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Digital transformation for safer circular lithium-ion battery supply chains: a blockchain ecosystem-data perspective

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ABSTRACT

Lithium-ion battery (LIB) circular supply chains (CSCs) present unique safety challenges among operation processes. Blockchain technology can be a promising solution for addressing these challenges, by enabling effective tracking and verification of safety-related information throughout the supply chain. However, how blockchain can mitigate safety issues from a supply chain perspective is poorly understood. This study proposes a theory-supported framework through intervention-based research (IBR) to provide guidance for LIB CSC safety management. The conceptual framework and theoretical propositions set the foundation for research on a comprehensive blockchain ecosystem specifically designed for CSC safety management. The framework includes the design of a blockchain architecture with capabilities tailored to address safety concerns, the involvement of multiple stakeholders, and the development of a safety measurement matrix. This study suggests research and practical directions which lay the groundwork for leveraging blockchain technology to improve safety management in LIB CSC. This research contributes to sustainable supply chains by proposing a conceptual framework for mitigating safety concerns in LIB CSC, paving the way for effective blockchain implementation. In addition, this study contributes to advancing the theoretical design understanding and application of blockchain technology in CSC safety management.

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1. Introduction

Sustainability initiatives – such as renewable energy storage and low-emission electric vehicles – have led to increasing lithium-ion battery (LIB) demand. It has also led to a substantial increase in the number of spent lithium-ion batteries (LIBs), giving rise to significant environmental, social, and economic challenges (Harper et al. 2019). Circular supply chains (CSCs) (especially within a circular economy perspective) have emerged as a promising approach to address resource and sustainability challenges (Mossali et al. 2020). LIB CSCs have several hurdles, particularly with respect to safety concerns – where the issue has received scant scholarly attention.

The circular economy supports component and material recovery from spent LIBs and return to CSCs extending their lives through circular practices including reuse, remanufacturing, and recycling. Yet, we see stories of LIB safety issues in this process including electric vehicles exploding, spent LIBs catching fire and explosions during waste collection, explosions on the shop floor and in recycling facilities. Safety concerns in CSCs can lead to significant environmental issues, including the release of hazardous gases and waste, social issues such

as threats to human health and life safety, and substantial economic impacts. Improper practices among supply chain processes, such as mechanical damage, inappropriate storage, and transportation, are part of the causes and concerns associated with these events (Chen et al. 2021). These issues are prevalent throughout the supply chain including circular or closing-the-loop processes associated with a circular economy.

Safety issues within LIB CSCs encompass different processes, including transportation, storage, and recycling (Neumann et al. 2022). The complexity of CSCs, involving multiple stakeholders and managing vast amounts of dynamic multidimensional data, presents significant challenges in effectively addressing safety concerns (Harper et al. 2019). Current research is focused on the safety of battery components, LIBs, or products containing LIBs in supply chains. Increasingly complex LIB CSCs and interconnected organisations are calling for investigations of supply chain safety from an inter-organisational perspective (Gobbo et al. 2018). Blockchain technology has been proposed as a viable solution to mitigate these challenges for safety management (Koh, Orzes, and Jia 2019).

Blockchain technology has seen greater integration with circular economy and sustainable practices in current research (Pournader et al. 2020). Blockchain research has traditionally focused on practical perspectives. There is a greater need for theoretical development and foundation building to advance blockchain application for both scholarly and practical development across disciplines (Koh, Dolgui, and Sarkis 2020; Zhu, Bai, and Sarkis 2022). This study – guided by intervention-based research (IBR) (e.g. Chandrasekaran, de Treville, and Browning 2020) – seeks to bridge this gap by exploring the design of a blockchain ecosystem and introducing a theoretical framework based on safety management performance. The study investigates whether and how blockchain might efficiently and effectively mitigate safety concerns within LIB CSCs especially using shared data and performance measurement. We offer multiple theoretical propositions – some of which use various foundational theories including stakeholder, affordances, and relational view theories – to facilitate further exploration of blockchain technology in this context and with broader implications for similar sustainability concerns. This theoretical linkage and perspective address a gap that has seen limited theoretical advances in most blockchain and supply chain research (see Zhu, Bai, and Sarkis 2022).

In summary, this paper addresses a research gap concerning the application of blockchain technology for LIB circular supply chain (CSC) safety management. The study provides both theoretical and practical implications contributing to the understanding and advancement of blockchain performance measurement and evaluation applications in supply chains. The findings of this research can also contribute by significantly improving safety management in LIB CSCs, thereby promoting further adoption of sustainability technology and circular economy practices.

The research questions that we seek to answer in this study include:

RQ1. What critical elements exist in a blockchain framework for the safety management of circular supply chains?

RQ2. What relationships exist between blockchain-based performance measures and safety mitigation?

RQ3. What research is needed to further advance knowledge in this arena?

The remainder of the paper is organised as follows: Section 2 summarises the literature on LIB CSCs, safety management, blockchain technology, and its applications. Section 3 describes the architecture of the blockchain ecosystem for LIB CSCs safety management. Section 4 presents safety performance-based theoretical

considerations for the introduction of the blockchain ecosystem. Section 5 includes a discussion of research implications and practical implications. The conclusion is summarised in Section 6.

2. Background

We begin this section with a comprehensive overview of the literature on LIB CSCs, focusing on processes safety management performance measurement, and the applications of blockchain technology. This section shows how the research in this study contributes to our current understanding of these topics. By synthesising the current knowledge, this background sets the stage for development of a framework and model. It will also inform the later research directions and propositions appearing later in this paper.

2.1. Circular lithium-ion battery supply chains

LIB CSCs include forward supply chain flows, but also reverse (circular flows) including reuse, remanufacture, and recycling of spent batteries (Alamerew and Brisaud 2020). Reuse, remanufacture, and recycling circular practices, help to improve overall supply chain resource efficiency, fostering a more sustainable and efficient supply chain (Ciez and Whitacre 2019). LIB CSCs support an ecologically conscious and sustainable battery industry.

The LIB CSCs include battery manufacturing, distribution, use, spent battery collection, and recycling. However, this LIB CSCs process lacks standardisation, with limited established protocols or regulations governing its operations (Zeng, Li, and Liu 2015). CSCs and circular economy practices can be very manual and dangerous. Effectively managing each process to ensure safety can go a long way to overcome trepidation to adopt circular practices who view the practices unsafe. This safety issue is especially pertinent to the LIB CSCs.

The initial step in the reverse (closing-the-loop) phase of CSCs involves the collection of spent batteries (Jin et al. 2022). Batteries at this stage are classified based on condition and suitability for reuse, remanufacture, or recycling. Batteries in good condition and possessing a significant amount of residual capacity can find applications in second-life scenarios (re-use). These batteries can act as backup power for telecommunications or be employed as energy storage for renewable energy systems (Shahjalal et al. 2022). Batteries that are not suitable for second-life applications can undergo a recycling process (Mossali et al. 2020). This process involves disassembling the batteries into various components, including the anode, cathode, electrolyte, and casing (Ciez and Whitacre 2019). The subsequent processing and refining

of these materials reduce need for virgin resources, as the resulting metals and minerals can be utilised in the production of new batteries (Gaines 2018).

The LIB CSCs represents a highly complex system involving a diverse range of stakeholders, including manufacturers, suppliers, distributors, retailers, recyclers, and regulators. Each stakeholder assumes a role in ensuring the safety of the supply chain, with distinct responsibilities and obligations (Chen et al. 2022). The interactions between these stakeholders are often complex and dynamic, necessitating effective communication and collaboration to address safety concerns and facilitate the efficient flow of materials and information throughout the supply chain (Morsing and Schultz 2006). Later in this section, we return to this collaboration and communication issue by discussing how blockchain can serve as a facilitating technology. But initially we continue our discussion on safety and performance measurement and managing for the LIB CSCs.

2.2. Safety issues and performance measurement in circular lithium-ion battery supply chain

LIB CSCs offer various economic and environmental benefits, such as resource efficiency, waste reduction, and reduced reliance on virgin resources (Gupta et al. 2019). To realise these benefits, it is essential to adequately address safety concerns and identify safety management performance measurements to ensure the safe handling of batteries throughout their direct and end-of-life processing. We focus primarily on the spent battery stage.

