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Technological insights on blockchain adoption: the electric vehicle supply chain use case

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Abstract

Purpose – Blockchain and distributed ledger technologies are increasingly prominent, yet their adoption remains complex. This paper addresses the common misalignment between blockchain technology and actual needs, often leading to project failure. It introduces a decision-making framework focused on the technological aspects of blockchain adoption.

Design/methodology/approach – We designed the framework by analyzing key decision drivers from existing literature and applied it to a real-world use case in the electric vehicle supply chain. The blockchain solution was tested with live production data.

Findings – Blockchain is beneficial for use cases requiring decentralized governance, but it often needs to be supplemented with additional technologies in industrial applications.

Originality/value – The framework provides a set of managerial-level questions that simplify the decision-making process for those without deep technical expertise, helping determine when blockchain is appropriate, valuable and superior to other technologies.

Keywords Blockchain adoption, Blockchain suitability, Electric vehicles, Supply chain, Hyperledger Besu

Paper type Case study

1. Introduction

Presently, companies are undergoing radical transformations driven by the Industry 4.0 revolution, characterized by information sharing and digitization (Fakhri *et al.*, 2020). This revolution is fueled by recent technological advancements in physical monitoring, data processing, virtualization and automation technologies (Bai *et al.*, 2020; Boccia *et al.*, 2021a, b; Caselli *et al.*, 2022; Fadda *et al.*, 2021). On the one hand, data acquisition and storage are becoming more cost-effective and accurate. On the other hand, peer-to-peer technologies such as blockchain (He *et al.*, 2022) and the Interplanetary File System (Capocasale *et al.*, 2022b) are reshaping established business paradigms (Perboli *et al.*, 2018).

Blockchain technology establishes trust among nontrusting parties without relying on intermediaries. It consists of a network of nodes managing a shared and distributed database. Tampering attempts are thwarted by replicating the state of the database on each node. Smart

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contracts, independently executed by each node, are used to modify the database's state. By leveraging the tamper-resilience of blockchain, smart contracts can enhance the fairness of critical processes, safeguard valuable resources and automate business operations. Given the relevance of such topics (Aringhieri *et al.*, 2022; Serrano, 2022; Boccia *et al.*, 2024), smart contract-based alternatives are gaining ground across various sectors, including finance (Pavlova, 2020), insurance (Gatteschi *et al.*, 2018a, b), structural health monitoring (Elia *et al.*, 2022), logistics (Pan *et al.*, 2021a, b; Peng *et al.*, 2022), retail (Pun *et al.*, 2021), energy (Ruffini *et al.*, 2022; Khan *et al.*, 2021) and more (Deshmukh *et al.*, 2022).

However, blockchain is a complex technology introducing numerous challenges across technical, legal and economic dimensions. Decision-makers often lack the necessary knowledge to make well-informed choices regarding blockchain adoption, leading to common misconceptions in the field (Schneider and Azan, 2022). Consequently, blockchain is sometimes selected for inappropriate reasons, even when better alternatives exist (Belotti *et al.*, 2019; Halaburda, 2018; Carson *et al.*, 2018; Labazova *et al.*, 2019). As a result, many blockchain projects have short lifespans, with an average discontinuation rate of approximately one year and a survival rate below 10% (Trujillo *et al.*, 2017). The failure to achieve tangible benefits and the technology's unsuitability for specific business cases are among the primary reasons for these project discontinuations, as indicated by a recent study (Rauchs *et al.*, 2019). An illustrative case is Tradelens, a supply chain management platform supported by IBM and Maersk, which was recently terminated due to its failure to achieve global industry collaboration (Kjærgaard-Winther, 2022).

In this context, it is imperative to develop standards and tools that simplify managerial decision-making regarding blockchain adoption. This process involves various factors, including technological, economic, managerial, legal and human considerations. However, our study specifically focuses on the technological aspect, representing the initial step toward a comprehensive framework. In particular, we address the following research questions:

(1) How can non-technical decision-makers assess the technological suitability of blockchain technology?

(2) Is blockchain suitable for enhancing the accountability of companies in global electric vehicle supply chains like the one described in Section 4?

This paper addresses these research questions and contributes to both academic research and practical applications. By developing a decision-making framework tailored for blockchain adoption, the paper bridges the gap between theory and practice. More precisely, our contributions to the current body of knowledge can be summarized as follows:

(1) Research implications. We propose a decision-making framework for blockchain adoption that abstracts the complexity of blockchain technology. The framework provides a structured methodology for assessing blockchain adoption, highlighting critical decision drivers often overlooked in the literature. Future research can build on this framework by exploring its application across different industries or integrating it with other decision-making tools. Additionally, the paper's insights into the technological requirements and limitations of blockchain in the electric vehicle (EV) supply chain context can guide further studies on optimizing blockchain performance in real-world scenarios.

(2) Practical implications. From a practical perspective, our framework can be used by businesses and industry practitioners to make informed decisions about blockchain adoption, potentially leading to more successful implementations in supply chains and other decentralized systems. The case study within an EV supply chain of a multinational corporation demonstrates the practical applicability of the framework, showcasing how it can improve supply chain transparency, data integrity and overall efficiency. Moreover, this use case represents one of the few supply chains where

blockchain adoption can be particularly successful, offering insights into the practical application of our framework.

(3) Societal impact. On a societal level, the adoption of blockchain technology in supply chains, as outlined in this paper, can influence public policy and industry standards by promoting transparency and accountability. This can lead to an improved quality of life through the production of more reliable and sustainable products, such as EVs, and by fostering trust among consumers and stakeholders. The implications for public attitudes toward technology and sustainability are also significant, as the adoption of blockchain in industries like the automotive sector can serve as a model for other industries aiming to enhance traceability and reduce environmental impact.

The remainder of this study is organized as follows: Section 2 provides a brief overview of blockchain technology and summarizes related work. Section 3 elucidates the blockchain adoption decision-making framework and introduces the Blockchain Adoption Decision Counselor, a tool simplifying the application of our framework. Section 4 details the application of our framework to a logistics use case inspired by a multinational corporation's EV supply chain. Finally, Section 5 concludes the paper.

2. Background

This section provides an overview of key concepts related to blockchain technology and includes a summary of relevant prior work.

2.1 Blockchain technology

Blockchain technology facilitates data sharing among distrustful parties, offering a solution to trust-related challenges without relying on intermediaries. A blockchain consists of a network of peers that share a common database, often referred to as a ledger. Notably, data can only be appended to this ledger, and each peer autonomously manages its own copy. Consequently, while peers can manipulate their individual copies, they cannot alter the global state of the ledger. The global ledger's state is determined by a majority consensus mechanism (Zheng *et al.*, 2018; Luo *et al.*, 2022). To simplify discussions, we assume an even distribution of voting power among peers, with the term "majority of peers" referring to the majority of voting power.

Blockchains are categorized based on their governance model (Buterin, 2015):

(1) **Permissionless**: Voting power is not assigned based on the identity of the peers, but through other means (e.g. the ownership of a resource). For this reason, permissionless blockchains are often public, as there is no association between peers with their (potentially multiple) identities, making access control rules unenforceable.

