2024) suggest, its realisation depends on the integration of device, network, service, and content layers, which together facilitate seamless interaction across physical and virtual environments. According to Lee et al. (2024), decentralised technologies such as digital twins, blockchain, smart contracts, and Web3 highlight the metaverse’s capacity not only to mirror the real world but also to support the autonomous creation and evolution of immersive content. Wang et al. (2025) extend this view by proposing a framework where the metaverse becomes a functional part of everyday life, with potential applications in supply chain management to enhance user experience, increase transparency, and support more informed decision-making. Despite this promise, significant barriers persist. High computational demands, infrastructure costs, and system integration challenges hinder implementation (Manoj Kumar and Chopra, 2023; Verhoef et al., 2021). Moreover, the energy intensity of metaverse applications raises growing environmental concerns, with potential implications for carbon emissions and digital sustainability (Kaplan and Haenlein, 2024).

To consolidate the above insights, Fig. 1 illustrates the integration of Web3 and the metaverse with other related decentralised technologies. It highlights their primary LMA layer(s) and corresponding supply chain functions, offering a functional overview that clarifies modular positioning and potential interoperability pathways.

2.2.2. Organisational perspective

The organisational context encompasses structural and process characteristics that constrain or facilitate technology adoption, such as firm size, technological expertise, managerial structure, and resource availability (Oliveira and Martins, 2011). In EVB CLSC, however, traditional operations still rely on centralised decision-making, contract-based governance, tiered supplier management, linear information flows, and periodic auditing and certification. These features often create transparency gaps, slow exception handling, and high coordination costs, especially across multiple lifecycle actors.

Research shows that organisational readiness plays a significant role in successfully implementing decentralised technologies. Resource constraints disproportionately affect smaller suppliers (Kouhizadeh et al., 2021), while the rapid evolution of decentralised technologies exacerbates knowledge and integration gaps (Mathivathanan et al., 2021; Sodhi et al., 2022). For such complex technologies, organisational learning capacity and technical expertise become particularly crucial (Dwivedi et al., 2022; Verhoef et al., 2021). Against this backdrop, Web3 and Metaverse imply clear role changes at the organisational level. For example, decision rights

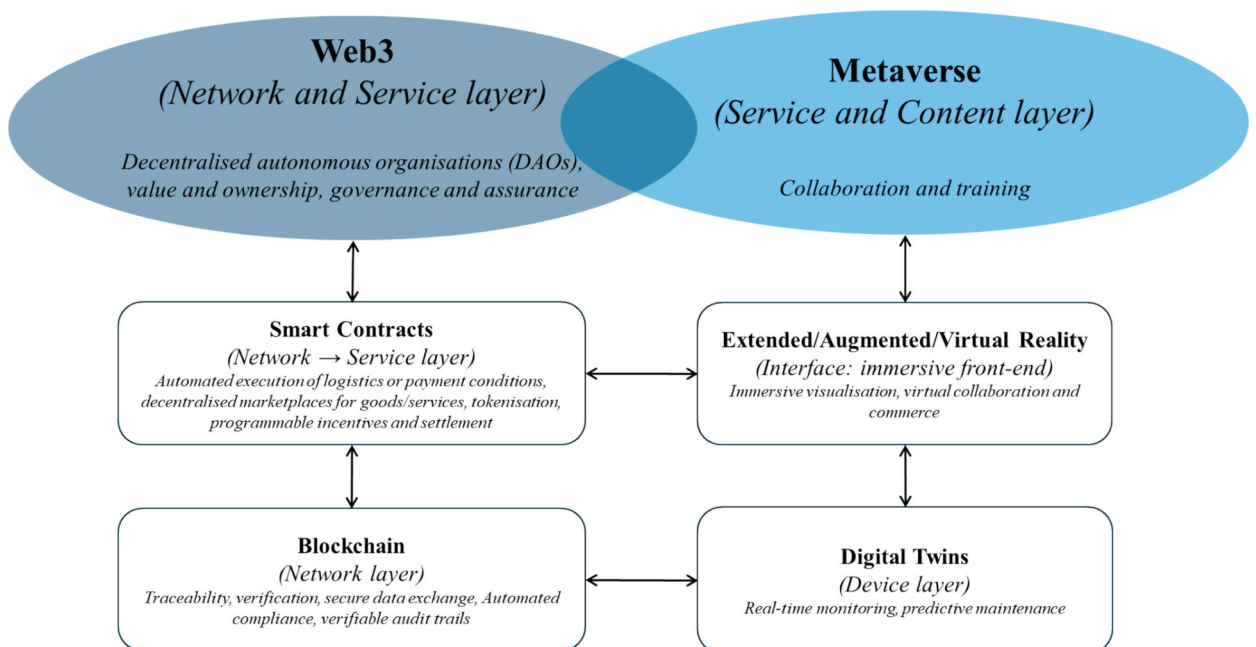


Fig. 1. Decentralised technology stack and operating paradigms.

shift from centralised control to distributed coordination; smart-contract automation replaces portions of contract enforcement and manual settlement. Practically, implementing a blockchain-based traceability system still requires cross-functional capabilities, such as distributed ledger technology, smart-contract skills, and data governance, to align operational rules with code and interfaces (Centobelli et al., 2021). Metaverse interfaces with digital twins further enable immersive collaboration, remote inspection, and training, strengthening trust and operational resilience (Dolgui and Ivanov, 2023). In short, the organisational dimension must evolve from control-heavy routines to programmable coordination with continuous assurance and value co-creation or capture, so that the potential of decentralised technologies for EVB CLSC operations can be realised.

2.2.3. Environmental perspective

The environmental context considers external pressures and opportunities that influence technology adoption, including competitive pressure, regulatory support, and industry characteristics (Baker, 2012). Environmental factors include strict sustainability regulations, growing market competition in EV sectors, and increasing stakeholder demand for transparency and traceability. This sector might be complicated by industry fragmentation across geographical regions and uneven technological capabilities (Ying et al., 2023), alongside regulatory uncertainties regarding data privacy, environmental compliance, and cross-border trade (Centobelli et al., 2021; Wang et al., 2023; Govindan et al., 2023).

Against these pressures, decentralisation offers concrete response mechanisms. Blockchain provides immutable audit trails and programmable reporting, supporting compliance with battery lifecycle and sustainability regulations (e.g., emissions in production and recycling), and enabling emerging digital passport schemes (Jia et al., 2024; Khan, 2024). Web3 improves multi-stakeholder transparency while respecting confidentiality constraints, thereby reducing information asymmetries among OEMs, suppliers, recyclers and regulators. Likewise, metaverse interfaces coupled with digital twins enable remote inspection, workforce training across borders, and strengthen global collaboration, shortening coordination cycles (Dwivedi et al., 2022).

Taken together, the environmental perspective explains why decentralised technologies gain traction in EVB CLSC. They operationalise regulatory compliance, stakeholder transparency and cross-border collaboration under conditions of fragmentation and uncertainty.

2.3. Theoretical framework

To address the challenges and guide the transition from traditional/centralised to decentralised supply chain operations, firms need to assess their current stage of technologies and determine their position within the broader trajectory of operational transformation. Using the TOE framework as a diagnostic lens, the transition from traditional centralised supply chain models to Web3/metaverse-enabled supply chain models can be seen as a shift in technological capability (e.g., from siloed ERPs to decentralised ledgers, smart contracts, and immersive digital twins through the LMA lens), organisational design (from hierarchical, buyer-controlled networks to decentralised, ecosystem-driven governance), and environmental alignment (from compliance-driven opacity to transparent,

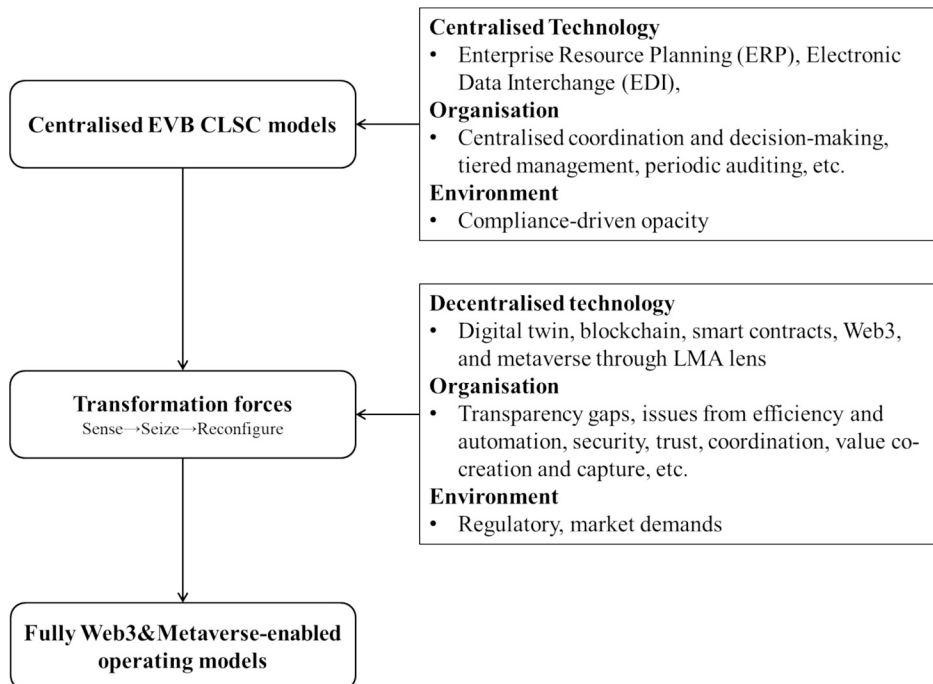


Fig. 2. Operational decentralisation framework for EVB CLSC.

verifiable, sustainability-oriented value chains) (Fig. 2). Understanding this progression allows firms to benchmark their readiness and identify necessary steps for advancement. However, successful transformation requires the development of dynamic capabilities, which is the ability to *sense* new technological opportunities, *seize* them through strategic investment and collaboration, and *reconfigure* internal structures accordingly (Teece, 2007). In the context of EVB CLSC, this might involve recognising the strategic potential of decentralised traceability or P2P coordination (*sensing*), reallocating resources to foster cross-sector collaboration or enhance workforce digital skills (*seizing*) and adapting governance models or legacy IT systems to integrate decentralised architectures (*reconfiguring*). This perspective extends the diagnostics lens to the transformational lens of the TOE framework by emphasising not only structural readiness but also an organisation’s adaptability and learning orientation.

3. Research methodology

2.4. Methodological framework

Our research method consists of five fundamental steps as shown in Fig. 3: (1) We formulate the research aim and questions drawing from practical problems and literature gaps; (2) Next, we systematically collect and preprocess (e.g., text cleaning, stop words removal, bigram and trigram establishment, lemmatization) text data from two distinctive sources – academic articles and industry documents (e.g., newspaper, wire feed); (3) We apply D-LDA model to extract the prominent topics from the pre-processed data to explore the current application of decentralised technology across EVB CLSC (RQ1&2); (4) We then apply burst detection analysis to explore the emerging trends within the extracted D-LDA topics relating to decentralised technology (RQ1&2); (5) Drawing from identified applications, we assess the feasibility of fully implementing Web3 and metaverse within EVB CLSCs using the TOE framework and propose the Web3/Metaverse transformation pathways as future research direction (RQ3).

2.5. Data collection and preprocessing

To answer the three RQs, we employ a systematic review methodology to explore current applications of decentralised technologies within the EVB CLSC. We collect data from two distinctive sources – industry documents (IDs) and academic articles (AAs). While IDs offer insights into practical implementation and industry-specific knowledge, AAs focus on advancing theoretical knowledge. Both sources complement each other to provide a holistic and comprehensive understanding of decentralised technologies’ applications. The document search, selection, and evaluation strategy was conducted in November 2024 and illustrated in Fig. 4. First, our systematic corpus collection begins by identifying suitable keywords and search terms. We finalise the most appropriate search terms, stemming from three key areas: (a) decentralised technologies, (b) EVs, and (c) batteries.

Then, IDs are collected from a well-known ABI/Inform Global, which provides full text of many types of industry documents such as

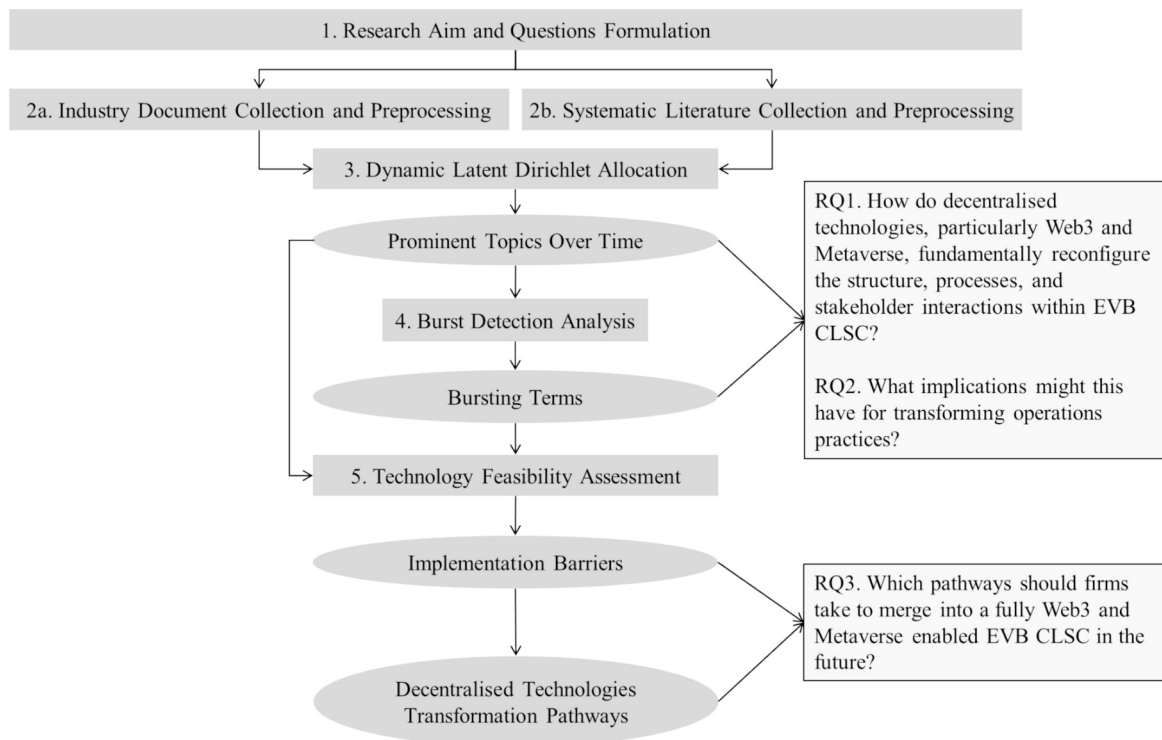


Fig. 3. Methodological framework.