LIB CSCs safety management includes various processes such as transportation, storage, and recycling (Neumann et al. 2022). The primary LIB CSCs process safety issues are risks of fire and explosion triggered by chemical, mechanical, social, or thermal factors (Chen et al. 2022). Considerable risks to LIBs occur due to their flammable electrolytes. These risks may result in thermal runaway, a situation where the battery can potentially explode or catch fire. Therefore, it is crucial to monitor and ensure the safe processing and operating of circular practices to mitigate the risk of fire and explosion incidents during LIB CSCs.

The presence of hazardous materials poses another safety concern in the LIB CSCs. LIBs contain dangerous substances including heavy metals, flammable electrolytes, and toxic compounds (Yang, Huang, and Lin 2022). The improper handling of these materials can pose risks to both the environment and workers involved – especially in end-of-life circular practices in the battery recycling process which are typically very manual (Mrozik et al. 2021). Regulations and industry standards

for spent batteries exist, and the following standards are critical to mitigating many hazards.

Cybersecurity threats pose to LIB CSCs activities, especially when handling sensitive safety-related information and data. The complex nature of supply chains involving multiple processes and stakeholders makes managing and protecting LIB data difficult. The data can include composition, activities, history, ambient context, battery performance, and details on supply chain stakeholders (Hua et al. 2020). To ensure the integrity and confidentiality of this data, robust security measures are needed to prevent unauthorised access or breaches.

Addressing these concerns can help ensure safe LIB CSCs. Robust performance measurements and metrics for various LIB CSCs stakeholders can support safe handling and processing of spent batteries – but also provide predictive and prescriptive management solutions. After all, the saying that you cannot manage what you cannot measure has its basis in scientific management.

Performance measurement is vital for effective supply chain management (Arzu Akyuz and Erman Erkan 2010). Both quantitative and qualitative performance measurements can be utilised to evaluate the performance of supply chain processes, including safety management (Gunasekaran, Patel, and Tirtiroglu 2001). Quantitative performance measurements can measure the frequency and severity of safety incidents or track compliance with safety regulations (Beamon 1999). Qualitative performance measurements include subjective and intangible measures based on such items as stakeholder perceptions or the quality of safety training.

Safety management performance of LIB CSCs using quantitative and qualitative performance measurements provides a more holistic picture. Performance measures help identify supply chain safety risks where they are prevalent – supporting targeted safety interventions (Aikhuele 2020). Measures can provide feedback on safety strategy effectiveness – allowing for adjustments to improve safety outcomes (Jiang et al. 2022). Performance measurements provide transparency and accountability to stakeholders in the organisation and its safety management activities (Rotheroe and Richards 2007). Safety performance measures and management mitigate safety challenges.

We identify four performance measurement categories from the literature, that are utilised in this study of safety management in the LIB CSCs. These four categories include: incident and risk management, transparency, knowledge and collaboration, and regulation compliance performance measures.

Incident and risk management performance incorporates both the type of incident and risk factor characteristics (Sarkheil 2021). LIB CSCs have multiple stages, each

with a set of unique and overlapping risks and challenges. These challenges and risks include fire, explosion, leakage, and environmental hazards (Escobar-Hernandez et al. 2016). Measurements may include the number of safety incidents, incident severity, incident response time, and broadly risk management strategy effectiveness (Leveson 2015). Robust incident and risk management reporting strategies allow organisations and stakeholders to proactively prevent or mitigate safety incidents.

Transparency (and access to data) in safety-related data management practices is important from multiple stakeholder perspectives. Managing CSCs safety usually means dynamic and multi-dimensional data factors (Chen et al. 2022). General transparency measurement includes data accuracy and completeness, accessibility and timeliness of data, and data sharing and communication performance amongst stakeholders. By systematically measuring and analysing data and transparency performance, organisations can refine their data management strategies, enhance communication channels, foster trust among stakeholders, and ultimately bolster the safety practices employed within the LIB CSCs.

Safety-related *knowledge and collaboration performance* among stakeholders is critical for ensuring safety (Burke et al. 2002). Knowledge and collaboration measures can include the level of stakeholder engagement and participation, and the quality and relevance of the knowledge shared among stakeholders (Zaunbrecher and O'Donnell 2020). Measuring and analysing knowledge and collaboration performance allows organisations to develop innovative solutions facing multiple actors.

Regulatory compliance performance has dimensions related to meeting safety standards, liability, and mandatory requirements as examples (Clarke 2006). Regulatory performance measurement primarily evaluates how well a supply chain process adheres to the relevant regulatory requirements and industry standards (Griffin and Neal 2000). Compliance with standards is based on various research studies especially related to the handling, transportation, and disposal of spent batteries. Non-compliance may lead to penalties, fines, and damage to a company's reputation – these monetary and punitive damages can be measures to track strategic performance of actors in the supply chain. The measurement of compliance and regulatory performance is essential for both internal organisational and external stakeholder management (Hervani, Helms, and Sarkis 2005).

These measures are focused on safety issues and concerns. Clearly, they are meant to complement broader business, environmental, and social performance measures. We include these as important and somewhat unique to safety concerns. The measures can include a variety of other dimensions not listed, for example the

number of injuries or property losses may fit into the first category of incidents. The second category may include the cost or efficiency of managing transparency, not only access and accuracy. Each category only offers exemplary measures; additional measures can be developed for LIB, but can also be used for other risky materials including hazardous or explosive wastes such as hydrogen supply chains (e.g. Tugnoli, Landucci, and Cozzani 2009). Additional safety performance measures and characteristic categories and issues do exist, but many are specific to an organisation or industry – some do overlap with our categories (e.g. Louvar 2010; Stricoff 2000). Given variations in different supply chains, materials, and activities, as well as the multi-stakeholder context of LIB CSCs, having a clear and identified set of performance measures is still needed. We now discuss blockchain technology, which can help performance measure management for a complex multi-stakeholder environment.

2.3. Blockchain technology and its applications

This section provides a review of blockchain technology and its applications focusing specifically on its relevance to CSCs. We identify benefits, challenges, and opportunities for blockchain technology and its potential for addressing safety issues in the LIB CSCs.

2.3.1. Blockchain technology

Blockchain technology is a decentralised and distributed digital ledger that ensures secure and transparent transaction recording (Sabeti et al. 2019). Unlike traditional information systems managed by a central authority, blockchain is maintained across a network of computers, with each transaction being added to the blockchain in an immutable and permanent manner after undergoing verification by a network of nodes (Nofer et al. 2017).

Blockchain technology can support managing safety-related data and transactions securely and transparently across the LIB CSCs. Its decentralised nature supports distributed governance for various data or transactions across the supply chain (Zwitter and Hazenberg 2020). A complete ledger is replicated across multiple nodes in the network, and transactions are verified and recorded through a consensus mechanism – fostering accountability and trust (Chen et al. 2018).

Blockchain can support data transparency since transactions are made visible to all network users – various stakeholders in the LIB CSCs. This transparency enhances accountability and minimises the potential for data misrepresentation or manipulation (Hastig and Sodhi 2020).

Once a transaction is recorded on the blockchain, it cannot be altered or deleted – an immutability of data.

This immutability is achieved through the cryptographic hashing of each block, forming a chain that is highly resistant to tampering (Rajasekaran, Azees, and Al-Turjman 2022).

Blockchain is designed with robust security measures, leveraging advanced cryptography and consensus algorithms to protect against unauthorised access, fraud, and other security risks (Wang et al. 2018b). Its decentralised architecture also reduces vulnerability to attacks by eliminating a single point of failure (Zwitter and Hazenberg 2020).

The incentivization mechanism (e.g. tokenization) of blockchain technology is a significant driver for user participation in safety management (Saberi et al. 2019). Stakeholders can be incentivized using tokens and rewards. Incentives are usually based on cryptography and smart contracts that ensure the security and trustworthiness of transactions and rewards between participants (Wankmüller et al. 2023). This incentivization encourages stakeholders to act in the network's best interests, ensuring the goal of safety mitigation. For example, observers may be incentivized to provide information and observations on providing data including access and regular updates as rewards. Additionally, this feature can be leveraged to promote other behaviours and initiatives, such as waste reduction and sustainability, making blockchain a powerful tool for advancing social and environmental goals. An additional exposition on incentivization appears later.

Lastly, smart contracts enhance the capabilities of blockchain technology by enabling automated transactions and complex operations (Macrinici, Cartoceanu, and Gao 2018). These self-executing algorithms operate on the blockchain, facilitating safety certification issue rule enforcement, and other aspects of agreements or business processes.