(2) **Permissioned**: Voting power is directly assigned to identities, thus the peer-identity relationship must be known to fairly distribute voting power. In particular, consortium blockchains are permissioned blockchains controlled by multiple consortium members, while fully private blockchains are controlled by a single one.

It's important to note that the governance model of a blockchain may evolve over time.

2.2 Blockchain's value proposition

Manipulating data in centralized systems controlled by a trusted third party only requires colluding with such a party. Instead, tampering with a blockchain requires colluding with the majority of its participants. The main value provided by blockchain comes from the assumption that the latter scenario is nearly infeasible, making blockchain data trustworthy. Thus, blockchain's value proposition is trust creation (Lumineau *et al.*, 2021). This, however, can have a few interesting applications. The most immediate one is preventing others from manipulating data, which may be helpful for due diligence practices, preventing censorship, or training machine learning models. Alternatively, blockchain may be used to demonstrate one's inability to manipulate data, which may enhance brand reputation and quality assurance. Finally, sharing a database with multiple other parties enforces a certain degree of standardization, which may simplify and streamline many business processes.

In Section 2.5, we further analyze how blockchain's value proposition may impact EV supply chains by reviewing the existing literature.

2.3 Problem statement

Many real-world systems inherently exhibit decentralization. For example, supply chains comprise numerous companies, and each company's actions impact the overall supply chain's performance (Xavier *et al.*, 2024). Consequently, managing supply chains in a decentralized manner and allowing each company to influence the best strategies for overall improvement is a logical approach.

The advent of blockchain technologies has unlocked opportunities to decentralize data management in systems that previously relied on trusted third parties. However, determining whether blockchain adoption is appropriate poses challenges. Blockchain is a complex technology fraught with hidden trade-offs and challenges (Sternberg *et al*., 2021). Grasping blockchain's intricacies demands a solid foundation in cryptography (e.g. digital signatures, cryptographic hash functions, zero-knowledge proofs), distributed consensus and state machine replication, nonrelational databases and more. Consequently, decision-makers frequently lack the technical expertise required to make informed choices regarding blockchain adoption. This issue is compounded by numerous misconceptions about blockchain-related topics, even within academic literature (Auinger and Riedl, 2018; Caldarelli, 2020). Often, hype becomes the primary driving force behind decisions. Hence, a high-level, user-friendly decision-making framework is overdue, one that highlights the merits of blockchain technology and, crucially, the prerequisites for realizing these benefits.

We have developed a framework to assist decision-makers in comprehending when blockchain is a suitable, valuable and superior solution compared to alternatives. Our framework offers several advantages.

(1) Streamlined decision process: Our framework simplifies blockchain adoption decisions, saving time.

(2) Structured methodology: Users follow a structured approach that reduces the risks of adopting blockchain for inappropriate reasons or overlooking critical decision factors.

(3) Accessibility: Our framework is accessible to individuals without prior blockchain knowledge or technical expertise.

(4) Alternative suggestions: When blockchain is not the optimal solution, our framework provides viable technological alternatives.

We believe that the insights provided in our study can contribute to raising awareness about blockchain technology and its genuine value proposition.

2.4 Methodology

Our framework is based on a decision flowchart. The questions used in our framework were extracted from the relevant literature. In particular, we queried the Scopus database as follows:

TITLE-ABS-KEY("blockchain decision*" OR "blockchain suitability" OR "blockchain adoption") AND ("flow chart" OR flowchart OR tree OR scheme OR "decision* model*" OR "decision* framework*").

We extracted 35 studies, two of which (Almeshal and Alhogail, 2021; Preece and Easton, 2024) had already thoroughly reviewed the existing literature on decision flowcharts. We used such reviews to identify relevant studies and extracted the decision drivers that they proposed. We further refined such decision drivers based on our past practical experiences and knowledge. Finally, we summarized them into 11 questions, which were validated with a focus group made up of experts from one of the leading IT companies in Europe. We now introduce the different questions giving a detailed description of how they impact the final decision of adopting or not a blockchain-based solution.

Table 1 highlights differences and similarities between our framework and the existing literature.

2.5 Related work

Blockchains may improve EV-related business processes in various ways and contribute to the creation of a sustainable and circular economy (Ribeiro da Silva *et al.*, 2023; Yang *et al.*, 2024). By using blockchain to store vehicle data, the identification of counterfeit vehicular parts could be simplified and data tampering issues related to modern vehicle power battery traceability systems could be reduced (Zhang *et al.*, 2022; Ma and Fang, 2022). Such data may also be leveraged to better assess the value of preowned vehicles (Subramanian and Thampy, 2021). Moreover, blockchain appears to be the natural technological choice to store digital battery passports, which are collections of relevant information on the production, testing and recycling of batteries (Soufi *et al.*, 2023). This would enhance the recycling of critical raw materials, which can be further incentivized through tokenization (Perez *et al.*, 2023; Li *et al.*, 2023). Additionally, blockchain may serve as an energy trading platform for EVs, enabling peer-to-peer energy trading among vehicles, energy grids and charging stations (Rana *et al.*, 2024).

Given its numerous potential applications and benefits, evaluating the suitability of blockchain for a given use case is a crucial step. According to Ref (Almeshal and Alhogail, 2021), blockchain suitability frameworks fall into three categories: decision models, conceptual frameworks and decision flowcharts.

Table 1. The table summarizes the literature on decision-making frameworks for blockchain adoption based on decision flowcharts

Ref.	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Hunhevicz and Hall (2020)	No	Yes	No	No	No	Yes	No	No	No	No	No
Wust and Gervais (2018)	No	Yes	No	No	No	No	No	No	No	No	No
Belotti *et al.* (2019)	No	Yes	No	No	Yes	No	No	No	No	No	No
Puthal *et al.* (2021)	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes
Hassija *et al.* (2021)	No	Yes	No	No	Yes	No	No	No	No	No	No
Pedersen *et al.* (2019)	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	No
Koens and Poll (2018)	No	Yes	No	No	No	No	No	No	No	No	No
Peck (2017)	No	Yes	No	No	No	No	No	No	No	Yes	No
Gatteschi *et al.* (2018a, b)	No	Yes	No	No	Yes	No	No	No	No	Yes	No
Lo *et al.* (2018)	Yes	Yes	No	No	Yes	No	No	No	No	Yes	No
Challener *et al.* (2019)	Yes	No	No	No	No	Yes	No	Yes	No	Yes	No
Maull *et al.* (2017)	No	Yes	No	No	Yes	No	No	No	No	No	No
Pahl *et al.* (2018)	Yes	Yes	No	No	No	No	No	No	No	No	No
Chowdhury *et al.* (2018)	Yes	Yes	No	No	No	No	No	No	No	Yes	No
Schletz *et al.* (2020)	Yes	Yes	No	No	No	No	Yes	No	No	Yes	No
Hassija *et al.* (2021)	Yes	Yes	Yes	No	Yes	No	No	No	No	No	No
This work	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source(s): It highlights the common adoption questions between our framework and those proposed in the literature

Decision models employ mathematical constructs to guide blockchain adoption decisions. For instance, BAF (Blockchain Applicability Framework) determines the ideal blockchain solution through a weighted evaluation of detailed user requirements (Gourisetti *et al.*, 2020).