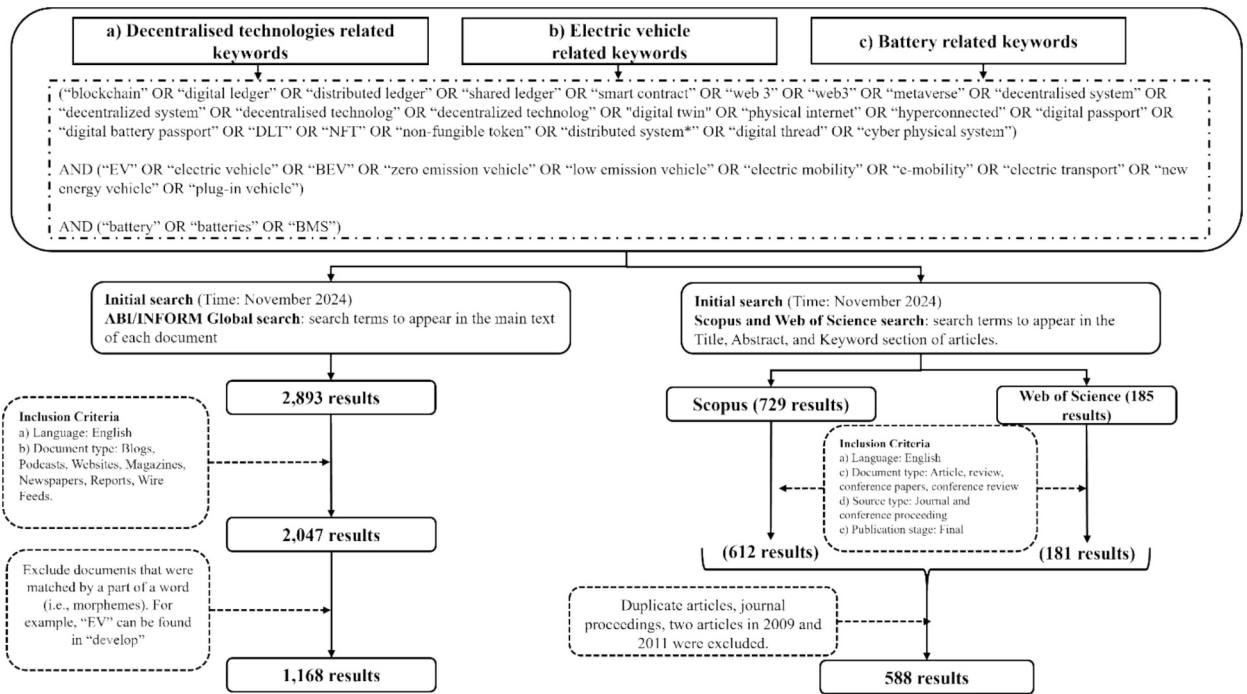


Fig. 4. Documents search, selection, and evaluation strategy.

newspapers, magazines, reports, wire feeds, blogs, podcasts, and websites. This is one of the most comprehensive business databases, offering the latest industry information. The database is widely used in studying logistics and supply chain management (Schoenher, 2009) and decentralised technologies such as blockchain and digital twin (Guo and Mantravadi, 2024; Mahmood et al., 2022). Digital technologies such as Web3 and Metaverse are rapidly evolving, with the industry often driving practical developments ahead of academic research, which tends to lag behind. As such, IDs (i.e., grey literature), including blogs, podcasts, websites, magazines, newspapers, reports and wire feeds, provide timely and context-specific insights into current practices, stakeholder perspectives, and technological advancements (Adams et al., 2017). The initial search of keyword combinations results in 2,893 documents. As we only keep excluding incorrectly matched documents (e.g., "ev" in "develop"), the final number of valid documents is 1,168. The frequencies of keywords related to decentralised technologies across all IDs and AAs are presented in Online Appendix A. All predefined keywords were matched in a substantial number of documents and with sufficient frequency, supporting the relevance and adequacy of our data sources in addressing the research questions.

We consolidate our findings with a peer-reviewed academic article. The same terms and keywords are used to extract articles from the Scopus and Web of Science databases. We target the title, abstract, and keywords of articles to ensure relevance, resulting in an initial set of 729 documents from Scopus and 185 from Web of Science. Next, we collectively establish inclusion and exclusion criteria, encompassing factors such as language, document type, source type, and publication stage. The dataset was refined to 612 documents from Scopus and 181 from Web of Science. Duplicate entries, conference proceedings, and two articles published in 2009 and 2011 (due to insufficient data for D-LDA analysis) were removed, resulting in a final dataset of 588 articles for further analysis.

Text data, particularly from industry documents such as newspapers or blogs in PDF format, is often messy and noisy. Therefore, rigorous text preprocessing is essential to ensure data quality. In this study, we employ a customised five-step procedure to clean the text data: (1) removing noise, such as HTML symbols, punctuation, non-alphabetical characters, and extraneous phrases (e.g., "copyrights" or "PDF generated by proquest.com"); (2) eliminating stop words; (3) filtering out overly general or excessively frequent terms, including "EVs", "electric", "vehicle", "BEV", "paper", "study", and "research"; (4) lemmatising words to their base forms; and (5) generating bigrams and trigrams to capture contextual phrases.

We utilise the abstract-level dataset for AAs as input to D-LDA because abstracts tend to be concise, focused, and coherent. In contrast, IDs are often lengthy and may contain substantial irrelevant information. Therefore, it is essential to refine the dataset to better align with our research questions. To achieve this, we divide each document into individual sentences and retain only those sentences that referenced keywords from one or more of the aforementioned key areas: (a) decentralised technologies, (b) EVs, and (c) batteries. As a result, we obtain 83,643 valid sentences for further analysis.

• **Descriptive analysis**

Fig. 5 shows the distribution of both IDs and AAs discussing decentralised technologies in the context of EVB’s CLSC. Notably, the volume of both IDs and AAs exhibits a similar range and a marked increase starting in 2019, reflecting growing interest and applications among practitioners and academics in the field of EVB. As detailed in Table 1, the academic articles predominantly originate from technical journals such as *IEEE*, the world’s largest technical professional organisation dedicated to advancing technology. Most industry documents are derived from company data reports, indicating the active deployment of decentralised technologies in business operations, products, and services.

2.6. Latent Dirichlet Allocation

To achieve RQ1, we apply a variant of the typical Latent Dirichlet Allocation (LDA) model, which is called Dynamic LDA (Blei and Lafferty, 2006). Traditionally, methods like Latent Semantic Indexing, Probabilistic Latent Semantic Indexing or Non-negative Matrix Factorization create a word-document matrix to assign papers to clusters, but these approaches can lead to exponentially large combinations and high computational costs. LDA addresses this by introducing a latent layer of clusters, reducing dimensionality and enabling more efficient classification of papers into these latent clusters. As we use the variant D-LDA, which allows us to explore the changes of the keywords within each topic over the years, this function is not available within the traditional methods.

D-LDA can provide a means to evaluate the long-term evolution, identifying gradual trends and persistent changes. The list of representative keywords and their probabilities per topic per year can be used as the input for the following burst detection analysis in Section 3.4. Compared to the cutting-edge BERTopic (Grootendorst, 2022), which leverages the BERT model to generate topic representations, D-LDA remains a more suitable choice for our analysis, especially when the goal is to identify a diverse set of top keywords within each topic. D-LDA is better equipped to capture the multifaceted nature of topics, such as the intersection of technologies, their applications in EVs, their role in battery technology, and the CLSC for batteries. In contrast, BERTopic tends to generate more convergent topics, with keywords that are closely related. This makes it difficult to capture the nuanced ways in which decentralised technologies are applied within the context of the EVB’s CLSC, a task for which D-LDA excels. The procedure of training and optimising the number of topics can be found in the Online Appendix B.

2.7. Burst detection analysis

While D-LDA provides an overview of each topic by showing the long-term appearance of dominant keywords, which help determine the main applications of decentralised technologies in EVB CLSC, it is essential to delve into the internal elements of applications to see how both practitioners and scholars create and innovate over time. Although D-LDA outputs can show how a list of top keywords for each topic changes over time, it does not provide a precise quantitative measure of how specific keywords suddenly spark in a short period of time.

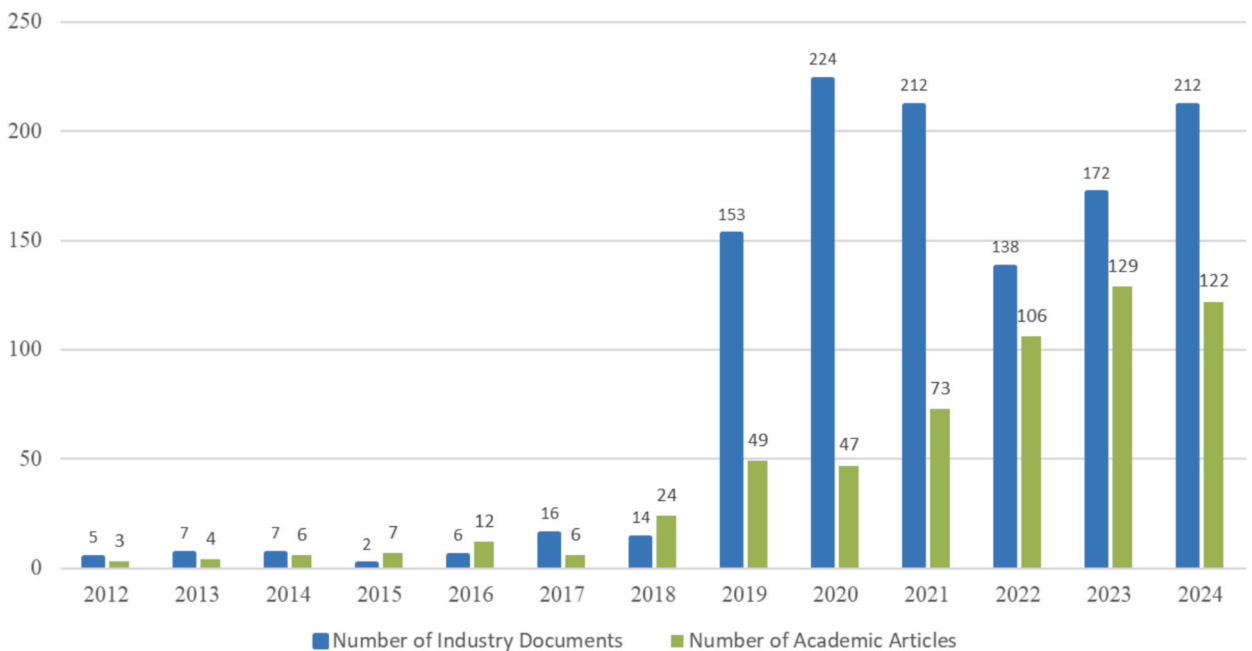


Fig. 5. Industry and academic document distribution from 2012 to 2024.

Table 1

Top 10 most frequent industry and journal sources.

Industry Document Source	Frequency	Journal	Frequency
Company Data Report	816	<i>IEEE Access</i>	22
Website	206	<i>Energies</i>	15
Newspaper	120	<i>SAE Technical Papers</i>	11
Magazine	26	<i>Journal of Energy Storage</i>	10
		<i>IEEE Transactions on Vehicular Technology</i>	10
		<i>Applied Energy</i>	10
		<i>IEEE Internet of Things Journal</i>	10
		<i>Batteries</i>	7
		<i>IEEE Transactions on Smart Grid</i>	6
		<i>Renewable and Sustainable Energy Reviews</i>	6

To address that problem, burst detection is a pop-up concept in text mining to find out how a phenomenon (i.e., bursty terms) appears, grows intensively and fades away for a period (Kleinberg, 2002; Yalcin and Daim, 2022). Bursty terms can illustrate sharp, short-term changes in frequency and, to some degree, indicate real-time emerging trends and hotspots of decentralised technologies in the context of EVB CLSC. Burst detection analysis is widely used for both IDs (e.g., newspapers and magazines) and AAs in the context of supply chain management (Kleinberg, 2002; Nguyen et al., 2022; Xu et al., 2020; Yalcin and Daim, 2022). The mathematical formula can be found in the Online Appendix C.