The distinctive features of blockchain technology position it as a valuable instrument for secure, transparent, and efficient data and transaction management. Its decentralised nature, transparency, immutability, security measures, incentivization mechanisms, and smart contract functionality collectively contribute to its transformative potential in various domains.

2.3.2. Application of blockchain technology

Blockchain technology has gained significant attention in recent years due to its set of capabilities with applications in finance (Gorkhali and Chowdhury 2022), healthcare (Mettler 2016), voting systems (Huang et al. 2021), and transport and logistics (Koh, Dolgui, and Sarkis 2020; Pournader et al. 2020), among others.

Table 1 summarises potential applications of blockchain in supply chain management and helps position our study. Various studies have explored and discussed the potential benefits and use cases of blockchain technology within the supply chain domain (Saberi et al. 2019; Zhu, Bai, and Sarkis 2022). For instance, some researchers have examined the role of blockchain in addressing food traceability issues in the supply chain, highlighting the benefits of using blockchain to ensure transparency and accountability (Baralla et al. 2021). Other studies have demonstrated the potential of blockchain to enhance supply chain sustainability by promoting end-of-life product management and waste reduction (Grati et al. 2023; Gupta and Bedi 2018). In addition, studies can investigate specific capabilities of blockchain, such as smart contracts, to improve supply chain models (Dolgui et al. 2020; Manimuthu et al. 2022).

While existing research has explored the application of blockchain technology in the LIB supply chain with a specific focus on reuse, remanufacture, and recycling (Ribeiro da Silva et al. 2023; Tripathy et al. 2023), and there are some studies that mention battery safety (Antônio Rufino Júnior et al. 2022), limited attention has been given to the use of blockchain for safety management from a circular supply chain process perspective.

In addition, there is a scarcity of studies that examine the theoretical foundations supporting the implementation of blockchain in supply chain processes. For example, Koh, Orzes, and Jia (2019) propose that researchers should develop a common set of constructs through qualitative theory building to support further theory development and theory testing efforts in technology application in the operation and supply chain domain. Koh, Dolgui, and Sarkis (2020) noted that successful implementation of blockchain technology in logistics and transport still requires theory to understand and explain. Through a literature review on the application of blockchain technology in the supply chain domain (Zhu, Bai, and Sarkis 2022) found that existing research lacks comprehensive theoretical development and theoretical applications. And they pointed out the need for more research from a theoretical perspective to help build a rigorous understanding and manage the practical adoption of blockchain technology in supply chain management. The IBR framework that integrates multiple theories can be a good study design to help build this theory and theoretical knowledge for blockchain management.

Our study aims to contribute to the literature by investigating the effectiveness of blockchain-based safety management in the LIB CSCs – with a focus on performance measurement and management. In contrast to existing literature that primarily emphasises practical implementations, this research places significant

Table 1. Literature review of blockchain applications and positioning of this study.

Authors	Industry/Section	Safety		Circular supply chain			Theory
		Product	Process	Reuse	Remanufacture	Recycle	
Dolgui et al. (2020)	–	–	–	–	–	–	✓
Manimuthu et al. (2022)	Automotive	–	–	–	–	–	–
Pournader et al. (2020)	Transport and Logistics	✓	–	–	–	–	–
Centobelli et al. (2022)	–	–	–	–	✓	✓	–
Saberi et al. (2019)	–	✓	–	–	–	✓	✓
Zhu, Bai, and Sarkis (2022)	–	–	–	–	–	–	✓
Tse et al. (2017)	Food	✓	–	–	–	–	✓
Baralla et al. (2021)	Food	✓	–	–	–	–	–
Koh, Dolgui, and Sarkis (2020)	Transport and logistics	–	–	–	–	✓	✓
Grati et al. (2023)	Automotive	–	–	✓	✓	✓	–
Gupta and Bedi (2018)	E-waste	–	–	✓	–	✓	–
França et al. (2020)	–	–	–	–	–	✓	–
Cheng et al. (2022)	Battery	✓	–	✓	–	✓	–
Ribeiro da Silva et al. (2023)	Battery	–	–	✓	✓	✓	–
Tripathy et al. (2023)	Lithium-ion battery	–	–	✓	–	✓	–
Antônio Rufino Júnior et al. (2022)	Lithium-ion battery	✓	–	✓	✓	✓	–
Koh, Orzes, and Jia (2019)	–	–	✓	–	–	–	✓
This Study	Lithium-ion battery	✓	✓	✓	✓	✓	✓

emphasis on theoretical considerations and explores how blockchain can enhance safety management performance. The theoretical and conceptual development in this study seeks to provide a comprehensive understanding of how blockchain technology and performance measurement can contribute to safer LIB CSCs.

3. Blockchain ecosystem for safety management

We now introduce a conceptual blockchain-based safety management ecosystem for LIB CSCs. The system, depicted in Figure 1, incorporates both forward and reverse supply chain processes and actors, key internal stakeholders such as raw material suppliers, LIB manufacturers, distributors, consumers, and recyclers. External stakeholders are also exemplified by regulators but can also include NGOs, communities, and standards organisations.

The blockchain ecosystem architecture consists of several components, including data acquisition, an oracle network, smart contracts, and a decentralised storage system, as illustrated in Figure 1. These components collaborate to uphold data integrity, transparency, and accountability throughout CSCs. The design of this ecosystem and its artefacts is informed by a number of sources, (e.g. Omar et al. 2021; Panwar and Bhatnagar 2020; Yadav et al. 2023), practical observation from practice, and secondary datasets such as OSHA¹ and UL,² more descriptions and relationships of these and other foundational reference sources appear in section 3.2).

The adoption of blockchain technology in CSC safety management offers several advantages. It enables the establishment of a reliable and accurate record of safety-related data across the entire lifecycle of LIB, from

raw material extraction to disposal or recycling. Secondly, blockchain facilitates interaction and data sharing among stakeholders, enhances visibility, cultivates reactions to safety issues among the entire supply chain network, promotes flexible collaboration (Gianakakis, Spanaki, and Dubey 2019), and further fosters the development of new business models and value networks that drive circular economy – and broader sustainability – advancement (Zhu, Bai, and Sarkis 2022). Additionally, by utilising smart contracts and tokenization, blockchain enhances the automation and efficiency of supply chain management, motivating a more circular and sustainable supply chain. Ultimately, the blockchain architecture has the potential to greatly enhance the LIB CSCs, promoting transparency, traceability, responsiveness, and ethical practices while providing greater inclusiveness into corporate safety concerns.

3.1. Participant stakeholders and performance data

This section highlights the key stakeholders within the blockchain ecosystem for the LIB CSCs. These stakeholders include raw material suppliers, LIB manufacturers, EV manufacturers, distributors, users, certified spent battery collectors, reuses, remanufacturers, recyclers, disposers, regulatory bodies, and data storage systems providers. By incorporating multi-stakeholder participation, the blockchain ecosystem supports comprehensive safety management performance measures, planning, governance, incentivization, learning, and improvement throughout the supply chain (Speklé and Verbeeten 2014).