Conceptual frameworks identify the factors to consider when adopting blockchain technologies based on researchers' practical experiences. Some frameworks concentrate on technological aspects, while others encompass nontechnological factors such as regulatory considerations (Scriber, 2018; Clohessy *et al.*, 2020; Labazova, 2019). Open-ended questions that should be addressed during blockchain adoption are proposed in Ref (Angelis and Ribeiro da Silva, 2019).

Decision flowcharts employ graphs where nodes represent closed-ended questions and edges indicate related answers. Users navigate a decision path based on their selected answers. Many authors utilize this strategy, proposing multi-step frameworks for blockchain adoption (Peck, 2017). A common approach is to build such frameworks based on experts' opinions gathered through surveys (Maull *et al.*, 2017). Another approach is to analyze multiple frameworks from the literature and consolidate them into a single one (Koens and Poll, 2018; Schletz *et al.*, 2020).

In general, most frameworks underline that blockchain should only be used when data must be shared and stakeholders do not trust each other or a common third party (Hassija *et al.*, 2021; Pahl *et al.*, 2018). Some frameworks delve deeper, offering guidelines for practical implementation strategies (Belotti *et al.*, 2019), examining security threats associated with blockchain use (Puthal *et al.*, 2021) and analyzing real-world use cases (Hassija *et al.*, 2021; Wust and Gervais, 2018; Gatteschi *et al.*, 2018a, b).

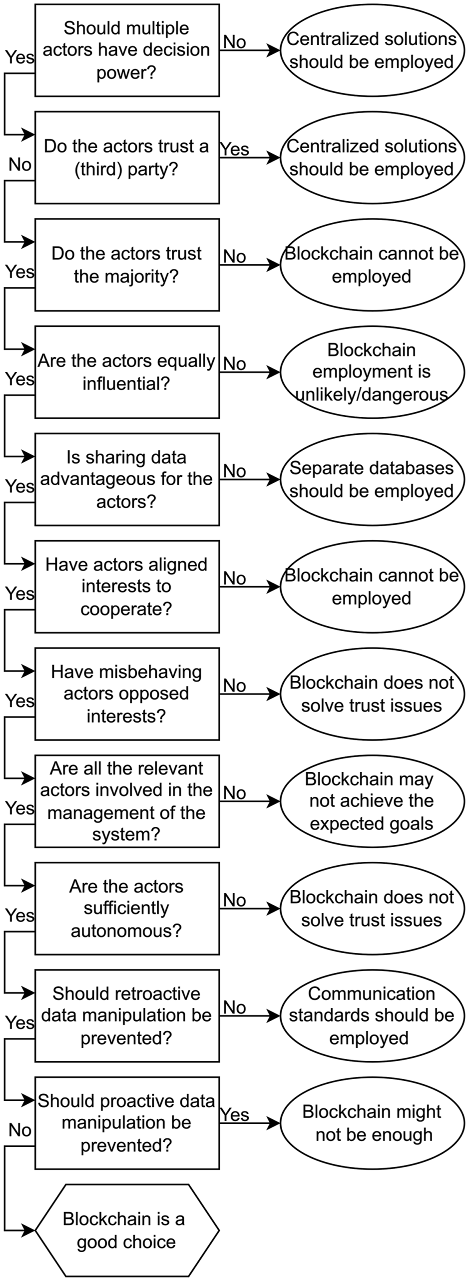
Not all frameworks target the same audience. Lo *et al*. (2018) describe a framework comprising seven main questions and four subquestions. However, some questions necessitate a strong technical understanding of blockchain technology to provide accurate answers. Pedersen *et al*. (2019) present a less technical ten-step decision-making framework, considering numerous aspects often overlooked in similar works. A framework explicitly designed for managers is proposed in Ref (Challener *et al.*, 2019). The authors emphasize the importance of developing proof of concepts to better assess the suitability of the technology and to consider which stakeholders should be involved and what data should be stored on-chain.

Some authors have tailored decision-making frameworks for blockchain adoption to specific use cases, such as logistics (Ar *et al.*, 2020; Ganeriwalla *et al.*, 2018; Hribernik *et al.*, 2020) and the construction industry (Hunhevicz and Hall, 2020). Additionally, decision-making frameworks for selecting the most suitable blockchain platform are available in the literature (Farshidi *et al.*, 2020).

All the aforementioned studies offer valuable insights on blockchain adoption. Nonetheless, we disagree with certain decision factors proposed in the existing literature. For instance, the requirement for multiple writers may be unnecessary: a group of entities may need to record data in a tamper-proof manner, even if written by a third party. In such cases, blockchain could provide a viable solution, as multiple record keepers could prevent data alteration by the writer. Hence, blockchain adoption should be driven by the presence of multiple decision-makers, allowing keepers to determine which data can be altered, rather than multiple writers. Table 1 provides a more detailed view of the differences and similarities between our framework and those already existing in the literature.

3. Blockchain adoption decision-making framework

This section describes our decision-making framework for blockchain adoption, which is graphically summarized in Figure 1. The framework helps decision-makers understand if blockchain is a sound technological solution. Nonetheless, a few additional remarks are in order to better understand our framework.



Source(s): Authors' own work

Figure 1. The proposed decision-making framework for blockchain adoption

(1) Blockchain is meaningful when decentralized governance is required. Even though the naming convention: *distributed ledger technology* has gained adoption, decentralization is what matters, not distribution (Come-from-Beyond, 2020).

(2) Blockchain is inefficient and should be used only when necessary. Blockchain is the only technology allowing for managing a database in a decentralized fashion. However, if the database can be managed by a single entity, other technological solutions are better (Challener *et al.*, 2019).

(3) Our analysis focuses on the technological perspective. In some scenarios, blockchain could be preferred to better technologies based on other factors, including marketing and cost-benefit tradeoffs. For example, a company may prefer to pay the transaction fees to deploy a smart contract on a public blockchain instead of sustaining the costs for designing, building, monitoring and patching a centralized production architecture.

As a consequence of the previous points, fully private blockchains have little to no potential for use, in our opinion. They can be employed to prevent accidental data modifications, but non-distributed ledgers are more efficient (e.g. ImmuDB (Paik *et al.*, 2020)). Thus, employing fully private blockchains can be a good marketing strategy but not a sound technological choice. For example, central bank digital currencies (Benedetti *et al.*, 2022) should not use blockchain if they are managed by a single entity (the central bank). Consequently, our framework deals with the suitability of public or consortium blockchains.

3.1 Q1: should multiple actors have decision power?

The most important aspect to consider when deciding on blockchain adoption is whether or not the system is decentralized. If decision power is not shared among multiple actors, centralized solutions (e.g. other distributed databases, such as Cassandra (Lakshman and Malik, 2010)) should be preferred: according to the scalability trilemma, decentralization comes at the cost of scalability or security (Schaaf *et al.*, 2021). Thus, compared to the blockchain, centralized solutions are more scalable and secure (Capocasale *et al.*, 2024).