2.8. Technologies feasibility assessment

To evaluate the feasibility of decentralised technologies in EVB CLSC, we developed a systematic analytical approach that builds upon the TOE framework following Davies et al. (2024). Our methodology consisted of two main phases: (1) barrier identification and (2) technology capability analysis, followed by a comprehensive feasibility assessment.

The first phase involves a systematic review of the literature to identify and classify barriers to technology adoption in EVB CLSC. We analyse papers from our dataset that specifically discussed implementation challenges, adoption barriers, and limiting factors. These barriers are then systematically classified using the TOE framework to provide a structured understanding of the challenges across technological, organisational, and environmental dimensions. This classification enables us to create a comprehensive barrier assessment framework specific to the EVB CLSC.

The second phase focuses on analysing the capabilities of emerging decentralised technologies, with particular attention to those showing limited current application in EVB CLSC, as shown in our previous analyses. We evaluate each technology's potential to address the identified barriers by examining its core capabilities, technical specifications, and reported applications in similar contexts.

The feasibility assessment synthesises these analyses by cross-referencing technology capabilities against identified barriers. Our assessment considers multiple criteria, including technical readiness level, implementation complexity, resource requirements, expected impact, and integration potential. This systematic approach allows us to identify promising future applications of these technologies across different stages of the EVB CLSC.

3. Results and discussions

3.1. D-LDA and burst detection results

We apply D-LDA models to two cleaned datasets separately – 588 abstracts from AAs and 83,643 valid sentences from 1,168 IDs.

Table 2

Decentralised technology-related topics from D-LDA.

Document Type	Topic	Some representative keywords
Industry Document (ID)	Topic ID2	Battery, lithium, ion, material, metal, blockchain
	Topic ID3	Battery, digital , twin , test, power, accelerate, conversion
	Topic ID6	Blockchain , technology, system, power, reduce, infrastructure
	Topic ID9	Blockchain , production, industrial, manufacturer, network
Academic Articles (AA)	Topic AA1	Charge, security, blockchain , system, energy, station
	Topic AA2	System, model, method, Datum, cyber physical , real time
	Topic AA3	Battery, digital , twin , BMS, cell, pack, design
	Topic AA4	Energy, power, system , grid, renewable, distribute , storage
	Topic AA5	Energy, power, battery, system, reduce, use, discharge, blockchain
	Topic AA6	Charge, service, information, network, blockchain
	Topic AA8	Energy, management, system, power, increase, digital , twin
	Topic AA9	System, framework, smart , contract , distribute, platform, grid
	Topic AA11	Blockchain , battery, recycling, traceability, supply chain
	Topic AA12	Battery, charge, blockchain , recommendation, system, utilize, operation

Since D-LDA requires the number of topics in advance, to ensure generality, we train each dataset through a range of 2 to 101 K topics, equating to 100 runs in total. This method was proven in prior research as an effective balance between overly broad topics and excessively narrow ones that lack semantic coherence (Chae and Olson, 2021). We use log perplexity scores to evaluate the model’s performance. A higher log perplexity score indicates a better model. For IDs, the scores remain relatively stable until a sharp decline at $K = 14$, indicating a notable decrease in the model’s ability to represent the data. For AAs, perplexity scores decline gradually, with consistent drops of over 0.01 per topic from $K = 2$ to $K = 12$. The smallest drop occurs at $K = 12$, after which the scores fluctuate more but continue trending downward. This pattern suggests $K = 12$ is the optimal number of topics, balancing specificity and semantic coherence. The line charts for log perplexity scores and detailed analysis can be found in Online Appendix B. As a result, we obtained 14 optimal topics for the IDs dataset and 12 optimal topics for the AAs dataset. The top 10 representative keywords and their $prob_{t,k,n}$ can be found in Online Appendix D.

At first glance, not all identified topics align directly with our focus on the applications of decentralised technologies within EVB’s CLSC. Therefore, we analyse topics that include decentralised technology-related keywords, as outlined in Table 2. The D-LDA model also identifies documents that strongly correlate with each topic, enabling a more detailed exploration of the specific applications associated with these topics.

Bursty terms are identified from the top representative keywords of each D-LDA topic, as detailed in Section 3.4. However, burst detection is effective only when keywords vary dynamically across time, a condition not met when we run D-LDA for our AAs (see Online Appendix D). Consequently, burst detection is applied solely to D-LDA topics derived from IDs, as strongly advocated by Kleinberg (2002). Our analysis primarily focused on topics related to decentralised technology applications (ID2, ID3, ID6, and ID9). Notably, “metaverse” emerged as a prominent term within topic ID1 from 2021 to 2023, suggesting further investigation. Fig. 6 presents the bursty terms extracted from these five topics. In the figure, blue bars represent emerging or ongoing terms, while grey bars indicate fading terms. To identify emerging trends, particular emphasis is placed on the blue bars.

Drawing on D-LDA and burst detection analysis, we identified 18 decentralised technology applications in the EVB sector, analysed through the LMA framework (see Online Appendix E). Our review reveals two key research gaps hindering the adoption of Web3 and

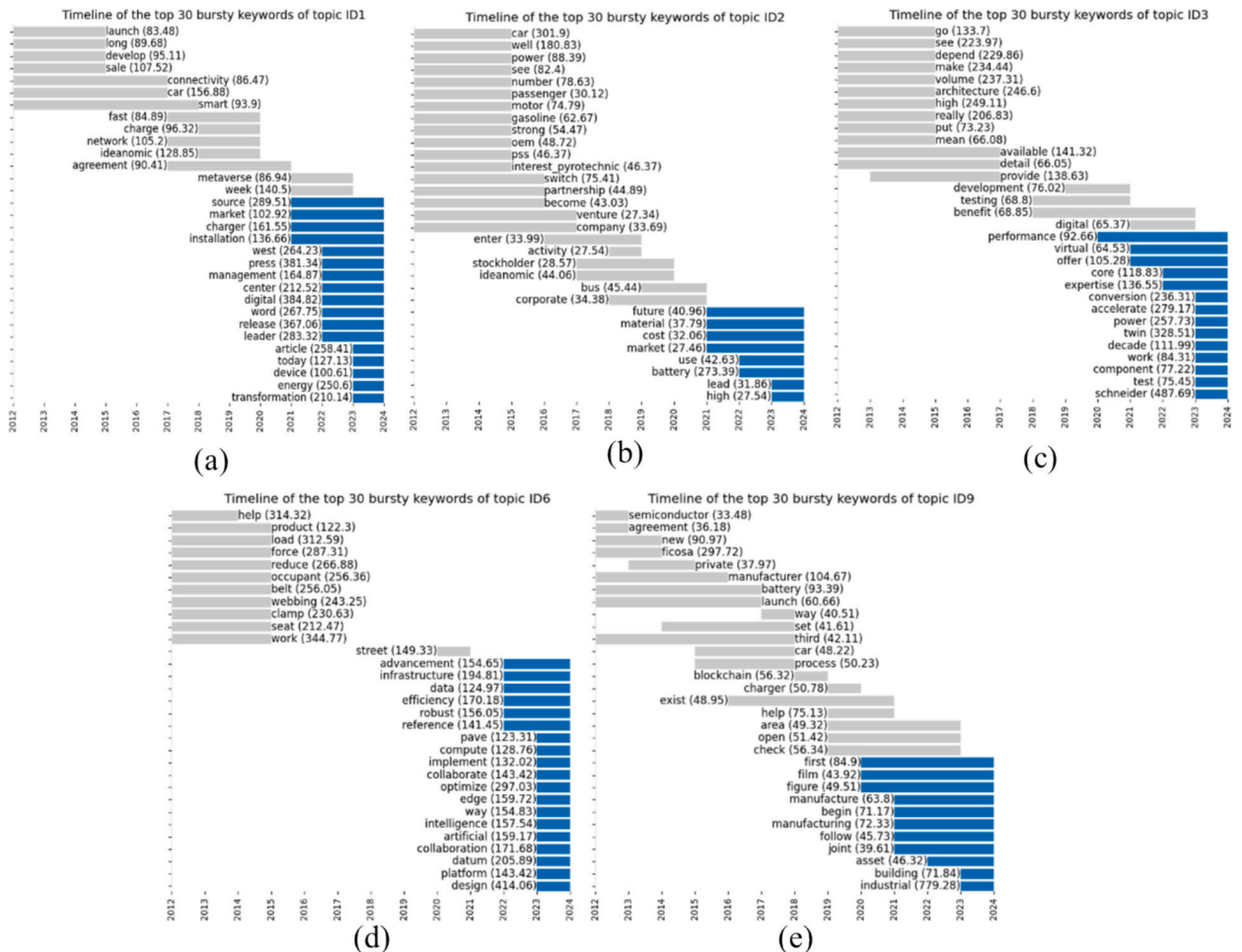


Fig. 6. Top 30 bursty keywords from topics relating to decentralised technology.

Metaverse in EVB CLSCs. First, current applications are fragmented across CLSC stages and lack integration into end-to-end operations. Second, no unified platform supports all layers of the LMA framework. The growing interest in Web3 and the Metaverse contrasts with limited organisational and market readiness, highlighting a gap between technological hype and practical implementation. Although these technologies show clear potential to enhance EVB CLSC efficiency, their deployment remains uneven and disconnected. Understanding the barriers to transformation is therefore essential. To address this, we further conduct a Technologies Feasibility Assessment focusing on four decentralised technologies: digital twin, metaverse, smart contracts, and Web3. Using the TOE framework, we evaluate barriers across three dimensions: technological (integration complexity, data standardisation, scalability), organisational (resource constraints, expertise gaps, implementation costs), and environmental (regulatory uncertainty, industry fragmentation, market readiness), as detailed in Online Appendix F.

The next section will explore how Web3 and Metaverse can fundamentally reconfigure EVB CLSC structures, processes, and stakeholder interactions, and examine these barriers in greater depth to inform future transformation pathways.

3.2. Web3 and metaverse in transforming EVB supply chain operations

We synthesise insights from the 18 key decentralised applications identified in Section 4.1 into two primary EVB CLSC: (1) the EVB CLSC encompassing operations from raw material extraction to EoL management, and (2) the EVB Circular Energy/Grid CLSC, which focuses on energy flow and charging station operations. To address our research questions, we first outline the structure and limitations of current centralised operations. We then present decentralised alternatives, highlighting the transformation drivers, implementation barriers, and strategic pathways for transitioning towards fully Web3/Metaverse-enabled operations across each aspect of the EVB CLSC.

3.2.1. EVB CLSC operations

Traditional CLSC operations for EVBs typically divide the supply chain into two disconnected segments: forward and reverse. This separation stems from the challenges associated with tracing, monitoring, and recertifying EVBs once they leave the factory or warehouse. As a result, while the forward supply chain increasingly faces long-term shortages of raw materials, the reverse supply chain – comprising repurposing, remanufacturing, and recycling – remains immature and unable to provide a sustainable and reliable supply of secondary batteries. This disconnect contributes to a significant volume of EVBs being discarded in landfills despite retaining considerable residual value. Blockchain technology offers a promising solution by enabling end-to-end visibility of battery components, from the cell level to in-use pack configurations, thereby addressing traceability and certification issues (Capocasale et al., 2025). Moreover, external collaboration remains limited due to the siloed nature of product development within EVB design teams. In this context, Metaverse-based virtual reality platforms for battery manufacturing emerge as secure and efficient tools for facilitating cross-geographical collaboration among stakeholders (Saravanan et al., 2025). Fig. 7 illustrates the enabling role of blockchain and Metaverse technologies in facilitating EVB CLSC operations.

(1) Metaverse-enabled Sustainable Design, Manufacturing and EoL Diagnostics

Traditionally, EVB design has been a sequential, computationally intensive process. Engineers rely on physical prototypes to evaluate size, power, and thermal trade-offs, while safety validation and range optimisation are tested under controlled lab conditions (White et al., 2021). This isolated approach prolongs iteration cycles (Deng et al., 2022), limiting collaboration between design and downstream teams, and restricting visibility into how EVB design influences later stages such as EoL reuse or remanufacturing. Furthermore, compliance with sustainability-oriented regulation (e.g., European Parliament, 2022) may force businesses to embed in early design phases. Therefore, the design process remains detached from real-world operational feedback and from circular economy imperatives.

Decentralised digital infrastructures transform this model by embedding digital twins and extending collaboration into immersive environments – Metaverse. Digital twins create a living design space where EVBs can be virtually modelled, stress-tested, and optimised before mass production. Siemens and UL Solutions demonstrate this through virtual sensor performance testing, propulsion and cybersecurity assessment, while Renesas's high-voltage twins enable companies like BYD to fine-tune battery performance under realistic stress scenarios. The simulations can be run under metaverse platforms, enabling EV stakeholders to co-design components in shared virtual environments (Musule et al., 2024). In fact, Franco et al. (2023) and Saravanan et al. (2025) developed a metaverse-based digital twin for a battery manufacturing pilot line. Furthermore, EV users can act as co-managers and co-creators, contributing feedback that is integrated into continuous quality improvement cycles via metaverse-based virtual showrooms (Bendoly and

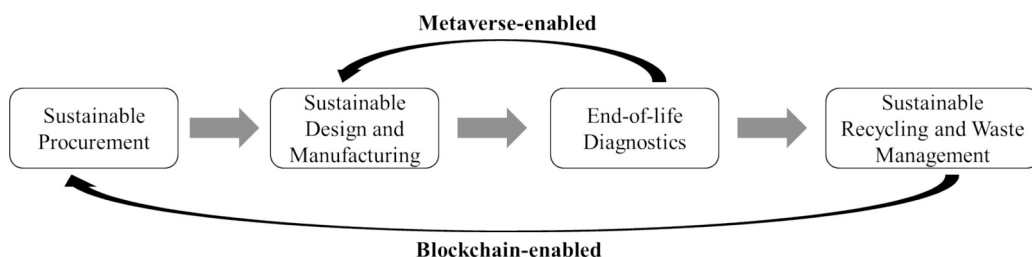


Fig. 7. Blockchain/Metaverse-enabled EVB CLSC operations.