Furthermore, this section delves into the various types of potential performance and other data requirements

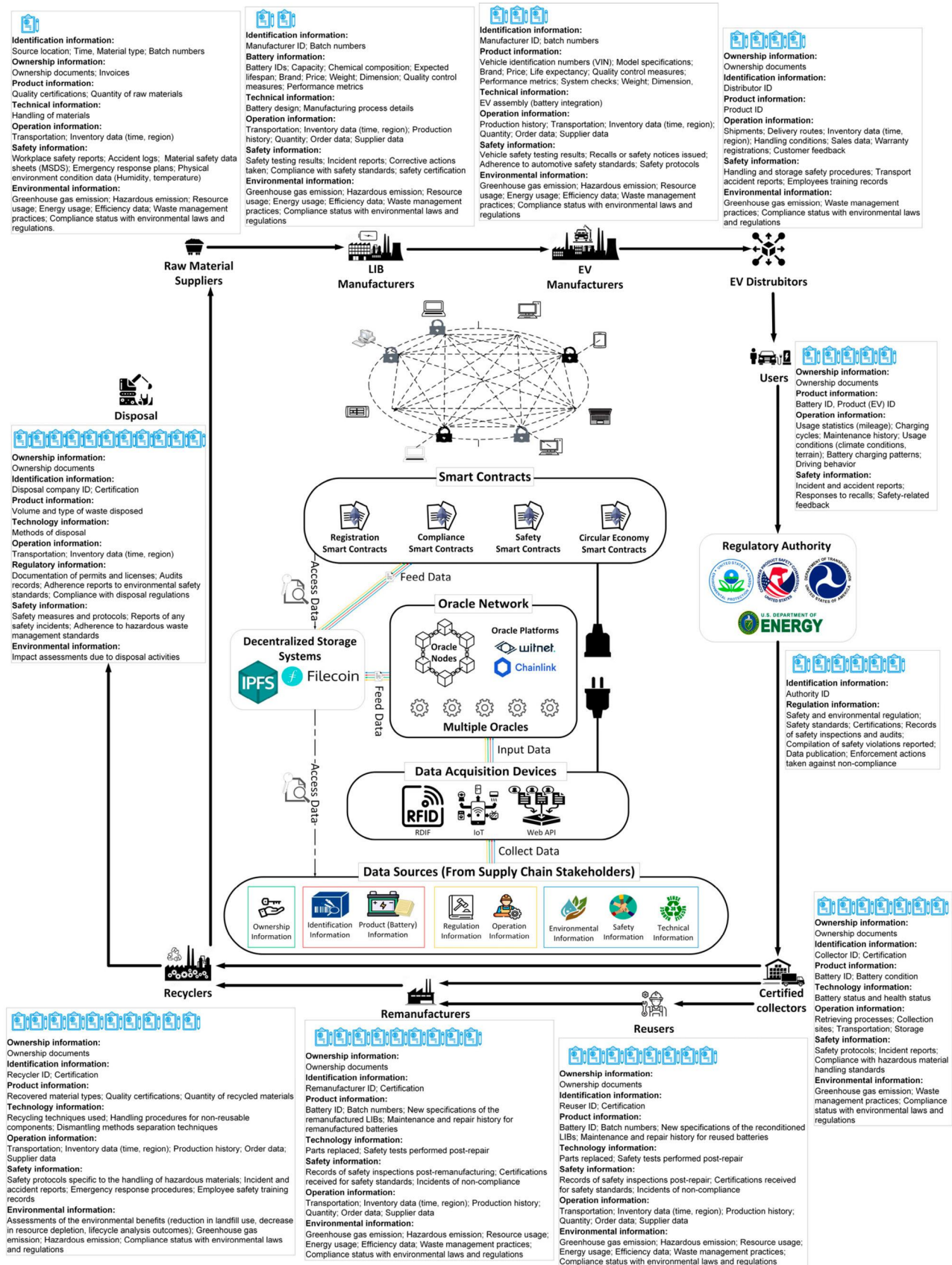


Figure 1. Blockchain-based safety management of circular lithium-ion battery supply chain.

that can be acquired from each stakeholder by data acquisition devices and oracle network into the blockchain system – data can also be accessed and used by various stakeholders in multiple ways. The blockchain integration significantly enhances the safety management capabilities of the system – towards a complete and more advanced *netocracy* for performance measurement (Bititci et al. 2012).

Raw material suppliers play a crucial role in LIB supply chains by providing the necessary raw materials for battery production (Olivetti et al. 2017). They ensure product safety by supplying safety-related data, including source, material quality and quantity, and material safety data to downstream stakeholders (see Figure 1). This information supports assessing the safety risks associated with raw materials for LIB production.

LIB manufacturers are responsible for battery production that meets safety and performance standards (Sharma 2024). They provide safety-related data on battery composition, production processes, quality control measures, and battery performance during use (Liu et al. 2021). Manufacturers must track battery performance, detect, and report safety issues or defects, and ensure compliance with safety standards. Sharing this information to consumers, regulators, and original equipment manufacturers (OEMs) supports safety improvements in the LIB CSCs.

EV manufacturers (as an OEM exemplar) utilise LIBs to power their vehicles. They are responsible for designing vehicles to handle the power requirements and potential hazards of LIBs. EV manufacturers implement safety features, such as thermal management systems to prevent LIB overheating and thermal runaway. They also collect safety-related data from their vehicles, including battery life expectancy data, which informs future improvements and maintenance. This data is valuable for monitoring and detecting safety issues during the useful life of LIBs and ensuring their proper disposal or recycling at the end of their life cycle.

EV distributors (as are distributors of other LIB products such as electronic tablets) are involved in transporting and storing batteries within the supply chain. Transport and storage present safety risks in logistics. These stakeholders collect and analyse safety-related performance and other data, such as delivery routes, inventory data, modes of transportation, and packaging materials, to ensure the safe delivery of LIBs.

Users, as end consumers of EVs and LIB containing products and materials, also have a significant role in safety management (Chen et al. 2022). They provide safety-related performance data on incidents and the context of incidents, usage statistics, charging cycles, and maintenance records, which is crucial for assessing

safety risks and potential hazards associated with battery use, ensuring the safe operation of EVs, and informing the development of safer and more sustainable products.

After the end-of-life or materials or product use closing-the-loop activities initiate, one of the first stakeholders are *certified collectors*. Certified collectors are responsible for collecting spent batteries from users and providing them for reuse, remanufacture, or recycling (Chen et al. 2023). The need to comply with regulatory requirements and safety standards during the collection, handling, and transportation of spent batteries. Safety-related performance data provided by collectors includes information on collection locations, transportation routes, and methods of handling and storing spent batteries to prevent incidents or accidents.

The *reuse* of spent batteries – and organisations involved in managing reuse such as resellers – involve assessing their remaining capacity and suitability for second-life applications (Montes et al. 2022). Safety-related performance data for reused batteries includes information on their condition, age, history of use, and potential safety risks. Proper safety management of reused batteries ensures user safety and prevents accidents or failures.

Remanufacturers extend the useful life of batteries, reducing waste and conserving resources (Hua et al. 2020). Safety-related performance data for remanufacturing includes tracking the quality and safety of restored components and ensuring compliance with safety regulations and standards. Data on the condition and performance of remanufactured batteries informs decisions regarding their reuse or disposal.

Recyclers are responsible for safely and efficiently recovering valuable materials from spent batteries (Neumann et al. 2022). They manage the hazardous materials contained in spent batteries to minimise harm to human health and the environment. Safety-related performance data in the recycling stage includes information on storage, handling, and the recycling process. Details such as the type and quantity of materials recovered, recycling methods used, and environmental impacts are included in this data.

Disposal is the final stage in a battery's lifecycle, where it is safely disposed of when it can no longer be used or recycled (Heelan et al. 2016). Proper disposal involves tracking and managing the process, including handling and transportation to appropriate facilities, compliance with regulations, and reporting of incidents or accidents. Safety-related performance and general data in this context include information on battery condition, disposal location, and any incidents or accidents that occur during the disposal process.

Regulatory authorities, such as the U.S. Department of Energy, Environmental Protection Agency (EPA), and Department of Transportation, play a significant role in the safety management of the LIB CSCs (Nævestad, Hesjenvoll, and Elvik 2021). They enforce safety regulations, ensure compliance with environmental standards, issue safety-related certifications, and monitor safety-related data to minimise risks associated with LIB CSCs. Regulatory policies tend to vary, for example, the EPA does not consider LIB reuse options as solid waste flows (Hoskinson 2023). Their involvement helps maintain the integrity and safety of the entire supply chain.

In conclusion, effective management of stakeholders and their interconnectedness within the LIB CSCs is a fundamental aspect of the conceptual blockchain ecosystem summarised in Figure 1. Moreover, performance and other data can be categorised into four key areas represented as four lines in Figure 1: ownership transform information (green), identification information and product or battery details (red), regulatory and operational information (yellow), and environmental, safety, and technical information (blue). Handling these multi-dimensional data connections is equally critical in this context. Addressing development of robust blockchain architectures capable of addressing these complex challenges is imperative to ensure the seamless and safety management of the LIB CSCs.

3.2. Blockchain architecture design

Guided by IBR, this architecture and its elements are considered as artefacts for blockchain integration. In this case we use conceptual and descriptive knowledge dimensions of IBR to define these artefacts within the blockchain ecosystem (see Iivari 2007) – which also sets the stage for future research. Blockchain architecture refers to the design and structure of a blockchain network and encompasses component and protocol artefacts (Zheng et al. 2017). It defines how data is stored, transactions are validated and added to the ledger, and consensus is achieved among the network participants. A well-designed blockchain architecture should consider factors such as scalability, security, decentralisation, efficiency, and incentivization (Latif et al. 2021).