It is important to underline that having decision power means having voting power to validate writing attempts in the context of blockchain. Blockchain can be described as a database that can be altered through a majority-based voting scheme. Thus, blockchain allows multiple actors to vote and decide which are valid database modifications. Remarkably, blockchain does not offer the same guarantees on reading attempts, as a single malicious actor could leak the contents of the database. Thus, blockchain improves data integrity and availability but weakens confidentiality.

Finally, we underline that validating writing attempts does not imply having writing rights. For example, in a trial, the judge decides what is admissible as evidence but cannot produce evidence. As discussed in Section 2.5, this remark is one of the main points of differentiation between our work and the existing literature.

3.2 Q2: do the actors trust a (third) party?

If an external entity or one of the actors is particularly trustworthy, the actors may be comfortable delegating their decision power to such an entity. In such a case, centralized solutions managed by the trusted party are better alternatives to blockchain for the same reasons outlined in the previous section. Vice versa, blockchain is a viable solution when no single party is trusted by all the actors. Almost all the decision-making frameworks present in the literature include this decision driver, which remarks its importance.

Remarkably, a blockchain can be itself a trusted third party. For example, those interacting with smart contracts on existing blockchain networks (e.g. Ethereum) are implicitly trusting the governance models of such networks.

3.3 Q3: do the actors trust the majority?

Blockchain does not completely solve trust issues: a precondition for using blockchain technology is that the majority of the actors are trustworthy (Capocasale, 2024). Thus, blockchain should only be used if actors are unlikely to collude. Otherwise, the malicious majority could tamper with or rewrite the database (51% attack) (Hao, 2022). Unfortunately, the literature has not given enough importance to such a relevant decision driver. We strongly encourage decision-makers to carefully consider the likelihood of 51% attacks before adopting blockchain, as such attacks are not uncommon (Martin, 2020; Voell, 2021). Launching 51% attacks is easier on small networks as it requires fewer actors to collude. Moreover, some blockchains may be attacked by an even lower percentage of colluding peers as a consequence of the voting protocol in use. Thus, particularly in consortium blockchains, the presence of a trustworthy (super)majority must be carefully checked.

3.4 Q4: are the actors equally influential?

Actors should hold a similar decision power so that blockchain may become a viable solution: if one of the actors has strong leverage against the others, such an actor is likely to enforce its centralized solution. In such a scenario, blockchain is unlikely to be successfully adopted, as the influential actor has no reason to share control of the database. Moreover, even if a blockchain were used, the influential actor could force others to align with its own decisions. Thus, the majority would probably be untrustworthy. Of course, in real-world scenarios, a perfect balance of influence is unlikely and subject to change over time. Thus, risk assessment strategies may be used to factor in the possibility that a minority may gain enough influence to manipulate other's decisions. Additionally, Porter's five forces analysis (Porter, 2008) is useful to determine the influence of the various actors. In particular, studying the bargaining power of customers and suppliers can help determine the balance of power among actors, which could provide insights into the applicability of blockchain technology.

For example, Amazon (Ritala *et al*., 2014) manages one of the biggest marketplaces in the world. Sellers have many advantages in selling their products on Amazon, including increased visibility, international expansion, and storage and shipping services. Nonetheless, sellers need to abide by Amazon's policies. Such policies are not negotiable, as Amazon has the upper hand in terms of bargaining power. In such a scenario, a blockchain solution is unlikely to be adopted, as Amazon can force the sellers to rely on Amazon's managed database. Conversely, blockchain could be adopted for the creation of a unified marketplace between Amazon and Alibaba (Havinga *et al*., 2016), as they are both e-commerce giants with similar bargaining power.

3.5 Q5: is data sharing advantageous for the actors?

Blockchains are shared databases. Actors who are not interested in sharing their data or receiving others' data are unlikely to join a blockchain network. Data that is not meant to be shared should be stored in centralized databases, as the database manager retains total power over the stored data. Nonetheless, blockchain can be leveraged in some use cases that require non-straightforward data-sharing approaches. We identified a few of them: partial sharing, delayed sharing, conditional sharing, and proof sharing.

Partial sharing refers to the necessity of sharing data with only some of the actors. In such a case, the best approach is to create a separate blockchain involving only the selected receivers. However, for costs or practicality, actors may prefer to store encrypted data in a single blockchain involving all the actors and share the decryption key with only the selected receivers. Thus, encrypted data are stored in a tamper-proof database and shared with all the actors, but only those who know the decryption key can recover the original data. Different encryption/decryption keys can be used to disclose data to different actor subsets.

Delayed sharing refers to the possibility of sharing data in the future while guaranteeing that it is not altered in the meantime. For example, some countries disclose classified documents after a certain amount of time. By storing encrypted documents in a blockchain and successively disclosing the decryption key, it is possible to guarantee the authenticity and integrity of the documents at disclosure time.

Conditional sharing refers to the possibility of sharing data only if a certain event occurs. For example, a company may have some confidential data that has to be shared only in case of litigation. Similar to the delayed sharing case, it is possible to use blockchain to guarantee the authenticity and integrity of encrypted data and successively reveal the decryption key, if necessary. Interestingly, if the event never occurs, blockchain is used to store data that is never shared.

Proof sharing refers to the possibility of not sharing the data directly but a proof computed on the data (e.g. zero-knowledge proofs (He *et al.*, 2022)) or a fingerprint of the data (e.g. the hash of the data (Zemler, 2019)). There are many reasons for using such approaches, including guaranteeing the integrity of the original data and minimizing the disclosure of information. Interestingly, blockchain is still used to share data, even if not in its original form.

3.6 Q6: have actors aligned interests to cooperate?

Blockchain systems are based on majority consensus, which can be reached if actors are incentivized to behave correctly according to some common rules. If actors do not have aligned interests, they are unlikely to join a blockchain network, and even if they did, they would be unlikely to follow the same rules. Thus, blockchain is applicable only if cooperating is advantageous for the actors and the actors are willing to cooperate (Naef *et al.*, 2022).

Often, public blockchains offer economic incentives to align the actors' goals and persuade them to behave correctly (Pan *et al.*, 2021a, b). Other forms of incentives are common in consortium blockchains. Often, such incentives come indirectly in the form of business opportunities and cost savings. In logistics, for example, sharing data can be beneficial for demand forecasting and paperwork reduction (Perboli *et al.*, 2020). Moreover, by tracking assets along the whole supply chain, it is possible to easily assign responsibilities to actors and reduce the risk of litigation (Perboli *et al.*, 2020). Thus, the actors of a supply chain may share a common interest that can enable and sustain long-term cooperation.

3.7 Q7: have misbehaving actors opposed interests?

Even if actors have a strong motivation to cooperate, they might have an even stronger motivation to cheat, which is particularly true when opportunities to make quick and easy gains arise. For this reason, it is important to ensure that misbehaving actors have conflicting goals so that one's gains would mean another one's loss. In this way, the risk of majority collusion attempts is minimized, as actors should behave against their interests to corrupt the system.