Oliiva, 2024; Stellantis, 2022). These immersive design spaces bridge geographic silos, allowing EV stakeholders worldwide via their avatars to collaboratively refine battery architectures in a faster and risk-free way.

By linking digital twins directly to operational and lifecycle data, the product design process shifts from static blueprinting to dynamic lifecycle integration. During design and operations, digital twins feed insights from on-vehicle battery management systems (BMS) (i.e., state-of-charge, health, and residual energy) into the design loop, enabling continuous parameter optimisation (Alamin et al., 2023; Eaty and Bagade, 2023; Wagle et al., 2023). At EoL, design teams gain visibility into component-level diagnostics, allowing them to virtually predict the remaining useful lifetime of EVB, especially after identifying faults (Branco and Fontanela, 2024), before deciding on remanufacturing or refurbishing. This closes the loop: design no longer neglects the downstream operations but actively engages reuse, remanufacture, and recycling strategies. Immersive supply chain control centres would ensure that the most value-preserving pathways for retired EVBs will be optimised and selected based on comprehensive virtual diagnostics.

With digital twins and the metaverse at the heart of the product design process, organisations can adopt a virtually collaborative operating model. R&D, manufacturing, supply chain, and sustainability units are now integrated into a virtual immersive workspace without boundaries, where design serves as the coordination hub for the entire battery lifecycle. In this envisioned world, a digital supply chain twin – defined as a real-time digital representation of network states (Ivanov and Dolgui, 2021) – can be extended into a metaverse-based virtual environment in which not only EVBs but also the facilities that produce, process, and support them are fully visualised and replicated. Experts can enter this virtual world through VR headsets or AR applications and making direct contact with each other without the need of middlemen, enabling richer and cross-fertilising collaboration and knowledge exchange. This transition shifts the paradigm from centralised power distribution toward a federated model of distributed decision-making and authority. Strategically, this shift repositions design as not only a technical function but also a business operation driver – shaping value creation, circularity, and competitive differentiation.

While digital twins offer strong potential for improving battery management and performance prediction, their implementation faces challenges such as data requirements and technical complexity (Singh et al., 2021; Wang et al., 2021). In parallel, the metaverse's underlying infrastructure and enabling technologies remain immature, limiting scalability (Dwivedi et al., 2022). Moreover, prolonged engagement in virtual environments may negatively impact user experience, potentially leading to mental health concerns such as anxiety, detachment from reality, and depression (Dwivedi et al., 2022). Artificial intelligence (AI) integration is proposed to overcome these barriers. They unlock advanced predictive and adaptive capabilities across the EVB CLSC. In this envisioned future, AI transforms from an analytical layer into an operational co-actor, aiming to enhance CLSC resilience (Ivanov et al., 2019; Nguyen et al., 2022). Intelligent agents embedded within digital twins and metaverse can act as autonomous "AI avatars" representing firms, facilities, or even individual users, capable of negotiating production, scheduling, or recycling decisions in real time. Such avatars improve scalability by decentralising decision-making, enabling thousands of autonomous yet coordinated optimisation processes to run simultaneously without human bottlenecks. Moreover, by transferring repetitive or high-risk decision loops to an AI-driven metaverse, operational exposure to human error, safety risks, and information asymmetry can be reduced. Federated learning architectures preserve data sovereignty while allowing collective intelligence across firms. Thus, AI evolves into a decentralised cognitive infrastructure that senses anomalies, seizes efficiency opportunities, and transforms processes through adaptive governance. This anticipates a future of risk-aware, self-optimising, and human-augmented EVB ecosystems.

(2) Blockchain-enabled Sustainable Procurement, Recycling and Waste Management

Traditionally, procurement in EVB supply chains is linear and extractive, relying heavily on upstream suppliers for critical materials such as lithium, cobalt, and nickel. Ensuring the reliability of sources is critical, yet it is challenging due to the fragmented and complex metal supply chain, making it difficult to verify origin, ethical standards, or environmental impact. The growing demand for EVBs, coupled with the long lead times required to deliver minerals, could strain the global procurement for raw materials, leading to potential shortages or bottlenecks (Gifford, 2022). Furthermore, these metals will soon run out, forcing EVB stakeholders to find new sustainable ways. Recycling and waste management at the EoL stage is similarly siloed, with retired EVBs often discarded due to degradation, lack of certification, or inefficient recycling coordination, leading to landfill accumulation and resource loss. As a result, procurement decisions are based on static forecasts and long lead times, while recycling is reactive and poorly integrated into upstream planning. As regulated by the European Parliament (2022), a minimum proportion of recovered materials (16 % cobalt, 85 % lead, 6 % lithium, and 6 % nickel) from both manufacturing and consumer waste must be reintegrated into the production of new batteries. Hence, a new sustainable procurement and waste management system is critical.

In the decentralised alternative, blockchain technologies enable a closed-loop procurement and waste management system by embedding traceability, authentication, and ownership transfer into the digital infrastructure. A study from Li et al. (2024) showed that blockchain traceability can have operational cost advantages, especially when the EV market is mature. Platforms like Circularise allow EV manufacturers, recyclers, and material processors to access verified data on material origin, carbon footprint, and recycling status (e.g., scrap processing, metal recovery), creating a shared ledger of material flows. Blockchain-integrated sensors track EVB condition, usage, and location through their entire lifecycle, and automate the transfer of ownership across stakeholders (Antônio Rufino Júnior et al., 2022; Li et al., 2024). This enables other EVB stakeholders to access a wider pool of suitable suppliers, mitigating the shortage of critical materials. These innovations reconfigure procurement from a cost-driven, supplier-centric function into a sustainability-driven, network-coordinated process, and transform waste management from a disposal activity into a strategic resource recovery operation. Procurement becomes adaptive and regenerative as manufacturers source from both primary suppliers and secondary material markets.

Additionally, centralised certification at the EoL stage is complex and often impractical, as batteries must undergo application, audit preparation, auditing, adjustments for non-conformities, and final approval by certifiers (Antônio Rufino Júnior et al., 2022). Without reliable tracing information from the first life, full authentication may not even be possible. Blockchain-based track-and-trace

technology addresses this challenge by embedding certification across the entire battery supply chain, eliminating the need for repeated recertification at EoL and enabling direct engagement with certifiers only where necessary (Antônio Rufino Júnior et al., 2022; Moors, 2023). More specifically, a EVB supply chain involves many stakeholders such as raw materials and parts providers, battery and EV producers, 3PL companies, battery collectors, battery recyclers and remanufacturers and regulatory authorities. In this concept, they all need to participate in the blockchain track-and-trace network and follow a certain procedure to make sure the authenticity of the battery is retained from the origin to the recycling stage. Each battery (or batch of batteries) is equipped with tactile (i.e., direct contact) or non-tactile (i.e., via signals) identifiers, following the classification of Antônio Rufino Júnior et al. (2022) to not only verify their origin but also record their performance measurements. Each stakeholder is responsible for uploading the data to a blockchain-based platform in their operations and ensuring these identifiers remain functional. During its first life in an EV, the BMS stores operational data, some of which is encrypted due to the presence of personal data. At the 2nd life stage, only verified stakeholders get access to necessary data through keys managed by the network. Because the identifiers are managed and used throughout the full lifecycle, there will be no need to recertify retired EVBs at the end of their first life. A notable real-world application of this approach is the collaboration between the London-based Circular company and SQM, the world’s second-largest lithium supplier. This ensures that recovered materials can seamlessly flow back into procurement streams, supporting a circular economy. Meanwhile, the role of central authorities in certification shifts from gatekeeping to setting regulatory baselines and auditing decentralised infrastructures. Therefore, waste management evolves into a predictive and collaborative process, where stakeholders coordinate disassembly, recovery, and redistribution of EVBs through decentralised platforms. This reduces raw material dependency, mitigates bottlenecks, and supports compliance with regulatory frameworks like the European Parliament’s battery directive.

Currently, blockchain-enabled sustainable procurement, recycling, and waste management are mostly deployed on traditional Web2 platforms due to their compatibility with existing ERP systems like SAP and Oracle. However, key challenges remain, particularly in EVB CLSC reverse flows, where data management is still centralised across fragmented ERP systems. This leads to issues in collaboration, communication, and coordination, as well as difficulties in information disclosure among supply chain partners (Kouhizadeh et al., 2021). Our analysis indicates growing momentum in Web3 adoption, particularly in decentralised data management, asset tokenisation, and stakeholder coordination across supply networks (Huang et al., 2023; Mourtzis et al., 2022). In the envisioned Web3 future, we propose that every EV battery, component, supplier and recycler can hold a unique digital identity anchored on blockchain, creating a transparent, verifiable “internet of value” for reverse logistics. Smart contracts automate trust, while P2P consensus replaces hierarchical certification systems, ensuring authenticity of both raw and recycled materials and carbon data. As DAOs emerge, suppliers can collaboratively set and audit recycling targets, allocate capacity, and govern incentives through tokenised mechanisms. This shifts CLSCs from transaction-driven to coordination-driven ecosystems, enhancing interoperability and reducing dependency on central authorities. Crucially, Web3 allows circular collaboration without exposing proprietary data – each actor controls access to their digital assets while participating in a shared trust layer. Operationally, this marks a structural evolution from rigid buyer–supplier hierarchies to agile, self-regulated value webs aligned with sustainability and transparency imperatives.

3.2.2. EVB circular energy/grid operations

This section will investigate (1) energy distribution from the grid to charging stations or households, and (2) the charging station operations for vehicles. Centralised EVB energy/grid operations systems are typically controlled by Transmission System Operators (TSOs) and charging network operators (CNOs). They manage energy distribution, charging station operations and payment processing through a hierarchical control system, siloed platforms with limited interoperability. While existing literature has considered the potential of home charging initiatives to reduce the peak and office charging to optimise the surplus of solar energy to the grids/storage (Needell et al., 2023), there are limited integrations of distributed energy resources or multiple-user optimisation, which would reduce the reliance on middlemen as well as optimise the energy distribution. Web3/Metaverse-enabled CLSC configurations offer a potential decentralised alternative that can facilitate P2P energy trading, real-time optimisation across multiple users and assets, and interoperable platforms that reduce bottlenecks and enhance grid resilience (Fig. 8).

(1) Metaverse-enabled Grid to Charging Stations

Centralised energy management schemes prioritise grid stability but often struggle with scalability, particularly under high EV

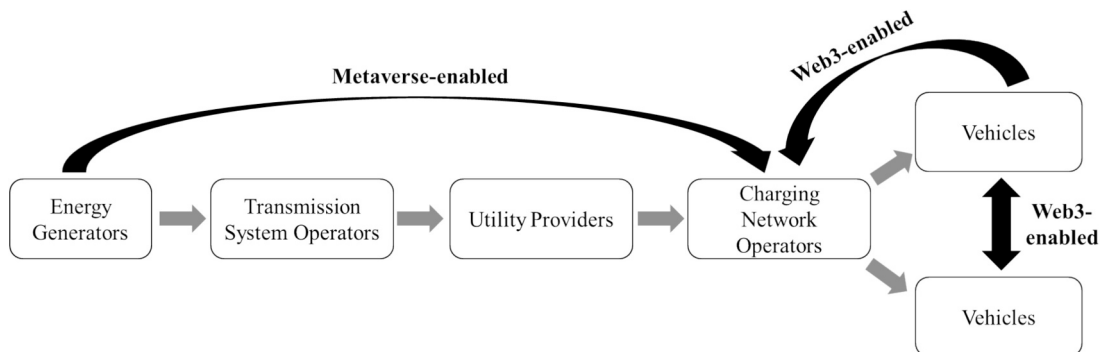


Fig. 8. Web3/Metaverse-enabled EVB circular energy/grid operations.

adoption scenarios (Rana et al., 2024; Yong et al., 2023). Energy typically flows unidirectionally from the grid or photovoltaic (PV) sources to charging stations or households, creating operational challenges such as grid overload during peak periods, inefficient load balancing, and limited transparency in energy sourcing. To address these limitations, the mixed-reality metaverse, including cyber-physical systems, digital twins, and blockchain, is increasingly integrated into (renewable) energy and BMS to enable smart grid infrastructure (Cavalcante et al., 2023; Franco et al., 2023; Yazdanipour et al., 2024). These technologies support real-time, distributed energy coordination, allowing utility companies to transition from central dispatch models to autonomous, peer-coordinated energy routing.