Figure 1 depicts the proposed blockchain architecture, specifically designed to enhance safety management within LIB CSCs. This architecture has been meticulously developed (see references below in the description), considering the distinct components of the supply chain, and its comprehensive description is provided in this section. By examining each element, the proposed blockchain architecture aims to establish a robust framework that

effectively addresses safety concerns throughout LIB CSCs.

In the blockchain architecture for safety management of LIB CSCs, the *distributed ledger* serves as a decentralised database that securely records safety-related data (Panwar and Bhatnagar 2020). This architecture can reduce the dependency on intermediaries (e.g. third-party audits) and improve traceability and transparency – attributes that are critical to support strict adherence to safety standards, in an accountable CSC ecosystem.

Nodes, which are devices storing a copy of the ledger, play a critical role in increasing transparency and traceability, maintaining the security and decentralisation of the blockchain network, verifying transactions, and participating in the consensus process (Yadav, Agrawal, and Kushwaha 2022). The immutable and time-stamped records maintained by nodes facilitate compliance with regulatory requirements, which is critical in safety management. In addition, to address scalability and efficiency issues, this blockchain ecosystem design recommends a hybrid setup that combines different types of nodes – full nodes, which store the entire blockchain and validate transactions and blocks; ‘light’ nodes, which only download part of the blockchain for simple transactions; and mining nodes, which also validate and add new blocks to the blockchain in systems (Taherpour and Wang 2024). This node structure allows for broader participation in the blockchain CSC safety management system. For example, smaller stakeholders such as small battery collectors, who may not be able to exert much influence in traditional centralised systems, can operate a light node in consensus process, thereby democratising the safety data verification process (Taherpour and Wang 2024).

In addition, the *type of blockchain* (e.g. public, private, and consortium blockchains) shapes how stakeholders interact with the system, influencing their rights, governance, and trust in the architecture (Toufaily, Zalan, and Dhaou 2021). The optimal blockchain model should be chosen based on specific needs for transparency, control, and collaboration among participants. Public blockchains are decentralised and open, allowing anyone to participate and contribute to the consensus process. These characteristics may ensure transparency and security but suffer from slower transaction speeds – affecting efficiency (Sabeti et al. 2019). A private blockchain is governed by a single organisation or a select group of entities.

Private blockchains typically provide faster transactions and scalability, crucial for managing sensitive data. However, their centralised nature may limit transparency for safety purposes (Sabeti et al. 2019). Consortium blockchain platforms operated by a group of

organisations, blend elements of decentralisation with controlled access (Manupati et al. 2020). This model is effective for the proposed blockchain ecosystem for LIB CSCs safety management, where collaboration among stakeholders is essential. It ensures shared control and transparency while protecting sensitive information, balancing stakeholder rights and operational efficiency.

Consensus mechanisms ensure agreement among network participants on the state of the ledger (Yadav et al. 2023). The choice of consensus mechanism, which governs legitimacy of nodes, is not merely a technical decision but a strategic one that shapes stakeholder engagement and participant rights in LIB CSCs safety management (Vatankhah Barenji et al. 2020). According to Bach, Mihaljevic, and Zagar (2018), Proof of Work (PoW), while providing a high degree of security through extensive computational work, raises sustainability concerns due to its significant energy requirements, which could be at odds with the principles of CSC. Proof of Stake (PoS) and Delegated Proof of Stake (DPoS), offer more energy-efficient solutions with a lower barrier to entry. Nevertheless, they carry the risk of promoting a disproportional influence for wealthier participants, potentially contravening the equitable principles necessary for effective safety management. Proof of Authority (PoA) pivots towards a governance-centric approach that benefits speed and energy consumption, yet its reliance on a set of pre-approved validators may curtail the broader goal of decentralisation.

Given these varied implications, the proposed blockchain ecosystem proposes integrated *Layer 2*³ scaling solutions that manage large volumes of transactions efficiently without overloading the main network (Rebello et al. 2024; Zhou et al. 2020). This capability is essential for handling the expanding scale of data and ensuring cost-effective transaction processing across stakeholders. In this blockchain architecture, it becomes imperative to innovate or select a hybrid consensus mechanism that best aligns with the operational efficiency, sustainability, and safety imperatives of LIB CSCs, accommodating the complex and dynamic needs of stakeholders.

Secure and transparent information sharing is essential in increasing stakeholder confidence and encourages wider participation in blockchain-based CSC, especially for safety management. *Cryptography* plays a vital role in ensuring security and privacy of sensitive data, such as battery design data, safety audits, accident reports, etc., utilising mathematical algorithms and encryption to protect data stored on the ledger (Xu et al. 2021). While blockchain is inherently transparent, cryptography, such as zero-knowledge proof, allows parties to verify the validity of a transaction without revealing the underlying

data, thereby protecting secrets and personal employee information, even within the public ledger (Yang and Li 2020).

Smart contracts, self-executing contracts coded to automate processes, are discussed in CSCs to increase accuracy, efficiency, and trustworthiness of processes (Dolgui et al. 2020). Potential applications of smart contracts in mitigating safety issues in LIB CSCs include registration, product tracking, safety management, and circular economy practices. This ecosystem suggests using dynamic smart contract modeling proposed by Dolgui et al. (2020), which allows for automatic adjustments in response to regulatory changes in supply chain safety management conditions.

All participants and devices involved in blockchain ecosystem for supply chains need to undergo verification and registration procedures (Yu et al. 2018). Data collection can be conducted by registered data acquisition devices and input to blockchain through oracle networks, then utilised within contracts while also being securely stored. The proposed blockchain ecosystem features stakeholder-specific access and functionalities – empowering participants with data views. Each participant accesses functionalities relevant to their role, enhancing security and efficiency. For instance, regulatory authorities can perform audits and compliance checks, while manufacturers access detailed battery and production data for safety control. In addition, participants who provide verified data and information will be incentivized for their contributions.

Incentive mechanisms embedded within the blockchain architecture are helpful to promote safety performance within LIB CSCs. They not only provide direct rewards that motivate stakeholders but also foster an environment of transparency, accountability, and economic viability, driving the supply chain towards more safety operations (Wankmüller et al. 2023). There are different types of incentive mechanisms that can be applied in the proposed architecture. For example, tokenization, which can represent ownership or entitlements related to physical goods or performance metrics. In LIB CSCs safety management system, tokenization could be utilised to represent elements such as safety certifications (non-fungible tokens, NFTs), or adherence to safety practices. Stakeholders could trade these tokens or use them to claim rewards, creating tangible value for safety practices. Additionally, performance-based incentives offer rewards to stakeholders based on achieving specific outcomes or benchmarks, such as fewer incidents and injuries, or increased safety training participation. Reputation systems, as another type of incentive mechanism, assign scores or ratings to participants based on their safety performance. This mechanism can encourage

better compliance with safety standards and foster a competitive spirit among participants to maintain high standards.

The *Oracle network* acts as a bridge between the blockchain network (on chain) and the outside world (off chain), providing data from external sources, such as battery (e.g. status of usage and health) and environmental (e.g. storage temperature and humidity) information related to safety (Omar et al. 2021).

Despite their utility, oracles introduce potential vulnerabilities and trustworthiness to the blockchain architecture, often referred to as the 'oracle problem' (Al-Breiki et al. 2020). For example, if the data source or the oracle itself is compromised, the incorrect or malicious data could be fed into the blockchain. Oracle operations are not always transparent, which may be at odds with the decentralised and open nature of blockchain. Stakeholders may not be able to verify the authenticity or accuracy of the data provided by Oracle, leading to trust issues. In terms of safety measurements in LIB CSCs, this could mean incorrect data about battery health or employee injury. Incorrect data can lead to incorrect smart contract execution, thus jeopardising the safety of CSCs. In addition, depending on the structure of the oracle network, it could cause technical issues such as a single point of failure (Al-Breiki et al. 2020). To mitigate the risks associated with oracles, several strategies can be employed in this architecture, for example using a decentralised oracle network; implementing checks to retrieve data from multiple independent stakeholders; and ensuring that data is transmitted through secure channels and using end-to-end encryption.