We examine the example of Bitcoin (Shang *et al.*, 2023). Each Bitcoin holder has a good motivation to misbehave and create new Bitcoins, as this would increase that holder's purchasing power. However, creating new Bitcoins inflates the existing supply, reducing the purchasing power of each other holder. Consequently, Bitcoin holders want to create Bitcoin for themselves while preventing others from doing the same. Thus, collusion attempts are unlikely, as Bitcoin holders have conflicting interests when misbehaving.

We now examine the example of a group of friends betting on the winner of a horse race. For simplicity, we assume that each friend picks a different horse. If the friends do not want to rely on trusted third parties, they could rely on a smart contract to collect the money in advance and then forward them to the winner: the verifiability and tamper-proof properties of the blockchain would guarantee the correct handling of the bet. Thus, blockchain may seem a good solution. Unfortunately, in this scenario, the majority of the friends will lose the bet and will likely collude to take back their money instead of forwarding the prize to the winner. Given those blockchain decisions (including the behavior of smart contracts) are based on majority agreements, the winner of the bet will not receive the prize. Thus, blockchain should not be employed when cheating attempts to favor the majority. Of course, if the contract is deployed on a public blockchain, then the friends' collusion would likely be insufficient, as only a global-scale collusion could invalidate the bet.

3.8 Q8: are all the relevant actors involved in the management of the system?

By leveraging blockchain, decisions can be taken through majority voting instead of being delegated to a trusted third party. Nonetheless, a blockchain system is a third party for the actors that do not have voting power. Thus, blockchain does not offer any additional trustworthiness guarantees to them, and blockchain members should not expect entities to acknowledge the trustworthiness of third-party managed blockchain systems.

In logistics, for example, consortium blockchains are often used to facilitate the exchange of data among supply chain companies (He *et al.*, 2022). Final retail consumers, however, are rarely part of the consortium, as they lack the means, the technical knowledge, the time, the economic incentives and the willingness to be involved in the consortium. To them, logistics blockchains are trusted third parties. Thus, supply chain companies should not join a blockchain system solely to increase data transparency for final consumers, as consumers have no reason to trust the data stored in a blockchain more than the data provided by their retailer. Thus, blockchain systems should be used to create value for their participants, not external entities.

3.9 Q9: are the actors sufficiently autonomous?

The resiliency of blockchain is proportional to its decentralization. Thus, actors should be as autonomous and independent as possible to guarantee sufficient resilience to errors and tampering attempts. If too many actors needed to rely on others to code smart contracts, keep an updated copy of the ledger, participate in the voting process, and validate transactions, then the blockchain would become seemingly decentralized but substantially centralized. In such a condition, blockchain does not offer any benefits over centralized systems but still imposes significant scalability drawbacks. Thus, blockchain should not be used if true decentralization cannot be guaranteed. In particular, decentralization cannot be improved by increasing the number of blockchain nodes managed by each actor, as distribution and decentralization are different concepts (Come-from-Beyond, 2020).

Nonautonomous actors are a threat to decentralization, as they rely on third parties that are potentially dishonest. Thus, nonautonomous actors might be exploited to strengthen the dishonest minority. Consequently, a small group of autonomous actors provides better decentralization and security guarantees than many nonautonomous actors.

3.10 Q10: should retroactive data manipulation be prevented?

Data stored in a blockchain can be considered tamper-resistant as long as the append-only property of the ledger is enforced by the honest majority. Thus, data cannot be manipulated after insertion if a blockchain is sufficiently decentralized, and updates can only be made by appending a newer version of the data to the ledger. Nonetheless, blockchain keeps both versions, allowing actors to track changes. Thus, blockchain is a good solution if preventing retroactive data manipulation is important (Mardiansyah and Sari, 2022). Nonetheless, if such a property is not relevant, standardizing the data exchange protocols among the actors is enough to share data efficiently.

In some scenarios, companies may prefer decentralized solutions to restrain themselves from performing retroactive data manipulation. Such a strategy can effectively increase the transparency and verifiability of the company's operations. For example, a poker service could use blockchain and multi-party computation (Zhong *et al.*, 2019) techniques to guarantee the fair extraction of cards and avoid accusations of favoring one of the players.

If preventing retroactive data manipulation is not a priority, each actor should manage its centralized database and use a standard data-sharing protocol to exchange information with the other actors. Interestingly, blockchains are sometimes adopted solely to enforce standardization (Olszewski, 2019).

3.11 Q11: should proactive data manipulation be prevented?

As previously discussed, blockchain can prevent retroactive data manipulation. Nonetheless, blockchain can rarely prevent proactive data manipulation (i.e. some manipulation that happens before the data is stored in the blockchain). In particular, oracle data can hardly, if ever, be verified and validated, as such data often convey information about the physical world (Bruni *et al.*, 2023).

In logistics, for example, the temperature of a frozen product at a given time is likely measured by the actor who is handling that product at that time. The other actors cannot measure such a temperature as they lack physical possession of the product. Thus, they need to rely on the accuracy of the handling actor's measurement, which they cannot verify. In such a scenario, blockchain is prone to the GIGO (garbage in, garbage out) problem (Chod *et al.*, 2020; Alkhudary *et al.*, 2022).

Conversely, Bitcoin transactions are fully digital, and each peer can independently verify them: by keeping a registry of the balance of each Bitcoin holder, each peer can determine who has enough coins to spend. Nonetheless, very few use cases can be modelled without relying on oracles, which limits blockchain usefulness when proactive data manipulation must be prevented.

3.12 Blockchain adoption decision counselor

The blockchain adoption decision counselor (BADC) is a tool that further simplifies the application of our decision-making framework. The tool is implemented by leveraging the angular framework (Novac *et al.*, 2021).

BADC exposes a graphical user interface that collects the user's answers and evaluates the feasibility of blockchain adoption. The tool proceeds to the next question as soon as the user answers the current one. Nonetheless, the user may decide to answer the questions in any order by selecting them through the slider. The results button loads a new view displaying BADC's evaluation of blockchain suitability (see Figure 2).

The evaluation view presents BADC's assessment based on suitability, usefulness and alternatives.

BADC classifies blockchain suitability into three categories: recommended, suboptimal and discouraged. The recommended category indicates that blockchain is the best technological alternative and that its adoption is encouraged. The suboptimal category indicates that blockchain is usable, but other technologies should be preferred. Nonetheless, other factors (e.g. economic or regulatory ones) could still make blockchain a good compromise. The discourage category indicates that blockchain is not applicable and should be avoided.

BADC also provides an evaluation of the usefulness of blockchain technology. In particular, BADC warns the user if blockchain is not sufficient to provide the expected value

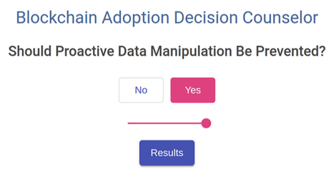


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Figure 2. The user interface of the BADC tool

proposition, for example, due to the presence of the GIGO problem. In some applications, blockchain may be coupled with additional technologies patching its shortcomings.