In this reconfigured landscape, decentralised technologies do not merely enhance technical performance – they fundamentally reshape operational logic. TSOs continue to play a critical role in maintaining grid stability and managing energy transmission. However, decentralisation transforms their function from centralised controllers to collaborative grid coordinators, integrating decentralised energy resources and local nodes into hybrid systems. Energy suppliers (i.e., utility companies), traditionally positioned as intermediaries between generators and customers, face disintermediation. Their role may shift towards platform facilitation and data services, as blockchain-based systems enable direct energy transactions between generators and end users. They can utilise metaverse-based platforms such as Microsoft Mesh which create shared, real-time virtual replicas of the grid and substations integrated with decentralised mechanism such as smart-contract-enabled coordination, or real-time negotiation and DAOs in a virtual marketplace. In this environment, energy assets such as battery energy storage systems are digitalised within the metaverse platform, enabling all actors to visualise system states and interact with the grid in real time. Smart contracts automate the energy exchanges by validating asset identities, verifying available capacity, and executing transactions once agreed conditions are met with the support from DAOs in making collective decisions among stakeholders. Some decision-making processes can be included such as load balancing, energy arbitrage, peak shaving, or ancillary services. Hence, organisational boundaries will become more fluid. Generators (i.e., energy providers) can now store surplus energy and engage directly in EV charging markets, optimising revenue through dynamic pricing and smart contract-based trading. CNOs, once dependent on fixed infrastructure and centralised suppliers, now interact directly with generators through decentralised platforms. They benefit from transparent access to a broader range of energy suppliers, reducing dependency on dominant sellers and enhancing supply sustainability.

However, the metaverse's implementation faces some key barriers – pre-implementation security concerns and post-implementation workforce demands (Queiroz et al., 2023). The former arises as traditional intermediaries like TSOs lose control, increasing risks of unauthorised access and data manipulation. The latter, such as managing immersive interfaces and integrating decentralised systems, require specialised skills and infrastructure, which may limit scalability. A metaverse-enabled grid-to-station ecosystem offers a transformative solution to emerging risks in decentralised energy operations. In this future, we propose that TSOs, generators, energy providers, and CNOs can negotiate through AI avatars in a Virtual Power Plant – a spatial digital twin of the energy network – to simulate and manage distribution flows. The metaverse functions as an operational interface for real-time collaboration, allowing human and non-human agents to visualise grid performance, test alternative energy routing scenarios, and coordinate charging schedules within a shared 3D environment (Lyu and Fridenfolk, 2024). When embedded with Web3 infrastructure, each substation, charger, and storage node acts as an autonomous agent transacting energy through smart contracts, reducing reliance on vulnerable central authorities. The immersive environment fosters behavioural understanding and shares situational awareness, making decision-making safer and more intuitive. Moreover, the AI-driven metaverse can mitigate scalability challenges by offloading complex tasks such as predictive maintenance or dispatch coordination on behalf of human operators, mitigating cognitive overload and reducing risk exposure. This integration transforms energy management from a centralised control problem into a participatory, decentralised, and continuously learning ecosystem.

(2) Web3-enabled Charging Stations for Vehicles

A critical focus is on streamlining operations at charging stations, particularly through interconnected EVB systems, which require position- and time-sensitive coordination. From an operations management perspective, the imbalance in charging station utilisation – where some stations are overloaded while others remain underused – reflects an emerging issue in capacity planning and load balancing under centralised, siloed ownership structures. Traditional systems lack real-time interoperability among fragmented charging stations (Lv and Zhu, 2023), making it difficult for CNOs to forecast demand accurately or dynamically allocate capacity across the network. Web3-based blockchain technologies reconfigure this by enabling secure, decentralised data storing and sharing in digital warehouses (Amitasree and Yadav, 2023; Kakkar et al., 2024). This can facilitate the development of secure and efficient smart grids, supporting vehicle-to-grid models (Meghana et al., 2022; Wei et al., 2023).

Through blockchain-enabled Road Side Units (RSUs), real-time utilisation data is broadcast across the network and relayed to EVs, whose blockchain-integrated BMS autonomously schedule charging based on current load conditions (Danish et al., 2020). This transforms load balancing from a static, forecast-driven process into a demand-responsive and adaptive system, where smart contracts dynamically and autonomously reserve underutilised stations. Unlike traditional digitalisation methods, data from EV and charging stations can be tokenised into digital assets, stored off-chain, and linked to a blockchain via cryptographic hashes or pointers which helps protect the personal information. Web3-enabled tokenised data warehouses can also aggregate diagnostic and fault information across stations, enhancing operational visibility, maintenance planning, and throughput while reducing downtime. Charging stations then broadcast relevant information to RSUs, and EVs process this data to solve optimisation problems matching with their requirements, identifying the best-suited charging stations with minimal operational costs for both users and operators. Upon arrival at a charging station, an authentication mechanism verifies the EV: a random number generated by the tokenised data of an EV is decrypted by the EV's private key and compared to the original number at the reservation stage, ensuring secure vehicle-to-station authentication prior to charging. Finally, a payment function manages transactions between EVs and charging stations, automatically settling charges based on the time required to reach the desired state of charge. Bottlenecks are no longer addressed reactively but are anticipated and

mitigated algorithmically, as decentralised data flows allow for predictive load balancing and congestion avoidance.

Retired EVBs can further augment capacity planning and operations at charging stations. Evaluated for residual capacity (typically 70–80 %) and economic viability for secondary applications, they can serve as stationary storage to support circular economy integration in vehicle-to-grid systems (Aguilar Lopez et al., 2024; Hassan et al., 2023). A blockchainified buffer storage system based on spent EVBs, as proposed by Manoj Kumar & Chopra (2023), can provide auxiliary support during frequency fluctuations, enhancing grid stability. Integrating retired EVBs in this manner effectively increases the operational capacity of charging stations, turning otherwise idle batteries into active assets that smooth load, support renewable integration, and enhance overall system resilience.

Service level agreements are traditionally governed by centralised operators who control user authentication and payment processing. These processes rely on identity-based contracts and manual verification, often resulting in delays, limited transparency, and privacy risks. Users need to disclose personal data to access services, which exposes them to cybercriminals. Blockchain and Web3 technologies are reshaping service and financial operations in EVB charging ecosystems.

They enhance privacy by safeguarding personal information from exposure to charging station providers (AlJabri et al., 2019; Zhai et al., 2024). This redefines service operations, as service level agreements are now enforced through smart contracts that automatically execute and verify service terms – such as energy delivery, uptime. At the same time, decentralised identifier technology allows users to hide personal data, while usage and charging records are stored in tamper-proof blocks. These contracts ensure transparency, reduce service disputes, and enable programmable trust between users and providers. On the financial side, the secure transfer of digital tokens from user wallets to station wallets at the point of charging reflects a shift from traditional payment processing to decentralised financial operations (Ashfaq et al., 2020; Awais et al., 2022; Pustisek et al., 2016). This eliminates the need for centralised banks, reduces transaction latency, and enables real-time settlement based on dynamic pricing models.

The emergence of vehicle-to-vehicle (V2V) battery exchange, enabled by blockchain-based P2P energy trading and Web3 technologies, is beginning to reconfigure core operations in EV charging – particularly in inventory management, capacity planning, and decentralised coordination (Kakkar et al., 2024). Traditionally, battery availability and charging capacity are managed through centralised infrastructure, leading to bottlenecks, underutilised assets, and range anxiety due to uneven distribution. In contrast, blockchain-based crowdsourcing enables prosumers to dynamically exchange repurposed EVBs, especially with renewable energy (Grasso et al., 2019; Ibrahim et al., 2024), transforming batteries from static inventory held by operators into mobile, user-managed energy assets. Clustering algorithms group users based on location and energy needs, while matching algorithms optimise exchange logistics, effectively decentralising inventory visibility and allocation. Each EVB owner can have a unique decentralised identity verified by the consensus of genuine users, while each battery can be tokenised as non-fungible tokens (NFTs), both stored on-chain. Then, they broadcast their surplus or need of EVBs to RSUs, and smart contract can match owners themselves securely without relying on a central authority such as CNOs. When EVB owners meet and swap the physical batteries, smart contracts will go through multiple stages of communication and authentication through owners' secret keys (Das et al., 2023). Once the swapping is done, smart contracts will release the NFT representation from the sellers while trigger the payment to the buyers. This allows real-time and automated balancing of supply and demand across micro-locations, reducing the cost for centralised stockpiling and enabling just-in-time, just-in-place battery provisioning. Conventionally, pricing and profit are controlled by operators, who set fixed tariffs and manage infrastructure through hierarchical systems. Smart contracts can automate transactions at electricity market prices (Kaushal et al., 2023), shifting pricing authority from fixed tariffs to algorithmic consensus. Users can also monetise from their data through P2P verification and rewarding systems instead of contributing to the financial wealth of CNOs' platforms. Since the operators now play a platform provider role rather than a seller role, this disintermediation redistributes value creation and capture: prosumers become active market participants, monetising surplus energy or battery capacity directly, while transaction costs and privacy risks associated with centralised platforms are minimised.

Despite the operational benefits of Web3 in decentralising EVB charging supply chains, several technological and socio-environmental barriers remain. Web3 platforms often suffer from inefficiencies and latency due to energy-intensive consensus mechanisms like proof-of-work, which hinder real-time interoperability and scalability (Park et al., 2023). These limitations are particularly problematic for time-sensitive coordination between vehicles and charging stations. To address these barriers, we propose that every EV can become an autonomous economic agent, negotiating directly with energy providers through Web3-based smart contracts. Vehicles equipped with on-board AI avatars would effectively communicate their charging preferences, state-of-health, and carbon-intensity targets to nearby stations, which respond dynamically with optimal pricing and energy mix offers. These interactions occur seamlessly on decentralised platforms where transactions, settlements, and data sharing are automated and verifiable, eliminating traditional intermediaries. The system can scale naturally to millions of vehicles and stations that interoperate through common protocols rather than central schedulers. Moreover, such V2V energy exchange reduces systemic risk: demand surges or grid imbalances are mitigated through autonomous load redistribution. Over time, this vision could realise a self-organising energy marketplace where sustainability incentives, charging logistics, and customer experience coalesce into a unified Web3-native operations model. The result is a transparent, user-centric, and resilient EV charging ecosystem aligned with circular economy principles.

Table 3 summarises how EVB supply chain operations are transformed from traditional, centralised to decentralised, autonomous governance.

Table 3
Summary of the operational transformation from centralisation to decentralisation.

CLSCs	Target Operations	Traditional Operations	Decentralised Alternative	Fundamental Shift (RQ1)	Organisational Implications (RQ2)	Existing barriers	Visionary Web3 and Metaverse (RQ3)
EVB CLSC Operations	Sustainable Design, Manufacturing and EoL Diagnostics	<ul style="list-style-type: none"> • Tested under controlled lab conditions leading to static blueprinting product design and manufacturing processes. • Sequential EVB design and operations • Limited collaboration 	<ul style="list-style-type: none"> • Metaverse-enabled immersive design spaces • Digital twins-enabled on-vehicle battery management systems (BMS) 	<ul style="list-style-type: none"> • Concurrent EVB design and operations through new virtually collaborative operating model across departments, stakeholders and countries • Dynamic lifecycle integration 	<ul style="list-style-type: none"> • Faster and continuous quality improvement cycles • Knowledge exchange • Safe and sustainable by design enables the EVB CLSC, reducing EVB waste and critical raw material usage 	<ul style="list-style-type: none"> • Data requirements • Technical complexity • Immature infrastructure • Limiting scalability 	<ul style="list-style-type: none"> • AI-enhanced digital twins and metaverse act as autonomous design avatars co-creating product improvements across OEMs.
	Sustainable Procurement, Recycling and Waste Management	<ul style="list-style-type: none"> • Static forecasts and long lead times for procurement • Retired EVBs often discarded due to degradation, lack of certification, or inefficient recycling coordination to the upstream stages • Unmet target for metal recycling from EoL EVBs 	<ul style="list-style-type: none"> • Blockchain-based EVB traceability, authentication, and ownership transfer 	<ul style="list-style-type: none"> • Predictive and collaborative process • Cradle-to-cradle certification of EVB • From a cost-driven, supplier-centric function into sustainability-driven, network-coordinated a process • Waste management from a disposal activity into a strategic resource recovery operation 	<ul style="list-style-type: none"> • A closed-loop coordination between procurement and waste management systems • Elimination of recertification at the EoL stage, reducing costs and increasing speed • Automate the transfer of ownership across stakeholders 	<ul style="list-style-type: none"> • Limited Web3 adoption • Market uncertainty • New paradigms • Limited expertise 	<ul style="list-style-type: none"> • Web3-enabled unique digital identity ensures transparent value distribution to miners and recyclers. • Decentralised procurement DAOs automate supplier auditing and fair-trade verification.
EVB Circular Energy/Grid Operations	Grid to Charging Stations – Energy Distribution Management	<ul style="list-style-type: none"> • Centralised energy management schemes run by TSOs and energy providers • Grid overload during peak periods, inefficient load balancing 	<ul style="list-style-type: none"> • Mixed-reality metaverse, including cyber-physical systems, digital twins, and blockchain 	<ul style="list-style-type: none"> • From central dispatch models to autonomous, peer-coordinated energy routing • TSOs transform to collaborative grid coordinators • Energy suppliers face disintermediation, potentially transform to platform facilitation and data services • Generators and CNOs can directly deal with each other 	<ul style="list-style-type: none"> • Generators and CNOs can have a wider access to the competitive market • Faster supply–demand matching and lower operations costs 	<ul style="list-style-type: none"> • Early security concern • Limiting scalability 	<ul style="list-style-type: none"> • Immersive metaverse energy twins (e.g., Virtual Power Plant) synchronise distributed renewable assets and charging nodes. • AI avatars negotiate optimal flow distribution, creating a scalable, self-regulating, and circular service ecosystem.
	Charging Stations to Vehicles – Capacity planning, inventory management and service operations	<ul style="list-style-type: none"> • Centralised, siloed ownership structures in capacity planning and load balancing • Centralised authentication and payment processing • Range anxiety and limited charging stations 	<ul style="list-style-type: none"> • Blockchain-enabled roadside units • Web3 data warehouse • Web3-enabled blockchain platform • Web3-enabled V2V EVB exchange 	<ul style="list-style-type: none"> • Load balancing from a static, forecast-driven process into a demand-responsive and adaptive system • Dynamic capacity from spent EVBs • Payments through mutual consensus • Just-in-time and just-in-place 	<ul style="list-style-type: none"> • Provide auxiliary support during frequency fluctuations, enhancing grid stability • Secure payment and information sharing • Reduce the need for stockpiling energy and battery storage systems 	<ul style="list-style-type: none"> • Inefficiencies and latency due to energy-intensive consensus mechanisms • Limiting scalability 	<ul style="list-style-type: none"> • Vehicles and stations operate as autonomous Web3 agents, transacting energy, data, and carbon tokens through decentralised smart contracts. • AI avatars and Web3 contracts autonomously coordinate supply–demand balancing, enabling risk-free, participatory energy operations across prosumer networks.