Decentralised storage systems, such as Interplanetary File System (IPFS) and Filecoin, are used for secure and redundant storage of large data files on the blockchain (Wang, Zhang, and Zhang 2018a). They distribute data across a network of nodes, enhancing security and reducing vulnerability to hacking or data loss (Omar et al. 2021). This type of storage enables secure and transparent storage of large files, such as documents, images, or videos.

Designing an effective blockchain architecture involves considering these artefacts and their interactions to ensure the desired functionalities and properties (affordances) of the network. The architecture should align with the specific requirements of safety management for the LIB CSCs (Tsolakis et al. 2021).

This design of blockchain architecture presents an architecture for a practical implementation, but it should be noted that several additional steps are required for a successful implementation – and require practical and research development. Specifically, the development of a sequence diagram and algorithm, followed by

programming and running the applications, are essential for assessing the feasibility of the proposed architecture. Due to the complexity of initially introducing the conceptual design and its artefacts, these steps are not expounded upon in this manuscript – but do require future study.

4. A theoretical study framework for blockchain ecosystem evaluation

Expanding upon the blockchain ecosystem architecture presented in Section 3, this section introduces a theoretical framework, by integrating prescriptive theorising (Hanisch 2024), for a safety performance-driven blockchain ecosystem, as depicted in Figure 2.

According to prescriptive theorising, theories are developed not only to explain phenomena but also to guide solutions to practical problems (Hanisch 2024). Prescriptive theorising aims to provide recommendations, guidelines, or frameworks for decision-making and behaviour. Prescriptive theorising has an important role to play in responding to major challenges from current social practices, including the norms of sustainability and corporate social responsibility (Hanisch 2024). For example, Hanisch et al. (2023) proposed a theoretical model based on prescriptive theorising (of which IBR methodology can support) to provide insights into governance frameworks and implementation strategies for digital transformation. Therefore, we propose this conceptual framework for guiding practical problems of blockchain application in CSC safety management.

The efficacy of this proposed blockchain architecture remains uncertain, and there are theoretical propositions that warrant further investigation, as their relationship has not yet been empirically verified. We view this framework as a design principle that can be reused for multiple instances of multi-stakeholder information and communication systems, and especially for blockchain based artefact implementations (see Chandrasekaran, de Treville, and Browning 2020 for a discussion on IBR and reusability-generalizability of design principles). The instance in this case is for a blockchain ecosystem that supports safety management performance for LIB CSC safety management.

To effectively address safety issues, it is imperative to identify the performance measurements and critical factors that contribute to safety management – performance measures and other data appear in Section 3.1. The design of the blockchain architecture should incorporate specific capabilities that facilitate effective safety management. This entails involving multiple stakeholders in the development process and collecting data from various sources to accurately measure safety performance.

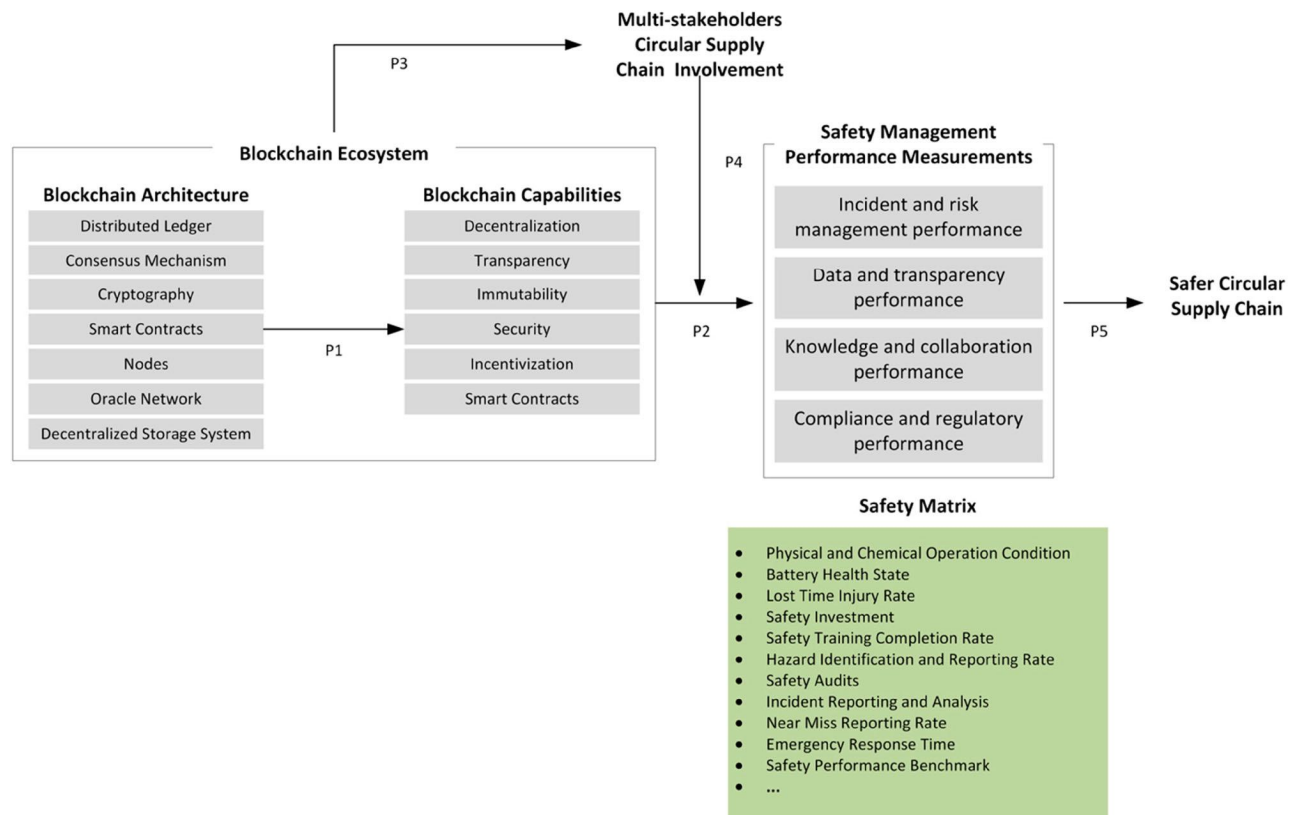


Figure 2. Conceptual framework of blockchain-based safety management.

To ensure the practical development of the blockchain for mitigating safety issues, the incorporation of relevant theories is necessary for broader advancement. Architecture on practical production is insufficient; theoretical concepts can ensure more effective blockchain architectures. However, there often exists a gap between practical implementation and theoretical support in the discourse surrounding blockchain applications (Zhu, Bai, and Sarkis 2022). According to IBR, prescriptive theoretical investigation and contribution are important for solving practical problems in operations management (Chandrasekaran, de Treville, and Browning 2020). Additionally, soft systems methodology proposes that developing conceptual models is a critical step of system thinking in action research (Bustard, He, and Wilkie 1999). To bridge this research gap, we propose a theoretical framework that incorporates performance measurement and utilises other pertinent theories.

This framework incorporates theories from organisational, operational, information systems, and ecological domains to guide the creation and deployment of a blockchain-based safety management system for the LIB CSCs. Stakeholder theory (Parmar et al. 2010), relational view (Dyer and Singh 1998), critical factor theory (Frankel 1998), and affordance theory (Kouhizadeh, Zhu, and Sarkis 2023) are theories supporting this framework.

IBR is employed to generally guide the development of the blockchain architecture elements to facilitate blockchain capabilities for safety management in this framework. The relational view was applied to assess how unique value is created using blockchain applications. Critical factor theory examines the interaction between the blockchain ecosystem and performance measurements for safety management. Stakeholder theory is incorporated to analyse the impact of the blockchain ecosystem on multiple stakeholders and the impact of stakeholder involvement on CSC safety management. Finally, affordance theory guides the development of safer LIB CSCs for their intended support of various stakeholder requirements (affordances) sought by the blockchain ecosystem.

The theoretical framework presented in this study (Figure 1) offers a comprehensive design for the development and implementation of a blockchain-based safety management system tailored to the LIB CSCs. Research propositions, investigated relationships among elements of the framework, grounded in theory are provided to guide generic implementation requirements and research directions for blockchain technology, particularly from a performance measurement perspective. Figure 2 summarises the various propositional relationships we now introduce.