In addition to the previous classifications, BADC also suggests potential technological alternatives that may be preferable to the blockchain. Thus, decision-makers may follow the suggestion and change their technological orientation.

4. Use case: electric vehicle supply chain

This section discusses how we used our decision-making framework to determine the applicability of blockchain technology to a logistic use case based on the EV supply chain of a multinational company. We conducted such an activity in the context of the Cyber security cOmpeteNCe fOr Research anD InnovAtion (CONCORDIA) project (CONCORDIA Consortium, 2016).

The decision to consider a blockchain-based solution depends on the specific nature of the interactions among partners in an EV supply chain. In this supply chain, there are three main actors: the car manufacturer, the battery producer and the logistics provider. Traditionally, the car manufacturer has been the dominant player, often imposing its own supply chain monitoring system on the other two. Additionally, logistics and spare parts production have typically been managed by multiple companies. However, in the context of electric mobility, this business paradigm has changed significantly.

First, the battery producer is usually a single entity with decision-making power equal to that of the car manufacturer. Second, because batteries and their components require specific tracking of transportation parameters (e.g. temperature, charge level, etc.), the supply chain has become more similar to that of fresh food. Given the high volume of batteries, the need to transport them across several continents due to the concentration of battery producers in China, and the necessity to assemble them into car batteries in other regions, car manufacturers are compelled to use only one or, at most, two third-party logistics (3PL) companies (Fadda *et al.*, 2022).

This results in a three-actor system where no party can rely solely on the others' data storage systems, creating a need for data sharing to reduce potential litigation in the event of battery failures. As a result, blockchain has been identified as a promising technology for tracking the EV supply chain.

4.1 Use case description

The EV market is dominated by influential actors. The demand for electric batteries comes in large part from a few multinational companies, which are often battery cell suppliers' biggest clients. Moreover, a limited number of suppliers can fulfill the demand of EV manufacturers. Similarly, only a few shipping companies can handle the volumes imposed by such a large and distributed supply chain. Hence, the current market conditions impose the creation of long-lasting relationships, as changing partners is impractical.

Nonetheless, the current lack of timely, correct, authentic and verifiable information may hinder long-term commercial relationships. Companies do not want to pay for the errors of their partners but assessing responsibilities in a fair and verifiable way is difficult when data is scattered across multiple information systems, as reconstructing the sequence of events affecting a given battery or vehicle is not possible. In particular, shocks, high temperatures and an inappropriate state of charge may cause premature degradation of the batteries.

We worked with a multinational EV manufacturer to assess the suitability of blockchain in the context of their EV supply chain. Currently, battery cells are shipped by suppliers to the vehicle manufacturer's battery assembly plant. After being assembled, batteries are delivered to the vehicle assembly plant. A complex process is used to assemble vehicles, which are then shipped to the dealer. External logistic companies handle the transportation of the batteries. Sensors are used to monitor the batteries' temperature, position, vibration level and charge level. Currently, each company manages its information system and has limited visibility into events affecting batteries and vehicles managed by other companies in the supply chain.

The objective of the use case is to use Industry 4.0 technologies to improve the logistic processes in terms of cost and quality (Boccia *et al.*, 2021a, b). In particular, the use case presents some requirements.

(1) Companies want to track batteries and vehicles along the whole supply chain. The tracking system should guarantee the timely, safe, secure and cost-effective charging, monitoring and certification of the vehicles (batteries).

(2) Tracking information should be delivered in real-time to all the supply chain companies, which helps guarantee the safety of the operators and the correctness of the charge level at the moment of delivery.

(3) Different internal and external operators may recharge the vehicles (batteries) if needed.

(4) The charging service is provided in predefined areas by mobile or fixed devices.

(5) Cyberattacks targeting the charging areas put at risk both the vehicles and the power grid. Thus, charging areas should be carefully secured and monitored.

(6) Data should be shared only with the supply chain companies.

(7) The system should guarantee data correctness, authenticity, availability and integrity.

(8) Access to the companies' systems should be granted to trusted operators and any intrusion should be prevented and mitigated.

(9) The system should comply with the current regulations (e.g. GDPR).

(10) A universal source of truth should assign responsibilities to companies in case negative events arise. The responsibility assignment process should be fair, unambiguous, transparent and auditable.

4.2 Value proposition

A blockchain-based tracking system may comply with the majority of the requirements of our use case, as digitally signed transactions would be ordered, timestamped and recorded across multiple nodes. Thus, a blockchain could guarantee data authenticity, integrity and availability. Moreover, blockchain's transparency could improve the fairness and verifiability of the responsibility assignment process, and some cyberattacks could be neutralized or mitigated by blockchain's redundancy and resiliency. Thus, a blockchain-based system would enable the fair and unequivocal assignment of responsibility by linking adverse events, affected batteries, involved actors and the time of occurrence.

Sharing standardized data through a blockchain system may offer additional benefits to the partners. In particular, the additional data available to the partners may reduce decision uncertainty, improving the machine learning and optimization techniques applied to demand forecasting and production process scheduling (Boccia *et al.*, 2017). Moreover, information tracking could be used as a form of health guarantee for refurbished and used vehicles, increasing their market value (TechCrunch, 2022).

Nonetheless, blockchain also introduces many challenges (e.g. technical, economic and legal). However, a more pressing question should be answered before analyzing the potential benefits and obstacles of designing a blockchain-based solution: can a blockchain be used in the first place? In other words, do the fundamental assumptions of blockchain hold in this use case?

We describe the application of our decision-making framework to the previously described use case to answer such a fundamental question.

4.3 Decision-making framework application

In this section, we apply our decision-making framework to assess the suitability of blockchain for the examined EV supply chain.

4.3.1 Q1: should multiple actors have decision power?. A unified information system for the entire supply chain is desirable to prevent data from scattering across multiple information systems. Thus, such a unified system should be democratically managed by the totality of the supply chain companies.

4.3.2 Q2: do the actors trust a (third) party?. Supply chain companies are motivated to avoid responsibilities to reduce economic losses, making them unreliable. Moreover, external companies should not have access to the supply chain data. Thus, we could not identify a party that was trusted by all the supply chain companies.

4.3.3 Q3: do the actors trust the majority?. Current market conditions necessitate the creation of long-term relationships. The supply chain companies are likely trustworthy, as losing a client/supplier is likely to cause severe business drawbacks. We could identify ten different companies in the examined supply chain, each having a strong motivation to guarantee the quality of the final EV. Thus, the majority is likely trustworthy.

4.3.4 Q4: are the actors equally influential?. Actors have similar bargaining power in the examined use case. A few EV manufacturers drive the demand for electric batteries, a few battery suppliers can fulfil such demand, and a few logistic companies have the necessary means to handle such volumes. Of course, the supply chain also includes other minor companies which are likely to follow the decisions of the big players as they do not have sufficient influence to oppose them. Thus, the system is generally balanced overall, with no single company having enough influence on all the others.

4.3.5 Q5: is data sharing advantageous for the actors?. Data sharing allows for transparently assigning responsibilities and building long-term relationships among companies. Moreover, sharing standardized data may reduce decision uncertainty, improve demand forecasting and simplify production planning. By detecting failures in the early stages of the supply chain, it could be possible to improve the quality of the final EVs, which could be beneficial to the brand reputation of the supply chain companies.

