Decentralizing Electric Vehicle Supply Chains: Value Proposition and System Design

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***Abstract*—Distributed ledger technologies are transforming existing business models and business relationships. In particular, blockchain allows non-trusting parties to manage a shared database in a decentralized way and improve the transparency, authenticity, and reliability of the exchanged data. Nonetheless, decentralized paradigms are not yet well established, resulting in only a fraction of blockchain-based applications being successful in the long term.**

In this paper, we present a blockchain-based solution for the electric vehicle supply chain that we designed in the context of the CONCORDIA project of the European Cybersecurity Competence Network. We describe the goals, the value proposition, the main design choices, and the architecture of our system. Moreover, we discuss the electric vehicle supply chain, analyzing the improvements and limitations introduced by our blockchain-based solution. We analyze our solution from the managerial and technical points of view through a lean business methodology for blockchain solutions. In particular, we developed an economic impact assessment to evaluate the potential costs and revenues of the application of blockchain technology in a supply chain context. Although the blockchain system is inspired by the supply chain of a multinational automotive company, it can be applied to any other multi-actor supply chain.

***Index Terms*—Blockchain, electric vehicles, supply chain, Hyperledger Besu, GUEST method, Lean Business.**

I. Introduction

THE electric vehicle market is dominated by a few big actors. In particular, battery producers and vehicle manufacturers have similar bargaining power. On one side, vehicle manufacturers are often the biggest clients for their suppliers. On the other side, very few suppliers can fulfill vehicle manufacturers' battery demands. Hence, long-lasting relationships are almost forced by the current market conditions, as changing partners is not possible.

Nonetheless, the current electric vehicle supply chain is affected by issues that may hinder the creation of long-term relationships. Frequently, batteries and vehicles never reach the final consumer or require early maintenance operations since shocks, high temperatures, and an inappropriate state of charge may cause premature degradation of the battery cells. However, assigning responsibilities is difficult as each company manages a separate information system: reconstructing the sequence of events affecting an object is challenging when data is scattered. Thus, companies may end up paying for the errors of their partners, which hinders long-term cooperation.

Peer-to-peer technologies such as the blockchain [23] and the Interplanetary File System [7] may provide a solution to the current electric vehicle supply chain issues. In particular, blockchain allows a set of non-trusting parties to decentralize the management of a shared database improving the transparency, authenticity, and reliability of the exchanged data [27, 1].

In the context of the Cyber security cOmpeteNCe fOr Research anD InnovAtion (CONCORDIA) project [12], we designed a system to improve the tracking of electric batteries and vehicles, which allows us to fairly assign responsibilities: we monitor the state of batteries and vehicles and record the collected data in a blockchain ledger. In particular, the data in the blockchain is ordered and timestamped, which allows for verifying which actor is handling a given object when a harmful event occurs. The blockchain-based solution is developed by considering the guidelines of the lean methodology presented in [28], one of the main methodologies for deploying a blockchain-based solution in supply chain and logistics. We show how a blockchain-based solution can boost the electric vehicle market, reducing litigation costs and improving the trust of the parties.

The remaining part of this paper is structured as follows: Sec. II summarizes the main background concepts, Sec. III outlines the value proposition of the proposed solution, Sec. IV describes the implementation of the proposed solution, and Sec. V concludes the paper.

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II. Background

This section introduces the main concepts used in this study, summarizes the related works, and identifies the main contributions provided by this study.

A. *Electric Vehicle Supply Chain*

In the context of this study, we focus on an electric vehicle supply chain inspired by the supply chain of a multinational automotive company. In particular, battery cells produced by the suppliers are delivered to the vehicle manufacturer's battery assembly plant. After being assembled, battery packs are delivered to the vehicle assembly plant. At this point, vehicles are assembled through a complex process [4] and then shipped to the dealer. The transportation of battery packs is usually performed by external logistic companies, and the temperature, position, vibration level, and charge level of the battery packs are constantly monitored by sensors. Such data are collected by and persisted in an existing tracking system.

B. *Blockchain, Smart Contracts, and Oracles*

Blockchain enables data sharing among non-trusting parties without relying on trusted intermediaries. Blockchain is a database that can be updated through majority voting. Data can only be added to the database, which is named the ledger. Each party manages a copy of the ledger and has full control over its copy, but the global state of the ledger is decided based on what the majority of the copies stores [18, 23].

Smart contracts are computer programs that each party executes to update its copy of the ledger. Thus, only accidental or deliberate errors affecting the majority of the independent executions may alter the correct behavior of smart contracts. Thus, smart contracts are tamper-resistant computer programs that may be used to automate even mission-critical tasks [8, 19].

Oracles provide data to blockchain systems that cannot be otherwise obtained. Oracles are trusted third parties, as the provided data cannot be verified. However, oracles can rarely be eliminated from blockchain systems. Thus, oracles provide a fundamental service to blockchain systems but introduce the *garbage in, garbage out* (GIGO) problem [5].