The relational view theory emphasises the importance of inter-organisational relationships and networks in achieving competitive advantage. Developed by Dyer and Singh (1998), this theory proposes that firms can enhance their capabilities and overall performance by leveraging relationships with external stakeholders such as suppliers, customers, and even competitors. Applying this perspective to blockchain within the context of LIB CSCs underscores the potential for blockchain's architectural elements to bolster key capabilities such as transparency and immutability, thereby contributing to improved safety management.

The utilisation of blockchain technology has diverse impacts on safety management within the LIB CSCs (Chen et al. 2023). However, it is important to note that the design of different blockchain architectures significantly influences the capabilities and effectiveness of the blockchain ecosystem (Tuunanen, Walls, and Widmeyer 2016). These enhanced capabilities are instrumental in improving safety management practices and outcomes within LIB CSCs. To gain deeper insights into these relationships between blockchain architecture and capabilities, an analysis of the design functions and interrelationships of blockchain architecture and its inherent capabilities is necessary. Consequently, Proposition 4.1 proposes a research direction that focuses on exploring the implications of blockchain ecosystems (architecture and capabilities) on safety management within the context of the LIB CSCs. The first proposition aims to enhance our understanding of how specific design choices in blockchain architecture can contribute to blockchain capabilities and eventually to improved safety practices and outcomes.

Proposition 4.1: *Essential blockchain architecture artefacts impact blockchain capabilities in the safety management of circular lithium-ion battery supply chains.*

The performance measurement of safety management in LIB CSCs involves systematic evaluation of the effectiveness and efficiency of safety practices. Data quality theory provides a framework for improving the quality of data by ensuring its completeness, accuracy, consistency, timeliness, and relevancy (Hazen et al. 2017). This theory aims to ensure that data is suitable for its intended purpose and supports informed decision-making (Hazen et al. 2014). The capabilities enabled by blockchain architecture have implications for these data quality dimensions in supply chain safety management. The blockchain ecosystem offers a secure and tamper-proof record of data, ensuring the accuracy and integrity of data monitoring and tracking (Khurshid, Rajeswaren, and Andrews 2020). Additionally, the use of smart contracts facilitates

the verification of data and the issuance of safety-related certifications to stakeholders.

Managing safety in CSCs of LIBs generates a vast amount of data, which can lead to information overload. According to critical success factor theory, it becomes crucial to identify critical factors and key performance indicators (KPIs) to highlight relevant data (Mahmoud et al. 2020). Critical factors are key drivers of success that have a significant impact on project outcomes. Blockchain technology has the potential to assist in identifying critical factors and determining which stakeholders should access specific data with different capabilities. Figure 2 illustrates four main factors that motivate effective performance measurements in safety management. These four factors can serve as KPIs including incident and risk management performance, data and transparency performance, knowledge and collaboration performance, and compliance and regulatory performance, are specific metrics used to assess the performance of an organisation or business process in achieving its goals.

Our study posits that the adoption of a blockchain ecosystem (P2 in Figure 2) holds significant promise in augmenting the efficiency and effectiveness of performance measurements in safety management within LIB CSCs. The conceptual model and theoretical observations lead to the development of Proposition 4.2, which presents research questions to further explore the benefits and implications of the blockchain ecosystem in this context.

Proposition 4.2: *Different capabilities of the blockchain ecosystem influence performance measurement and support the determination of critical performance measures for assessing safety management in circular lithium-ion battery supply chains.*

Stakeholder theory – a prominent theoretical lens in organisational studies – emphasises the responsibility of organisations to consider the interests and needs of all stakeholders affected by their actions and decisions (Parmar et al. 2010). Stakeholders go beyond shareholders to include customers, suppliers, employees, regulators, local communities, and the environment. Stakeholder involvement is a critical aspect of supply chain management (Co and Barro 2009; Gupta et al. 2019). According to stakeholder theory, multiple stakeholders within an organisation or supply chain may have distinct relationships with its systems, which may be altered by safety (Parmar et al. 2010). Therefore, it is essential to engage with stakeholders and address their concerns and needs to fulfil obligations and create value for multiple stakeholders.

In the context of CSCs for LIB, numerous stakeholders with different relationships and interests are

involved (Luthra et al. 2022). The implementation of blockchain technology can potentially impact stakeholder involvement by leveraging its unique capabilities. The immutability of the blockchain ensures that data is tamper-proof and cannot be altered, providing a secure and reliable source of information for stakeholders. The transparency of the blockchain allows stakeholders to access and verify data, promoting trust and accountability within the supply chain. Moreover, the security of the blockchain ensures that sensitive data is protected and shared only with authorised parties. By utilising these capabilities, the blockchain ecosystem has the potential to enhance the reliability and efficiency of data sharing within the supply chain, thereby incentivizing more stakeholders to actively participate and engage in the process. Thus, the blockchain ecosystem can relate to multiple stakeholder engagements in CSCs (Kouhizadeh, Zhu, and Sarkis 2023).

The impact of the blockchain ecosystem (including the architectural design and affordances or capabilities) on multi-stakeholder integration, leads to the development of research Proposition 4.3.

Proposition 4.3: *The blockchain ecosystem enhances stakeholder engagement and differentially impacts stakeholders in the context of safety performance measurement.*

Stakeholder theory specifies that the involvement of multiple stakeholders within a supply chain can have varying levels of power and influence, ultimately impacting the overall performance of the supply chain (Atkinson, Waterhouse, and Wells 1997). Stakeholders can be categorised into internal stakeholders, referring to individuals or groups within an organisation, and external stakeholders, referring to those outside of the organisation who are affected by its actions (Mazur and Pisarski 2015). To enhance LIB CSCs safety through the integration of blockchain, it is important to involve not only internal stakeholders but also external stakeholders. Insufficient stakeholder engagement and collaboration will result in the failure of blockchain applications. For example, insufficient participation and collaboration between ocean shipping companies is one of the major causes of failure for TradeLens, a blockchain-based trading platform joint initiative by Maersk and IBM.⁴

In the context of blockchain-based LIB CSC safety management, the involvement of diverse types and a large number of stakeholders can contribute to more comprehensive and effective performance measurement. Defining critical factors and KPIs for safety management in LIB CSCs will be necessary and depend on what stakeholders are involved (Toor and Ogunlana 2010). Stakeholder

engagement can also impact the quality and effectiveness of critical factors in safety management performance measurement when supported by blockchain capabilities. Some stakeholders will be necessary to provide information, while others will use information. How and which stakeholders are involved in the blockchain ecosystem and in the information and performance measures development and usage will influence the outcome quality. Therefore, this study proposes that the number and variety of stakeholders with multiple roles involved will moderate the potential impact on blockchain safety performance measurement, leading to Proposition 4.4 (P4) and delineated by P4 in Figure 2.

Proposition 4.4: *The involvement of multi-stakeholders moderates the impact of blockchain technology on specific performance measurements in safety management.*

The safety concerns encountered at different stages of LIB CSCs exhibit unique characteristics (Chen et al. 2023). As a result, the measurement of safety performance may vary across stages, depending on the specific safety issues and their severity. It is necessary to establish appropriate safety management performance measurements to effectively identify safety issues and promote safer LIB CSCs.

Affordance theory, which focuses on the design of objects or systems and their potential for action, emphasises that users perceive different possibilities based on their experiences and knowledge (Du et al. 2019; Kouhizadeh, Zhu, and Sarkis 2023). Within the context of using blockchain to address safety concerns in LIB CSCs, various forms of affordance manifest. *Perceptible affordances* are immediately apparent, there are potential synergies between safety and circularity. For example, blockchain could foster supply chain safety issue responsiveness and achieve safer and circular supply chains, through reducing the environmental, social, and economic impacts of safety issues. *Hidden affordances* require exploration or learning and may involve enhanced communication effectiveness and efficiency, the establishment of new stakeholder relationships and collaboration flexibility, and the cultivation of trust in supply chains. *False affordances* are misleading trade-offs (antagonistic effects) between safety and circularity. For example, investments in safety practices may undermine investments in circular practices, or managers may abandon circular practices, such as using recycled materials or reused components, in favour of safety targets. In addition, blockchain-based safety management may lead to additional operational complexity and difficulties, might further result in unsafe behaviours or the incorrect selection of safety management performance

measurements. Recognising and leveraging the appropriate types of affordances can contribute to the development of effective safety management strategies and safer CSCs.