4.3.6 Q6: have actors aligned interests to cooperate?. Currently, market competition is among supply chains, no longer among organizations (Li *et al*., 2006). Hence, supply chain companies have a strong motivation to cooperate, as the value perceived by the final consumer is a sum of the value generated by each link in the supply chain. Thus, supply chain companies' performance is tied to the performance of the supply chain as a whole.

4.3.7 Q7: have misbehaving actors opposed interests?. If a company damages the batteries (or the vehicles) and does not take responsibility for it, the economic loss will affect some other member of the supply chain. In the worst case, the final consumer will purchase a defective vehicle, which would have a negative impact on the reputation of the whole supply chain. Thus, each supply chain company has a strong motivation to prevent selfish behaviors and to request the maximum process quality from the other supply chain members. Thus, misbehaving collusion attempts are unlikely.

4.3.8 Q8: are all the relevant actors involved in the management of the system?. All the supply chain members are meant to participate in the blockchain-based shared information system, except for the final consumers, who lack the proper means and incentives to maintain a blockchain node and increase the level of security and decentralization of the system. Thus, the value of the blockchain system must be measured according to the benefits provided to the battery suppliers, the vehicle manufacturers and the transportation companies. The benefits to the final consumer must not be considered, even though every supply chain aims at maximizing the value produced for the final consumer.

The goal of the system is to assign responsibilities among the supply chain companies to create long-term cooperation, and all such companies could be included in the management of the blockchain system.

4.3.9 Q9: are the actors sufficiently autonomous?. The supply chain of our EV supply use case comprises both small and big companies. Big companies have the skills and financial resources to set up and manage their blockchain node, while small companies will likely rely on the services provided by the bigger ones. Nonetheless, the ten big companies of our use case should be sufficient to create a truly decentralized blockchain system.

4.3.10 Q10: should retroactive data manipulation be prevented?. Retroactive data manipulation must be prevented to create a unified and reliable record of the events affecting a given battery (or EV), which is necessary to fairly, transparently and verifiably assign responsibilities. Supply chain companies should be prevented from hiding or reassigning responsibilities by tampering with the record.

4.3.11 Q11: should proactive data manipulation be prevented?. Preventing proactive data manipulation is desirable. Supply chain companies should be prevented from storing incorrect or imprecise data in the blockchain system. However, on-field data is obtained by leveraging sensors, which introduces the GIGO problem: companies may manipulate the sensors, displace them or disrupt the communication between the sensors and the blockchain system to prevent the recording of unfavorable data. If data cannot be reliably collected, responsibilities cannot be correctly assigned.

4.4 Blockchain suitability assessment

From our assessment, blockchain can be applied to the examined use case, but it is not enough to guarantee the desired results. We believe that the adoption of a unified information system based on blockchain could determine an improvement over the currently adopted solutions, as it would prevent retroactive data manipulation. The previous assessment can also be obtained through the BADC tool.

Blockchain must be complemented with other technologies to provide the expected benefits. In particular, designing opportune strategies to reduce the likelihood of proactive data manipulation is important. For example, if the cost of manipulating a sensor is higher than the benefit produced by such manipulation, then it is reasonable to assume that the sensor is unlikely to be manipulated. To this extent, Narrowband-IoT technologies and the involvement of telecommunications operators could guarantee a sufficient degree of data reliability (Bellifemine *et al.*, 2019). Nonetheless, in this study, we do not address the proactive data manipulation problem and keep our focus on blockchain adoption.

Given the positive blockchain suitability assessment, we now discuss the implementation of our solution.

4.5 Technical assessment and framework selection

Our use case involves a set of requirements related to privacy, regulatory compliance and operational efficiency. For this scenario, permissioned blockchain platforms stand out as the most suitable option. They are purpose-built to address the typical needs of industrial applications, offering efficiency, adaptability and the ability to restrict network access to designated members. Nevertheless, the market offers a variety of permissioned blockchain frameworks to choose from. A previous study (Capocasale *et al.*, 2022a) conducted a comprehensive comparative analysis of the primary permissioned blockchain frameworks, including Hyperledger fabric (Guggenberger *et al.*, 2022), Sawtooth (Moschou *et al.*, 2020), Hyperledger Besu (Fan *et al.*, 2022) and Quorum (Mazzoni *et al.*, 2021). The analysis encompassed several critical dimensions, such as governance, maturity, support, privacy features, interoperability, flexibility, resiliency, latency, efficiency and scalability.

Consequently, we made specific decisions regarding framework selection. Hyperledger fabric was eliminated from consideration due to concerns surrounding data verifiability and resilience against potential malicious actors. Security and maintaining true decentralization are paramount for our use case. After evaluating framework performance, we also opted to discard Sawtooth. Although Sawtooth's performance likely meets our requirements, we favored more efficient frameworks. Lastly, we ruled out Quorum as it is exclusively supported by ConsenSys, whereas Besu benefits from support by the Hyperledger consortium (including ConsenSys). Furthermore, Besu boasts a more active community on Github, a crucial factor for technologies intended for long-term use. Additionally, both Quorum and Besu are Ethereum-based, enabling us to leverage a wealth of tools and resources developed for the Ethereum blockchain ecosystem.

4.6 System design

This section discussed the main choices made while designing the system. The obtained architecture is represented in Figure 3.

We established a blockchain network comprising four Besu nodes, leveraging the IBFT 2.0 consensus algorithm. Besu offers a robust framework for permissioning, consisting of three layers: node permissioning, account permissioning and API permissioning. Node permissioning governs peer connections, with each node exclusively allowed to connect to the other nodes within our system. Account permissioning regulates which accounts possess the authority to update the ledger. To enhance concurrency, we granted permissions to several thousand accounts for each organization. API permissioning, on the other hand, controls which clients are authorized to invoke a node's API methods. To restrict access to known clients, we employed Keycloak and the OpenId Connect Client Credentials grant. It's crucial to note that account permissioning can be enforced at the network level, whereas node and API permissioning can only be enforced at the node level. Consequently, malicious nodes are unable to execute unauthenticated write operations but can respond to unauthenticated read

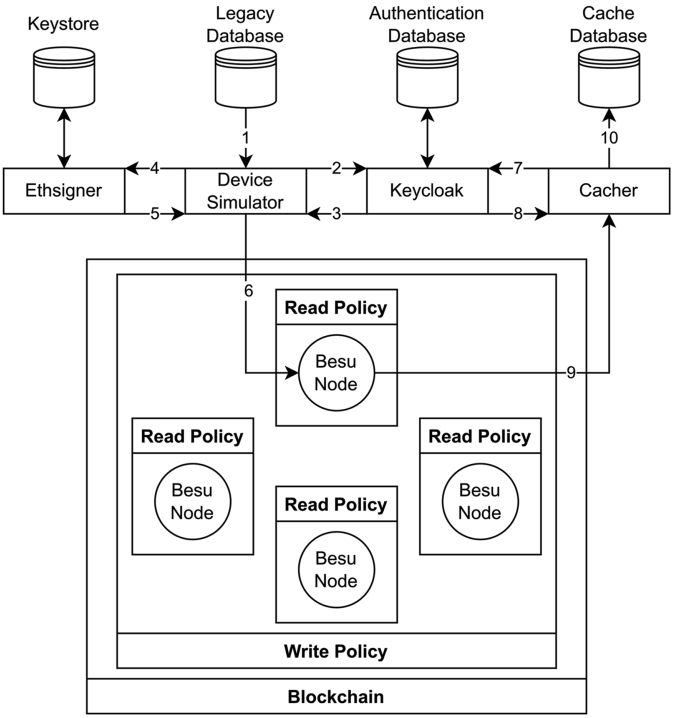

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Figure 3. Architecture of our solution

attempts. This constraint is a common limit of blockchain systems and may influence the technology's adoption. Once again, it's important to highlight that while blockchain enhances data integrity and availability, it does so at the cost of diminished confidentiality.