4. Theoretical and managerial contributions

4.1. Theoretical contributions

This study advances theoretical understanding at the intersection of digital transformation, decentralised operations, and circular supply chains. First, we extend the TOE framework by addressing its limitations in capturing the dynamic interdependencies and sociotechnical coordination underpinning emerging decentralised technologies. To overcome these constraints, we introduce the Operational Decentralisation Framework, which integrates TOE with the LMA and dynamic capabilities, in the context of EVB CLSCs. This integration reframes TOE from a static adoption model into a diagnostic-to-transformational lens capable of explaining how technologies enable distributed coordination, data sovereignty, and adaptive learning across organisational boundaries.

Second, by operationalising the LMA within the technology dimension, we classify decentralised technologies across four interdependent layers (i.e., device, network, service, and content) and show how blockchain, digital twins, smart contracts, Web3, and metaverse infrastructures interact across them. This layered view clarifies how technological convergence transforms *the architecture of coordination* in EVB CLSCs: from linear information flows to decentralised, data-driven ecosystems where value creation and capture occur simultaneously across physical and digital domains (Dolgui and Ivanov, 2023; Queiroz et al., 2019).

Third, by applying the Operational Decentralisation Framework to the EVB CLSC context, we not only explore current decentralised practices across various EVB operations aspects – design, manufacturing, EoL diagnostics, procurement, waste management, load balancing, capacity planning, inventory management and service operations – but also reveal persistent research and practice gaps. That is fragmented adoption across lifecycle stages, limited reverse-logistics integration, and the absence of unified cross-layer platforms. Our results also show that many firms remain at a *digitalisation* rather than a *decentralisation* stage. Emerging technologies such as decentralised AI, Web3 coordination mechanisms, and immersive digital environments are beginning to address these gaps by enabling end-to-end visibility, distributed control, and multi-actor collaboration. These patterns point toward an evolving operational architecture that gradually links isolated applications into integrated decentralised ecosystems.

Fourth, we contribute to a *forward-looking theoretical discourse* by identifying current technological and environmental barriers, such as integration complexity, data standardisation, scalability, and regulatory uncertainty, that our proposed visionary Web3 and Metaverse systems can alleviate. The analysis of AI, Web3, and metaverse scenarios demonstrates how overcoming these barriers will shift operations theory toward concepts of distributed governance, tokenised collaboration, and adaptive orchestration. These offer new explanatory constructs for studying operations in decentralised ecosystems. These future-oriented scenarios help synthesise our theoretical arguments by connecting maturity progression with dynamic capability development and ecosystem readiness, thereby providing a unified theoretical basis for understanding how decentralised operations emerge and evolve within sustainable EVB CLSC.

4.2. Practical contributions

Our study also provides several actionable contributions for managers, policymakers, and ecosystem stakeholders in the EVB sector. First, the Operational Decentralisation Framework serves as a strategic instrument for assessing technological maturity and adoption readiness of decentralised solutions across the EVB CLSC. By mapping technology use across the layered modular architecture (device, network, service, and content), firms can diagnose current capabilities, pinpoint gaps, and prioritise investments that strengthen transparency, traceability, and resilience. Because the framework links technological, organisational, and environmental dimensions, it also helps managers recognise which operational routines (such as data-sharing, certification, or collaboration) must evolve as systems become decentralised. Our four Web3/Metaverse visions further translate this assessment into practical roadmaps, guiding firms from foundational digitisation to full decentralised integration while maintaining strategic alignment with sustainability goals.

Second, our cross-stage analysis demonstrates how decentralised technologies reconfigure operational coordination rather than merely automate existing processes. For instance, AI-enabled digital twins and Web3-based traceability systems create shared operational intelligence that allows manufacturers, recyclers, and regulators to act on the same verified procurement data. This supports more integrated and adaptive decision-making across production, reuse, and recycling, improving cross-actor coordination and accelerating circular value capture. Managers can use this evidence to design data-governance policies and collaborative protocols that preserve autonomy while enabling interoperability.

Third, by diagnosing adoption barriers, such as integration complexity, scalability limits, and regulatory uncertainty, the study offers concrete implementation guidance. Firms can mitigate these challenges by developing modular system architectures, adopting open interoperability standards, and investing in workforce capabilities that combine data analytics with governance literacy. For technology providers and ERP vendors, the findings indicate demand for platforms that support decentralised identity management, smart-contract interoperability, and circular-economy compliance. For policymakers, the results highlight the importance of creating sandbox environments and interoperability standards to foster responsible experimentation with decentralised coordination models.

5. Conclusions

As governments and industries worldwide commit to sustainability goals, the need for innovative technology solutions in the EVB sector to address numerous environmental, resource, and recycling challenges is greater than ever. This study contributes to the emerging body of knowledge by shedding light on the operational transformation of EVB CLSC from centralised to decentralised governance, enabled by decentralised technologies, particularly Web3 and the metaverse. In doing so, the findings reveal that

blockchain and digital twins already provide measurable operational value in enhancing traceability, transparency, and predictive control, while emerging technologies such as AI, Web3, and metaverse infrastructures are beginning to reshape coordination, decision-making, and stakeholder engagement. By applying the Operational Decentralisation Framework, we clarify the mechanisms through which these technologies collectively transition EVB operations from centralised oversight to distributed orchestration, bridging technological, organisational, and environmental dimensions. Finally, our feasibility assessment identified the key barriers, such as integration complexity, scalability limits, and regulatory uncertainty, hindering the implementation of Web3 and the metaverse, offering a grounded basis for future directions.

This study acknowledges certain limitations that open avenues for future research. While the study relies on large-scale secondary data and text data from previous literature and industry documents, future empirical research could further explore and validate the findings through case studies, interviews with industry practitioners, or real-world pilot projects. Future research should also examine how governance, interoperability, and human–AI collaboration evolve as decentralised technologies mature within real EVB ecosystems. By linking the Operational Decentralisation Framework to dynamic capability and distributed governance perspectives, subsequent studies can further test how firms' sense, seize, and transform under decentralised operating conditions. Despite existing adoption barriers, the present findings provide a robust conceptual foundation for both researchers and practitioners seeking to operationalise decentralised and circular EVB CLSCs.

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CRedit authorship contribution statement

Quang Huy Duong: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Carlos F.A. Arranz:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Mao Xu:** Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft, Methodology, Resources, Visualization. **Li Zhou:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Wenxian Sun:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tre.2025.104583>.

Data availability

Data will be made available on request.

References

- Adams, R.J., Smart, P., Huff, A.S., 2017. Shades of grey: guidelines for working with the grey literature in systematic reviews for management and organizational studies. *Int. J. Manag. Rev.* 19, 432–454. <https://doi.org/10.1111/IJMR.12102>.
- Aguilar Lopez, F., Lauinger, D., Vuille, F., Müller, D.B., 2024. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. *Nat. Commun.* 15, 4179. <https://doi.org/10.1038/s41467-024-48554-0>.
- Ahmadi, L., Young, S.B., Fowler, M., Fraser, R.A., Achachlouei, M.A., 2017. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* 22. <https://doi.org/10.1007/s11367-015-0959-7>.
- Alamerew, Y.A., Brissaud, D., 2020. Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: a case study on electric vehicle batteries. *J. Clean. Prod.* 254, 120025. <https://doi.org/10.1016/j.jclepro.2020.120025>.
- Alamin, K.S.S., Chen, Y., Macii, E., Poncino, M., Vinco, S., 2023. Digital Twins for Electric Vehicle SoX Battery Modeling: Status and Proposed Advancements, in: 2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE). IEEE, pp. 1–6. 10.23919/AEITAUTOMOTIVE58986.2023.10217251.
- Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C., Plepys, A., 2021. Circular business models for electric vehicle lithium-ion batteries: an analysis of current practices of vehicle manufacturers and policies in the EU. *Resour. Conserv. Recycl.* 172, 105658. <https://doi.org/10.1016/j.resconrec.2021.105658>.
- AlJabri, O., AlDhaheri, O., Mohammed, H., Alkaabi, A., Abdella, J., Shuaib, K., 2019. Facilitating Electric Vehicle Charging across the UAE using Blockchain. In: 2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA). IEEE, pp. 1–4. <https://doi.org/10.1109/ICECTA48151.2019.8959705>.
- Amitasree, P., Yadav, S., 2023. Smart fault monitoring in EVSE using blockchain technology. In: 2023 10th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON). IEEE, pp. 808–812. <https://doi.org/10.1109/UPCON59197.2023.10434645>.
- Antônio Rufino Júnior, C., Sanseverino, E.R., Gallo, P., Koch, D., Schweiger, H.-G., Zanin, H., 2022. Blockchain review for battery supply chain monitoring and battery trading. *Renew. Sustain. Energy Rev.* 157, 112078. <https://doi.org/10.1016/j.rser.2022.112078>.