Proposition 4.5 aims to explore the relationship between safety management performance measurements and the resulting safety of LIB CSCs. It seeks to assess whether the implementation of blockchain-based safety management performance measurements could mitigate or exacerbate safety issues within circular supply chains.

Proposition 4.5: *Implementing blockchain technology improves safety management performance in broad-based systems, influencing specific measures and potentially introducing hidden and false affordances in circular lithium-ion battery supply chains.*

Summarising, this study establishes a robust framework for the development and implementation of a blockchain-based safety management ecosystem in LIB CSCs. We incorporate a theoretical framework based on various theories providing a solid foundation for future research and practical implications.

By leveraging propositions about the relationships between the blockchain ecosystem, multiple stakeholder engagement and involvement, safety performance measures, and potentially safer LIB CSCs, researchers and practitioners can further explore the implications, benefits, and challenges of implementing blockchain technology in safety management.

The propositions introduced here serve as a guide for directing future investigations in the field. With the continuous advancement of blockchain technology and the increasing importance of safety management in LIB CSCs it is necessary to investigate and refine this framework to promote the adoption of effective safety practices and enhance overall sustainability of CSCs and lower the barriers to the adoption of circular economic principles.

5. Research and practical implications

Within the realm of research and practical applications, this study builds upon the established conceptual framework and propositions, providing valuable insights and implications for the implementation of blockchain-based safety management in LIB CSCs. The implications presented here are intended to facilitate ongoing progress and innovation, promoting the safety and sustainability of LIB CSCs through the integration of blockchain technology.

5.1. Research implications

The propositions presented in this article serve as a starting point for empirical testing, requiring the utilisation of various methodologies such as surveys, experiments, and IBR (Bai and Sarkis 2022). Through rigorous testing, the proposed hypotheses can be validated, providing a deeper understanding of the concepts and their implications (Hennink and Kaiser 2022).

The complex relationship and interaction between blockchain technology and safety management in LIB CSCs warrants further theoretical investigation. It is essential to explore multiple theoretical perspectives to address the multifaceted issues associated with applying blockchain to enhance safety in the circular economy (Shen, Sung, and Zhang 2015). Future research should assess the effectiveness of the theories applied in this study in mitigating safety concerns in LIB CSCs, supported by blockchain technology. Moreover, the incorporation of additional theoretical perspectives that align with broader theories should be considered to provide a comprehensive understanding of the subject (Kurnia, Karnali, and Rahim 2015).

The integration of sustainability theory, which encompasses environmental and social dimensions, is vital in addressing safety issues as both environmental and social sustainability concerns. This integration expands the scope of sustainability by linking environmental, social, and economic aspects. Therefore, combining sustainability-oriented theories, including social sustainability, with information technology theories is necessary to gain a comprehensive understanding of the subject matter.

Addressing safety issues in LIB CSCs through the application of blockchain necessitates cross-disciplinary research that encompasses information technology, operations, sustainability, and safety. The integration of blockchain with complementary technologies such as artificial intelligence (AI) and machine learning (ML) can offer advanced data analysis capabilities for predictive maintenance and circular lifecycle management; big data analytics can process the extensive datasets to uncover optimisation safety management strategies; digital twin technology and 3D printing offer revolutionary approaches to LIB design, production remanufacture and recycling, promoting greater flexibility and waste reduction in CSCs; and advanced materials science could lead to safer battery components, for example solid-state batteries. These explorations not only address safety challenges but also drive technological advancements and efficiency improvements across LIBs CSC safety management. In addition, interdisciplinary research has the potential to yield new theoretical perspectives, further

provide valuable insights into effective safety management practices (Lindgreen et al. 2020).

The conceptual framework proposed in this research requires further evaluation and refinement. The framework brings together various theories to develop a comprehensive understanding of blockchain-based safety management, including elements such as the blockchain ecosystem, multi-stakeholder involvement, and safety performance measurements. Future research should focus on specific aspects of the framework, including the development of a blockchain architecture for safety management, the clarification of safety performance measurements, and the identification of a safety matrix to support safety performance assessment. These efforts aim to cultivate safer CSCs by leveraging the potential of blockchain technology.

5.2. Practical implications

The framework presented in this study offers valuable guidance for organisations involved in developing tools and blockchain ecosystems. By identifying the essential characteristics required to achieve effective safety management in LIB CSCs, the framework serves as a practical roadmap for designing and implementing these solutions.

The proposed architecture provides a concrete and practical design for organisations seeking to implement data requirements in their safety management practices. By following the architecture outlined in this study, organisations can establish a robust data infrastructure that supports the integration of blockchain technology and facilitates efficient safety management processes.

The study underscores the importance of addressing safety concerns in CSCs to foster its broader adoption. By shedding light on the complexities and criticality of safety measurements within this context, organisations are encouraged to prioritise safety as a central aspect of their operations. This emphasis on safety paves the way for more sustainable and secure practices in the circular economy.

The research findings have significant policy implications that should be considered by stakeholders and decision-makers. These implications include determining the roles and responsibilities of various stakeholders involved in safety management within the circular economy. Additionally, developing robust models around the implementation of blockchain-based safety solutions becomes crucial (Zhang et al. 2020). Furthermore, exploring the potential of decision support systems to facilitate informed decision-making in safety management is another important area to be considered in policy discussions (Dey 2001).

Finally, future practice should focus on implementing the framework and architecture proposed in this study – adapting them to specific organisational contexts. Organisations should proactively engage in knowledge sharing and collaboration to drive the adoption and continuous improvement of blockchain-based safety management practices in CSCs. Furthermore, organisations can explore partnerships with technology providers and government and regulatory bodies to ensure compliance and alignment with industry standards and regulations.

In conclusion, the research implications focus on testing propositions, evaluating constructs, and integrating theoretical perspectives. The practical implications involve tool development, addressing safety concerns, and considering blockchain implementation. By embracing these implications, organisations can enhance safety management practices and promote blockchain implementation in LIB CSCs. Continued efforts in research and innovation will contribute to advancing theory and practice in this area.

6. Conclusion

CSCs of the LIB industry present unique challenges in terms of safety, transparency, and efficiency. Blockchain technology offers significant potential for enhancing safety management by enabling effective tracking and verification of battery movement throughout the supply chain.

However, there is a noticeable research gap regarding the utilisation of blockchain to address safety issues within CSCs. Further investigation and exploration of blockchain technology are needed to improve safety management in LIB CSCs, guided by theoretical frameworks.

To bridge this research gap, we propose a theory-supported application of blockchain in LIB CSCs aimed at mitigating safety concerns. Our study presents a comprehensive blockchain ecosystem that encompasses the design of an architecture with specific capabilities tailored to safety management. This framework also emphasises the involvement of multiple stakeholders and the development of a safety measurement matrix. Additionally, we have developed theoretical-based propositions to explore the interactions and relationships within the conceptual framework, providing valuable insights for future research endeavours and practical blockchain implementations.

While this research provides a foundation for applying blockchain to CSCs safety management, it is important to acknowledge certain limitations. Due to space constraints, specific investigations, such as the development of blockchain implementation algorithms, were not

conducted in this study. Furthermore, the blockchain architecture requires further examination to enhance its practical implementation. Additionally, this study could be enhanced by empirically testing and verifying the proposed framework.

In summary, this research contributes by proposing the application of blockchain technology to the safety management of CSCs. The developed model combines practical implementation strategies with theoretical considerations, offering a roadmap for future blockchain applications not only in LIB safety management but also in other industries and domains. Future research and explanation of the proposed model, along with addressing the identified limitations, will contribute to the advancement of safety management participants and the realisation of safer and more sustainable CSCs.

Notes

1. Establishment Specific Injury and Illness Data (Injury Tracking Application) | Occupational Safety and Health Administration (osha.gov).
2. Tools, Apps and Databases | UL Solutions.
3. Layer 2 (L2) blockchain is a scaling solution that operates on top of Layer 1 (L1) blockchains like Ethereum or Bitcoin. L1 blockchains handle primary transactions and ensure security but can suffer from congestion and high fees. L2 solutions process transactions off the L1 blockchain, reducing fees and improving scalability while maintaining security through L1 settlement.
4. <https://www.maersk.com/news/articles/2022/11/29/maersk-and-ibm-to-discontinue-tradelens>.

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Data availability statement

The data that support the findings of this study are available from the authors, [AY, CZ], upon reasonable request.

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