To persist production data within the blockchain, we employed multiple clients and relied on Ethsigner for secure private key management. Specifically, clients, after obtaining a valid access token from the Keycloak server, interact with the Ethsigner service by submitting unsigned transactions. The Ethsigner service signs these transactions and returns them to the clients, which can then submit the signed transactions to the blockchain network. This approach eliminates the need for clients to possess cryptographic modules for transaction submission, which can be particularly advantageous for resource-constrained devices.

Within Besu, data can be stored in logs or contract storage. Logs are updated whenever a smart contract emits an event and serve as a cost-effective storage option. However, smart contracts cannot directly access log data. Instead, smart contracts have direct access to contract storage, which they use to persist their state. Nonetheless, storing data in contract storage is less efficient (Chow, 2016). We leveraged logs to maintain simplicity and efficiency in our smart contracts ad employed an event listener to duplicate blockchain data into an external relational database, labeled as the "cache database" in Figure 3. The cache database serves a dual purpose: it simplifies the integration of our system with legacy applications and relieves the blockchain nodes from the burden of responding to queries. It's essential to note that on-chain data remains unencrypted, as data sharing constitutes the core objective of adopting blockchain technology.

4.7 Performance evaluation

The adoption of blockchain hinges on its ability to efficiently process the data requirements of production systems. To rigorously assess the performance of our system, we incorporated actual production data into our evaluation.

Our testing encompassed a variety of AWS instance families to gauge the impact of critical factors, including RAM size, CPU count, and network bandwidth. Our network configuration comprised four Hyperledger Besu v21.1.0 nodes. Initially, we experimented with versions v22.7.4 and v22.7.6, but encountered reliability issues marked by frequent crashes. Consequently, we reverted to v21.1.0 for stability. We connected a single client to each node, with a coordinating service directing the clients in workload submission and synchronizing their interactions with the blockchain.

Workloads consisted of 1,600 transactions, evenly distributed at 400 transactions per client. These workloads were introduced into the blockchain at varying input rates. Our performance metric centered on the number of transactions processed per second (TPS), measured from the moment the coordinator initiated the workload until the final client completed its task.

We assessed three distinct instance families within the AWS ecosystem:

(1) AWS r5a.large instances, optimized for memory.

(2) AWS m5n.large instances, offering general-purpose capabilities with substantial bandwidth.

(3) AWS c6a.xlarge instances, tailored for compute-intensive tasks.

The outcomes of our performance evaluation are presented in Figure 4.

Notably, AWS c6a.xlarge instances outperformed the others. These instances are equipped with four vCPUs, twice the count found in the other two instance families. AWS m5n.large instances exhibited marginally superior performance compared to r5a.large instances, which we attribute to differences in their respective processor types. Thus, the enhanced network bandwidth of m5n.large instances and the augmented RAM in r5a.large instances may not significantly enhance the performance of our blockchain system. This outcome underscores that the present configuration's bottleneck resides in the performance of vCPUs.

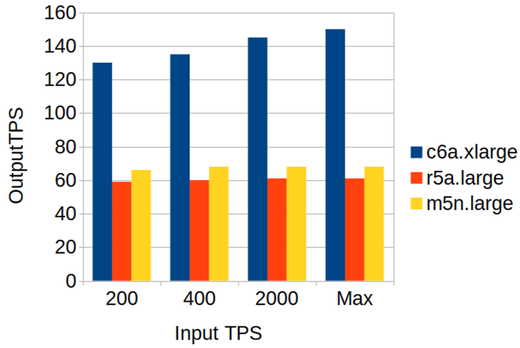

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Figure 4. Performance evaluation with multiple AWS instance families

5. Conclusions

Interest in blockchain technology is surging among individuals, countries and companies. Yet, the path to blockchain adoption is far from straightforward, given its complexity, which necessitates a reevaluation of traditional problem-solving approaches from a decentralized standpoint.

This work introduces a decision-making framework designed to help readers evaluate blockchain adoption. We explore various decision drivers that determine whether blockchain is not only applicable but also valuable and preferable to alternative technologies. Our framework offers a unique resource for decision-makers by encompassing key factors often overlooked in existing literature.

It has significant implications for both research and practice. For researchers, it provides a structured methodology that can be tested, refined and expanded across different industries and technological contexts. For practitioners, the framework serves as a guide to making informed decisions about whether and how to implement blockchain technology, potentially leading to more successful and sustainable adoption. Additionally, by highlighting the need for complementary technologies alongside blockchain, the framework encourages a holistic approach to technology integration, which is critical for addressing blockchain's inherent limitations.

Notably, the framework is accessible to individuals without an in-depth understanding of blockchain intricacies, enabling managers to drive blockchain adoption efficiently within their organizations without requiring extensive blockchain expertise.

Through practical application in a logistics use case centered on a multinational EV supply chain, we found that blockchain applications can be advantageous. However, it is vital to recognize that blockchain must be complemented by other technologies—for example, to solve the GIGO (garbage in, garbage out) problem. Our framework underscores the critical relationship between decentralization and blockchain system security. A key takeaway is that blockchain should only be considered when a sufficient level of decentralization can be assured.

Future research should explore the application of this framework in different industries, such as healthcare, finance and logistics, to assess its adaptability and robustness across various contexts. Additionally, studies should examine how the framework can be integrated with other decision-making tools and methodologies to create a more comprehensive approach to technology adoption. While our framework primarily addresses the technological perspective of blockchain adoption, successful implementation hinges on various factors, including economic, legal and human considerations.

As part of future work, we aim to expand our framework to encompass these additional dimensions, offering comprehensive support for decision-makers navigating the multifaceted landscape of blockchain adoption. Another avenue for future research could involve developing blockchain-based solutions that prioritize data privacy and security, addressing the growing concerns about digital trust in an increasingly connected world.

The framework presented in this paper is a first step toward a more systematic approach to blockchain adoption. However, as blockchain technology and its applications evolve, so must the tools and frameworks used to evaluate its suitability. Continuous refinement and adaptation of this framework will be essential to ensure that it remains relevant and effective in guiding decision-makers through the complex landscape of blockchain adoption.

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