- Ashfaq, T., Javaid, N., Javed, M.U., Imran, M., Haider, N., Nasser, N., 2020. Secure energy trading for electric vehicles using consortium blockchain and k-nearest neighbor. In: 2020 International Wireless Communications and Mobile Computing (IWCMC). IEEE, pp. 2235–2239. <https://doi.org/10.1109/IWCMC48107.2020.9148494>.
- Awais, M., Ahmad, A., Ahmad, S., Shoukat, A., 2022. Advanced billing architecture for charging of electric vehicles using blockchain. In: 2022 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP). IEEE, pp. 128–132. <https://doi.org/10.1109/ICT-PEP57242.2022.9988861>.
- Babich, V., Hilary, G., 2020. OM forum—distributed ledgers and operations: what operations management researchers should know about blockchain technology. *Manuf. Serv. Oper. Manag.* 22, 223–240. <https://doi.org/10.1287/msom.2018.0752>.
- Baker, J., 2012. *The Technology–Organization–Environment Framework*, 10.1007/978-1-4419-6108-2_12 231. Springer, New York, NY, p. 245.
- Banza, C.L.N., Nawrot, T.S., Haufroid, V., Decrée, S., De Putter, T., Smolders, E., Kabyla, B.I., Luboya, O.N., Ilunga, A.N., Mutombo, A.M., Nemery, B., 2009. High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environ. Res.* 109, 745–752. <https://doi.org/10.1016/j.envres.2009.04.012>.
- Bendoly, E., Oliva, R., 2024. Holding North: Recognizing identity and advancing contribution in operations management. *J. Oper. Manag.* 70, 518–522. <https://doi.org/10.1002/JOOM.1306>.
- Bernhart, W., 2019. Challenges and Opportunities in Lithium-ion Battery Supply, in: *Future Lithium-Ion Batteries*. The Royal Society of Chemistry, pp. 316–334. 10.1039/9781788016124-00316.
- Blei, D.M., Lafferty, J.D., 2006. Dynamic topic models. *ACM International Conference Proceeding Series* 148, 113–120. <https://doi.org/10.1145/1143844.1143859>.
- Bouckaert, S., Pales, A.F., McGlade, C., Remme, U., Wanner, B., Varro, L., D'Ambrosio, D., Spencer, T., 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector [WWW Document]. URL <https://trid.trb.org/View/1856381> (accessed 12.16.24).
- Branco, C.T.N.M., Fontanela, J.M., 2024. A design methodology to employ digital twins for remaining useful lifetime prediction in electric vehicle batteries, in: *SAE Technical Papers*. SAE International. 10.4271/2023-36-0132.
- Büyükközkcan, G., Göçer, F., 2018. Digital supply chain: literature review and a proposed framework for future research. *Comput. Ind.* 97. <https://doi.org/10.1016/j.compind.2018.02.010>.
- Capocasale, V., Bruni, M.E., Perboli, G., 2025. Technological insights on blockchain adoption: the electric vehicle supply chain use case. *Eur. J. Innov. Manag.* 28, 23–48. <https://doi.org/10.1108/EJIM-06-2024-0701>.
- Cavalcante, I., Júnior, J., Manzollí, J.A., Almeida, L., Pungo, M., Guzman, C.P., Morais, H., 2023. Electric vehicles charging using photovoltaic energy surplus: a framework based on blockchain. *Energies (Basel)* 16. <https://doi.org/10.3390/en16062694>.
- Centobelli, P., Cerchione, R., Esposito, E., Oropallo, E., 2021. Surfing blockchain wave, or drowning? Shaping the future of distributed ledgers and decentralized technologies. *Technol Forecast Soc Change* 165, 120463. <https://doi.org/10.1016/j.techfore.2020.120463>.
- Chae (Kevin), B., Olson, D., 2021. A topical exploration of the intellectual development of *decision sciences* 1975–2016. *Decis. Sci.* 52, 543–566. <https://doi.org/10.1111/decis.12326>.
- Chen, P.-K., Ye, Y., Huang, X., 2023. The metaverse in supply chain knowledge sharing and resilience contexts: an empirical investigation of factors affecting adoption and acceptance. *J. Innov. Knowl.* 8, 100446. <https://doi.org/10.1016/j.jik.2023.100446>.
- Chirumalla, K., Kulkov, I., Parida, V., Dahlquist, E., Johansson, G., Stefan, I., 2024. Enabling battery circularity: Unlocking circular business model archetypes and collaboration forms in the electric vehicle battery ecosystem. *Technol. Forecast Soc. Change* 199, 123044. <https://doi.org/10.1016/j.techfore.2023.123044>.
- Damar, M., 2021. *Metaverse shape of your life for future: a bibliometric snapshot*. *J. Metaverse* 1.
- Danish, S.M., Zhang, K., Jacobsen, H.-A., 2020. A blockchain-based privacy-preserving intelligent charging station selection for electric vehicles. In: 2020 IEEE International Conference on Blockchain and Cryptocurrency (ICBC). IEEE, pp. 1–3. <https://doi.org/10.1109/ICBC48266.2020.9169419>.
- Das, D., Banerjee, S., Chatterjee, P., Ghosh, U., Biswas, U., 2023. A secure blockchain enabled V2V communication system using smart contracts. *IEEE Trans. Intell. Transp. Syst.* 24, 4651–4660. <https://doi.org/10.1109/TITS.2022.3226626>.
- Davies, J., Sharifi, H., Lyons, A., Forster, R., Elsayed, O.K.S.M., 2024. Non-fungible tokens: the missing ingredient for sustainable supply chains in the metaverse age? *Transp. Res. E Logist. Transp. Rev.* 182, 103412. <https://doi.org/10.1016/j.tre.2024.103412>.
- Deng, C., Kim, A., Lu, W., 2022. A generic battery-cycling optimization framework with learned sampling and early stopping strategies. *Patterns* 3, 100531. <https://doi.org/10.1016/j.patter.2022.100531>.
- Dolgui, A., Ivanov, D., 2023. Metaverse supply chain and operations management. *Int. J. Prod. Res.* 61, 8179–8191. <https://doi.org/10.1080/00207543.2023.2240900>.
- Dolgui, A., Ivanov, D., Potryasaev, S., Sokolov, B., Ivanova, M., Werner, F., 2020. Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain. *Int. J. Prod. Res.* 58, 2184–2199. <https://doi.org/10.1080/00207543.2019.1627439>.
- Dutta, P., Choi, T.-M., Somani, S., Butala, R., 2020. Blockchain technology in supply chain operations: applications, challenges and research opportunities. *Transp. Res. E Logist. Transp. Rev.* 142, 102067. <https://doi.org/10.1016/j.tre.2020.102067>.
- Dwivedi, Y.K., Hughes, L., Baabdullah, A.M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M.M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C.M.K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D.P., Gustafsson, A., Hirsch, C., Jebabli, I., Janssen, M., Kim, Y.-G., Kim, J., Koos, S., Kreps, D., Kshetri, N., Kumar, V., Ooi, K.-B., Papagiannidis, S., Pappas, I.O., Polyviou, A., Park, S.-M., Pandey, N., Queiroz, M.M., Raman, R., Rauschnabel, P.A., Shirish, A., Sigala, M., Spanaki, K., Wei-Han Tan, G., Tiwari, M.K., Viglia, G., Wamba, S.F., 2022. Metaverse beyond the hype: multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *Int. J. Inf. Manag.* 66, 102542. <https://doi.org/10.1016/j.ijinfomgt.2022.102542>.
- Eaty, N.D.K.M., Bagade, P., 2023. Digital twin for electric vehicle battery management with incremental learning. *Expert Syst. Appl.* 229, 120444. <https://doi.org/10.1016/j.eswa.2023.120444>.
- European Parliament, 2022. New EU rules for more sustainable and ethical batteries | Topics | European Parliament [WWW Document]. European Parliament. URL <https://www.europarl.europa.eu/topics/en/article/20220228STO24218/new-eu-rules-for-more-sustainable-and-ethical-batteries> (accessed 6.9.25).
- Franco, A.A., Loup-Escande, E., Loiseaux, G., Chotard, J., Zapata-Dominguez, D., Ciger, J., Leclere, A., Denisart, L., Lelong, R., 2023. From battery manufacturing to smart grids: towards a metaverse for the energy sciences. *Batter. Supercaps* 6, e202200369. <https://doi.org/10.1002/batt.202200369>.
- Ghosh, A., Lavanya, Hassija, V., Chamola, V., Saddik, A. El, 2024. A Survey on Decentralized Metaverse using Blockchain and Web 3.0 technologies, Applications, and more. *IEEE Access*. 10.1109/ACCESS.2024.3469193.
- Gifford, S., 2022. Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century [WWW Document]. URL https://www.faraday.ac.uk/wp-content/uploads/2022/09/Faraday_Insights_6_Updated_Sept2022_FINAL.pdf (accessed 10.10.24).
- Govindan, K., Nasr, A.K., Saeed Heidary, M., Nosrati-Abarghoee, S., Mina, H., 2023. Prioritizing adoption barriers of platforms based on blockchain technology from balanced scorecard perspectives in healthcare industry: a structural approach. *Int. J. Prod. Res.* 61, 3512–3526. <https://doi.org/10.1080/00207543.2021.2013560>.
- Grasso, F., Talluri, G., Giorgi, A., Luchetta, A., Paolucci, L., 2019. Peer-to-peer energy exchanges model to optimize the integration of renewable energy sources: the e-cube project. *L'energia Elettrica* 96. <https://doi.org/10.36156/ENERGIA06.02>.
- Grootendorst, M., 2022. BERTopic: Neural topic modeling with a class-based TF-IDF procedure. 10.48550/arxiv.2203.05794.
- Gu, H., Liu, Z., Qing, Q., 2017. Optimal electric vehicle production strategy under subsidy and battery recycling. *Energy Policy* 109. <https://doi.org/10.1016/j.enpol.2017.07.043>.
- Guo, D., Mantravadi, S., 2024. The role of digital twins in lean supply chain management: review and research directions. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2024.2372655>.
- Han, Y., Fang, X., 2024. Systematic review of adopting blockchain in supply chain management: bibliometric analysis and theme discussion. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2023.2236241>.
- Hassan, A., Khan, S., Li, R., Su, W., Zhou, X., Wang, M., Wang, B., 2023. Second-life batteries: a review on power grid applications, degradation mechanisms, and power electronics interface architectures. *Batteries* 9, 571. <https://doi.org/10.3390/batteries9120571>.
- Huang, H., Lin, J., Zheng, Z., 2023. From Blockchain to Web3 & Metaverse, From Blockchain to Web3 & Metaverse. 10.1007/978-981-99-3648-9.

- Hylving, L., Schultze, U., 2020. Accomplishing the layered modular architecture in digital innovation: the case of the car's driver information module. *J. Strateg. Inf. Syst.* 29, 101621. <https://doi.org/10.1016/J.JSIS.2020.101621>.
- Ibrahim, Y., Mizouni, R., Otrok, H., Singh, S., Khadkikar, V., Zeineldin, H., 2024. Blockchain based crowdsourcing framework for Vehicle-to-Vehicle charging. *J. Netw. Comput. Appl.* 226, 103871. <https://doi.org/10.1016/j.jnca.2024.103871>.
- Ivanov, D., Dolgui, A., 2021. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control* 32, 775–788. <https://doi.org/10.1080/09537287.2020.1768450>.
- Ivanov, D., Dolgui, A., Das, A., Sokolov, B., 2019. Digital supply chain twins: managing the ripple effect, resilience, and disruption risks by data-driven optimization, simulation, and visibility. *Int. Ser. Oper. Res. Manage. Sci.* 309–332. https://doi.org/10.1007/978-3-030-14302-2_15.
- Jia, J., Chen, W., Wang, Z., Shi, L., Fu, S., 2024. Blockchain's role in operation strategy of power battery closed-loop supply chain. *Comput. Ind. Eng.* 198, 110742. <https://doi.org/10.1016/j.cie.2024.110742>.
- Kakkar, R., Chaudhary, S., Gupta, R., Tanwar, S., Kumar, S., 2024. Blockchain-based decentralized application for electric vehicle scheduling at charging station, in: *Proceedings of the 2024 ACM Southeast Conference on ZZZ*. ACM, New York, NY, USA, pp. 2–8. 10.1145/3603287.3651182.
- Kang, D.H.P., Chen, M., Ogunseitan, O.A., 2013. Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environ. Sci. Technol.* 47, 5495–5503. <https://doi.org/10.1021/es400614y>.
- Kaplan, A., Haenlein, M., 2024. To be or not to be: will virtual worlds and the metaverse gain lasting traction? *Calif. Manage. Rev.* 66, 5–22. <https://doi.org/10.1177/00081256241259188>.
- Kaushal, R.K., Jain, S., Shankar Rao, R.G., Thirumalaimuthu, B., Rawat, R., L, N., 2023. A Payment System for Electric Vehicles Charging and Peer-to-Peer Energy Trading, in: *2023 7th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)*. IEEE, pp. 984–991. 10.1109/I-SMAC58438.2023.10290505.
- Khan, Y., 2024. Volvo says users can track source of battery metals in its EVs [WWW document] (accessed 11.25.25). *Wall Street J.* <https://www.wsj.com/articles/volvo-says-users-can-track-source-of-battery-metals-in-its-evs-54f6e4f7>.
- Kleinberg, J., 2002. Bursty and hierarchical structure in streams, in: *Proceedings of the Eighth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining - KDD '02*. ACM Press, New York, New York, USA, p. 91. 10.1145/775060.775061.
- Kouhizadeh, M., Saberi, S., Sarkis, J., 2021. Blockchain technology and the sustainable supply chain: theoretically exploring adoption barriers. *Int. J. Prod. Econ.* 231. <https://doi.org/10.1016/j.ijpe.2020.107831>.
- Kumar, A., Liu, R., Shan, Z., 2020. Is Blockchain a silver bullet for supply chain management? Technical challenges and research opportunities. *Decis. Sci.* 51, 8–37. <https://doi.org/10.1111/deci.12396>.
- Lee, L.-H., Braud, T., Zhou, P.Y., Wang, L., Xu, D., Lin, Z., Kumar, A., Bermejo, C., Hui, P., 2024. All one needs to know about metaverse: a complete survey on technological singularity, virtual ecosystem, and research agenda. *Foundations and Trends® in Human-Computer Interaction* 18, 100–337. <https://doi.org/10.1561/1100000095>.
- Li, W., Cheng, R., Garg, A., Wang, N., Gao, L., 2024. Batteries boost the internet of everything: technologies and potential orientations in renewable energy sources, new energy vehicles, energy interconnection and transmission. *Sustain. Energy, Grids Networks* 37, 101273. <https://doi.org/10.1016/j.segan.2024.101273>.
- Li, J., Liu, F., Zhang, J.Z., Li, L., Ferreira, J., 2024a. Forward-reverse blockchain traceability: promoting electric vehicles with battery recycling in the presence of subsidy. *Ann. Oper. Res.* 1–28. <https://doi.org/10.1007/s10479-024-06108-z>.
- Li, W., Cheng, R., Garg, A., Wang, N., Gao, L., 2024b. Batteries boost the internet of everything: technologies and potential orientations in renewable energy sources, new energy vehicles, energy interconnection and transmission. *Sustainable Energy Grids Networks* 37, 101273. <https://doi.org/10.1016/j.segan.2024.101273>.
- Li, X., Wang, W., Jin, K., Gu, H., 2024c. A blockchain-enabled personalized charging system for electric vehicles. *Transp. Res. Part C Emerg. Technol.* 161, 104549. <https://doi.org/10.1016/j.trc.2024.104549>.
- Lin, H.F., 2014. Understanding the determinants of electronic supply chain management system adoption: using the technology-organization-environment framework. *Technol. Forecast Soc. Change* 86. <https://doi.org/10.1016/j.techfore.2013.09.001>.
- Lv, R., Zhu, S., 2023. Optimized recommendation of multiple types of charging stations for charging based on smart contracts. In: *2023 3rd International Conference on Intelligent Communications and Computing (ICC)*. IEEE, pp. 213–216. <https://doi.org/10.1109/ICCS9986.2023.10421094>.
- Lyu, Z., Fridenfolk, M., 2024. Digital twins for building industrial metaverse. *J. Adv. Res.* 66. <https://doi.org/10.1016/j.jare.2023.11.019>.
- Mahmood, S., Chadhar, M., Firmin, S., 2022. Cybersecurity challenges in blockchain technology: a scoping review. *Hum. Behav. Emerg. Technol.* 2022, 7384000. <https://doi.org/10.1155/2022/7384000>.
- Manoj Kumar, N., Chopra, S.S., 2023. Blockchain-assisted spent electric vehicle battery participation for load frequency control problems in interconnected power systems is resilient, low-carbon, and offers revenues to the operators. *Sustain. Energy Technol. Assess.* 57, 103209. <https://doi.org/10.1016/j.seta.2023.103209>.
- Mathivathanan, D., Mathiyazhagan, K., Rana, N.P., Khorana, S., Dwivedi, Y.K., 2021. Barriers to the adoption of blockchain technology in business supply chains: a total interpretive structural modelling (TISM) approach. *Int. J. Prod. Res.* 59. <https://doi.org/10.1080/00207543.2020.1868597>.
- Meghana, P., Yammani, C., Salkuti, S.R., 2022. Blockchain technology based decentralized energy management in multi-microgrids including electric vehicles. *J. Intell. Fuzzy Syst.* 42, 991–1002. <https://doi.org/10.3233/JIFS-189766>.
- Moors, C., 2023. Battery-makers turn to blockchain as sourcing rules get stricter – Circular CEO [WWW Document]. S&P Global. URL <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/battery-makers-turn-to-blockchain-as-sourcing-rules-get-stricter-8211-circular-ceo-74661967> (accessed 12.9.24).
- Mourtzis, D., Panopoulos, N., Angelopoulos, J., Wang, B., Wang, L., 2022. Human centric platforms for personalized value creation in metaverse. *J. Manuf. Syst.* 65, 653–659. <https://doi.org/10.1016/J.JMSY.2022.11.004>.
- Musule, A., Esparza, F.J., Neira-Tovar, L., Diaz, C., 2024. Enhancing Electromobility Component Training Through Mixed Reality: A Proposal Model, in: *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. Springer Science and Business Media Deutschland GmbH, pp. 358–367. 10.1007/978-3-031-60881-0_22.
- Needell, Z., Wei, W., Trancik, J.E., 2023. Strategies for beneficial electric vehicle charging to reduce peak electricity demand and store solar energy. *Cell Rep. Phys. Sci.* 4, 101287. <https://doi.org/10.1016/J.XCRP.2023.101287>.
- Nguyen, T., Duong, Q.H., Van Nguyen, T., Zhu, Y., Zhou, L., 2022. Knowledge mapping of digital twin and physical internet in supply chain management: a systematic literature review. *Int. J. Prod. Econ.* 244, 108381. <https://doi.org/10.1016/J.IJPE.2021.108381>.
- Oliveira, T., Martins, M.F., 2011. Literature review of information technology adoption models at firm level. *Electron. J. Inform. Syst. Eval.* 14, 110–121.
- Pan, S., Ballot, E., Huang, G.Q., Montreuil, B., 2017. Physical Internet and interconnected logistics services: research and applications. *Int. J. Prod. Res.* 55, 2603–2609. <https://doi.org/10.1080/00207543.2017.1302620>.
- Park, A., Wilson, M., Robson, K., Demetis, D., Kietzmann, J., 2023. Interoperability: our exciting and terrifying Web3 future. *Bus. Horiz.* 66, 529–541. <https://doi.org/10.1016/J.BUSHOR.2022.10.005>.
- Perboli, G., Merlo, F., Vandoni, C., 2025. Decentralizing the future: value creation in Web 3.0 and the metaverse. *Open Res. Europe* 5, 226. <https://doi.org/10.12688/OPENRESEUROPE.20906.1>.
- Pustisek, M., Kos, A., Sedlar, U., 2016. Blockchain based autonomous selection of electric vehicle charging station. In: *2016 International Conference on Identification, Information and Knowledge in the Internet of Things (IIKI)*. IEEE, pp. 217–222. <https://doi.org/10.1109/IIKI.2016.60>.
- Queiroz, M.M., Fosso Wamba, S., Pereira, S.C.F., Chiappetta Jabbour, C.J., 2023. The metaverse as a breakthrough for operations and supply chain management: implications and call for action. *Int. J. Oper. Prod. Manag.* 43, 1539–1553. <https://doi.org/10.1108/IJOPM-01-2023-0006>.
- Queiroz, M.M., Telles, R., Bonilla, S.H., 2019. Blockchain and supply chain management integration: a systematic review of the literature. *Supply Chain Manage.: Int. J.* 25, 241–254. <https://doi.org/10.1108/SCM-03-2018-0143>.
- Rajaeifar, M.A., Ghadimi, P., Rauguei, M., Wu, Y., Heidrich, O., 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries: a sustainability perspective. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2021.106144>.

- Rana, M.T., Numan, M., Yousif, M., Hussain, T., Khan, A.Z., Zhao, X., 2024. Enhancing sustainability in electric mobility: Exploring blockchain applications for secure EV charging and energy management. *Comput. Electr. Eng.* 119, 109503. <https://doi.org/10.1016/j.compeleceng.2024.109503>.
- Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., Amante García, B., 2019. Towards sustainable business models for electric vehicle battery second use: a critical review. *J. Environ. Manage.* 245, 432–446. <https://doi.org/10.1016/j.jenvman.2019.05.095>.
- Ritala, P., Ruokonen, M., Kostis, A., 2024. The metaverse flywheel: creating value across physical and virtual worlds. *Calif. Manage. Rev.* <https://doi.org/10.1177/0008125624125270>.
- Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L., 2019. Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* 57, 2117–2135. <https://doi.org/10.1080/00207543.2018.1533261>.
- Saravanan, S., Vijay, U., Tran, S., Mathew, M.M., Apostolova, D.Y., Gandarias, I., Leclere, A., Lelong, R., Franco, A.A., 2025. Metaverse for battery manufacturing: connecting students from different geographical locations to solve battery manufacturing problems in the virtual reality space. *Batter Supercaps* 2500098. <https://doi.org/10.1002/BATT.202500098>.
- Savaskan, R.C., Bhattacharya, S., Van Wassenhove, L.N., 2004. Closed-loop supply chain models with product remanufacturing. *Manag. Sci.* 50. <https://doi.org/10.1287/mnsc.1030.0186>.
- Schoenherr, T., 2009. Logistics and supply chain management applications within a global context: an overview. *J. Bus. Logist.* 30, 1–25. <https://doi.org/10.1002/j.2158-1592.2009.tb00109.x>.
- Singh, S., Weeber, M., Birke, K.P., 2021. Implementation of Battery Digital Twin: Approach, Functionalities and Benefits. *Batteries* 2021, Vol. 7, Page 78 7, 78. 10.3390/BATTERIES7040078.
- Sodhi, M.S., Seyedghorban, Z., Tahernejad, H., Samson, D., 2022. Why emerging supply chain technologies initially disappoint: blockchain, IoT, and AI. *Prod. Oper. Manag.* 31, 2517–2537. <https://doi.org/10.1111/poms.13694>.
- Stellantis, 2022. FIAT Metaverse Store, the world's first metaverse-powered showroom, a revolution in customer experience [WWW Document]. Stellantis. URL <https://www.media.stellantis.com/em-en/flat/press/flat-metaverse-store-the-world-s-first-metaverse-powered-showroom-a-revolution-in-customer-experience> (accessed 11.25.25).
- Tao, F., Qi, Q., Liu, A., Kusiak, A., 2018. Data-driven smart manufacturing. *J. Manuf. Syst.* 48. <https://doi.org/10.1016/j.jmsy.2018.01.006>.
- Teece, D.J., 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. *Strateg. Manag. J.* 28, 1319–1350. <https://doi.org/10.1002/smj.640>.
- Thierry, M., Salomon, M., van Nunen, J., van Wassenhove, L., 1995. Strategic issues in product recovery management. *Calif. Manage. Rev.* 37. <https://doi.org/10.2307/41165792>.
- Verhoef, P.C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Qi Dong, J., Fabian, N., Haenlein, M., 2021. Digital transformation: a multidisciplinary reflection and research agenda. *J. Bus. Res.* 122. <https://doi.org/10.1016/j.jbusres.2019.09.022>.
- Volvo Cars, 2019. Volvo Cars to implement blockchain traceability of cobalt used in electric car batteries [WWW Document]. Volvo Cars. URL <https://www.media.volvocars.com/global/en-gb/media/pressreleases/260242/volvo-cars-to-implement-blockchain-traceability-of-cobalt-used-in-electric-car-batteries> (accessed 12.16.24).
- Wagle, M., Agnihotri, A., Bhangale, P., Patare, A., Murali, M., 2023. Estimation of state of charge in electric vehicle using the battery digital twin. In: 2023 3rd International Conference on Intelligent Technologies (CONIT). IEEE, pp. 1–7. <https://doi.org/10.1109/CONIT59222.2023.10205542>.
- Wang, G., Zhang, Z., Nandhakumar, J., Manoharan, N., 2025. Everyday metaverse: the metaverse as an integral part of everyday life. *J. Manag. Inf. Syst.* 42, 310–342. <https://doi.org/10.1080/07421222.2025.2455772>.
- Wang, J., Zhu, C., Miao, C., Zhu, R., Zhang, X., Tang, Y., Huang, H., Gao, C., 2023. BPR: blockchain-enabled efficient and secure parking reservation framework with block size dynamic adjustment method. *IEEE Trans. Intell. Transp. Syst.* 24, 3555–3570. <https://doi.org/10.1109/TITS.2022.3222960>.
- Wang, W., Wang, J., Tian, J., Lu, J., Xiong, R., 2021. Application of digital twin in smart battery management systems. *Chin. J. Mech. Eng.* 34, 57. <https://doi.org/10.1186/s10033-021-00577-0>.
- Wang, Y., Han, J.H., Beynon-Davies, P., 2019. Understanding blockchain technology for future supply chains: a systematic literature review and research agenda. *Supply Chain Manage.: Int. J.* 24, 62–84. <https://doi.org/10.1108/SCM-03-2018-0148>.
- Wei, Y., Zhu, Y., Qin, Y., Li, Y., Wang, H., Han, X., Lu, L., Ouyang, M., 2023. A hierarchical framework for vehicle-to-grid (V2G) distributed control combining peer-to-peer blockchain with systemic scheduling. In: 2023 13th International Conference on Power and Energy Systems (ICPES). IEEE, pp. 436–441. <https://doi.org/10.1109/ICPES59999.2023.10400140>.
- White, C., Thompson, B., Swan, L.G., 2021. Comparative performance study of electric vehicle batteries repurposed for electricity grid energy arbitrage. *Appl. Energy* 288, 116637. <https://doi.org/10.1016/J.APENERGY.2021.116637>.
- Wrålsen, B., Prieto-Sandoval, V., Mejia-Villa, A., O'Born, R., Hellström, M., Faessler, B., 2021. Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers. *J. Clean. Prod.* 317, 128393. <https://doi.org/10.1016/j.jclepro.2021.128393>.
- Xu, S., Zhang, X., Feng, L., Yang, W., 2020. Disruption risks in supply chain management: a literature review based on bibliometric analysis. *Int. J. Prod. Res.* 58, 3508–3526. <https://doi.org/10.1080/00207543.2020.1717011>.
- Yadav, A.K., Shweta, Kumar, D., 2023. Blockchain technology and vaccine supply chain: exploration and analysis of the adoption barriers in the Indian context. *Int. J. Prod. Econ.* 255. <https://doi.org/10.1016/j.ijpe.2022.108716>.
- Yalcin, H., Daim, T.U., 2022. Logistics, supply chain management and technology research: an analysis on the axis of technology mining. *Transp. Res. E Logist. Transp. Res.* 168, 102943. <https://doi.org/10.1016/j.tre.2022.102943>.
- Yazdanipour, S., Arani, F.M., Jahromi, A.A., 2024. Investigating cyberattacks against off-grid solar-powered electric vehicle charging stations. In: 2024 IEEE/PES Transmission and Distribution Conference and Exposition (t&d). IEEE, pp. 1–5. <https://doi.org/10.1109/TD47997.2024.10556091>.
- Ying, H., Peng (David), X., Zhao, X., Chen, Z., 2023. The effects of signaling blockchain-based track and trace on consumer purchases: insights from a quasi-natural experiment. *Prod. Oper. Manag.* <https://doi.org/10.1111/poms.13968>.
- Yong, J.Y., Tan, W.S., Khorasany, M., Razzaghi, R., 2023. Electric vehicles destination charging: an overview of charging tariffs, business models and coordination strategies. *Renew. Sustain. Energy Rev.* 184, 113534. <https://doi.org/10.1016/J.RSER.2023.113534>.
- Yoo, Y., Henfridsson, O., Lyytinen, K., 2010. Research commentary — the new organizing logic of digital innovation: an agenda for information systems research. *Inf. Syst. Res.* 21, 724–735. <https://doi.org/10.1287/isre.1100.0322>.
- Zhai, D., Liu, J., Zhang, T., Wang, J., Du, H., Liu, T., Wang, T., Zhang, C., Kang, J., Niyato, D., 2024. EPDB: an efficient and privacy-preserving electric charging scheme in internet of robotic things. *IEEE Internet Things J.* 11, 32464–32477. <https://doi.org/10.1109/JIOT.2024.3426536>.
- Zhou, Q., Huang, H., Zheng, Z., Bian, J., 2020. Solutions to scalability of blockchain: a survey. *IEEE Access* 8, 16440–16455. <https://doi.org/10.1109/ACCESS.2020.2967218>.
- Zhou, X., Li, J., Li, F., Deng, X., 2023. Recycling supply chain mode of new energy vehicle power battery based on blockchain technology. *Comput. Integr. Manuf. Syst.* 29, 10.13196/j.cims.2023.04.029.