C. *Related Works*

Blockchains can improve various electric vehicle-related business processes. Some authors described generic vehicle traceability and battery health monitoring systems based on various technologies (e.g., Hyperledger Fabric [24, 16], IOTA [14, 15], and Ethereum [15, 33]). A solution for tracking pre-owned electric vehicles through a hybrid blockchain is described in Ref. [29]. In Ref. [21], the authors proposed an algorithm to detect abnormal battery charging and designed a blockchain-based solution for collecting battery data. The authors empirically demonstrated the effectiveness of their solution by leveraging a public battery data set [21]. Some authors designed blockchain solutions to improve the security of battery management systems [3, 22].

A few authors analyzed the issues of the current electric vehicle supply chain and the main benefits related to blockchain adoption for battery recycling [9, 10]. Some authors proposed blockchain-based policies to favor battery recycling [10] and vehicle sales [30].

Due to space constraints, we redirect the reader to [2] for a comprehensive outlook of the current blockchain applications in electric vehicle supply chains.

D. *Problem Statement*

Our analysis of the related works highlights that many studies focus on generic supply chains and validate their results through laboratory experiments. However, production-level system designs and on-filed experiments are necessary to adopt blockchain in industrial environments. This study represents a step in such a direction, as we describe the application of a blockchain solution to a supply chain inspired by a multinational automotive company. In particular, we discuss the current challenges of the electric vehicle supply chain, the value proposition of the proposed blockchain solution, the architecture we designed, and the tests we performed with real data.

III. Objectives, Value Proposition, and Limitations

This section presents our solution's benefits and limitations from a managerial standpoint.

A. *Value Proposition*

The members of a supply chain can create long-lasting relationships by adopting a common source of truth to assign responsibilities. To this extent, blockchain can be leveraged instead of involving trusted third parties. Thus, a blockchain-based system would allow us to fairly and unequivocally assign responsibilities by linking harmful events, batteries affected, handling actors, and time.

Of course, actors may find ways to trick or circumvent the monitoring process, as discussed in Sec. III-C. However, we believe that the risks related to cheating surpass the actual benefits. Moreover, data can be altered only before being added to the blockchain, and the system is automated, which means that only carefully planned cheating attempts could go unnoticed. Thus, the system acts as a deterrent against malicious behaviors.

Finally, sharing standardized data through a blockchain system may offer additional benefits to the partners. In particular, blockchain implicitly solves some cybersecurity problems (e.g., ransomware and denial-of-service attacks). Moreover, the additional data available to the partners may be used to reduce decision uncertainty, which could improve the machine learning and optimization techniques applied to demand forecasting and logistic process scheduling. For example, costs could be reduced by detecting failures in the early stages of the supply chain. Similarly, brand reputation could be improved, as tracked vehicles are less likely to require early maintenance. Moreover, information tracking could be used as a form of health guarantee for refurbished and used vehicles, increasing their market value [31, 20].

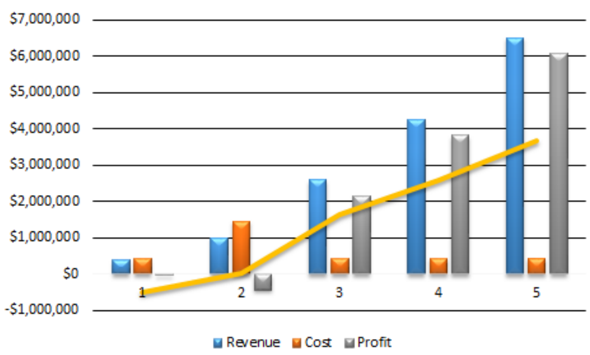

Fig. 1. Economic impact assessment results.

B. Economic Impact Assessment

We developed an evaluation framework to evaluate the economic impacts of the application of a blockchain framework in a supply chain context. The costs related to the development and maintenance of the infrastructure are evaluated considering three different time horizons.

- Pilot phase: in this phase, the main sources of costs are the design and development of the infrastructure and the administrative tasks (e.g., the design of the governance model, the commercial contract negotiations, and the compliance with national policies and laws).
- Commercialization phase: in this phase, the IT-related costs are mainly related to the full development and upscale of the infrastructure. Other costs are related to the administrative and legal efforts to define the commercial contract negotiation and the governance model.
- Ongoing (running) phase: in the third phase, the main costs are related to the administrative efforts and the maintenance of the infrastructure.

It is possible to highlight the following revenue stream sources:

- Blockchain revenues: these revenues come from transaction fees for smaller actors and annual fees for larger ones.
- Capital expenditures savings.
- Operational expenditure savings. They also include efficiency savings: cost reduction comes from optimizing activities and processes, enabling streamlined documentation, labor cost reduction, and legal cost reduction (by reducing conflicts and litigations between different actors).

A first economic impact assessment of our use case was conducted with the collaboration of some managers of the automotive company. The results are reported in Fig. 1 and outline a potential simulation of the costs and revenues in 5 years. As shown, in the first two years the costs are higher than the profits, while revenues start to grow from the third year.

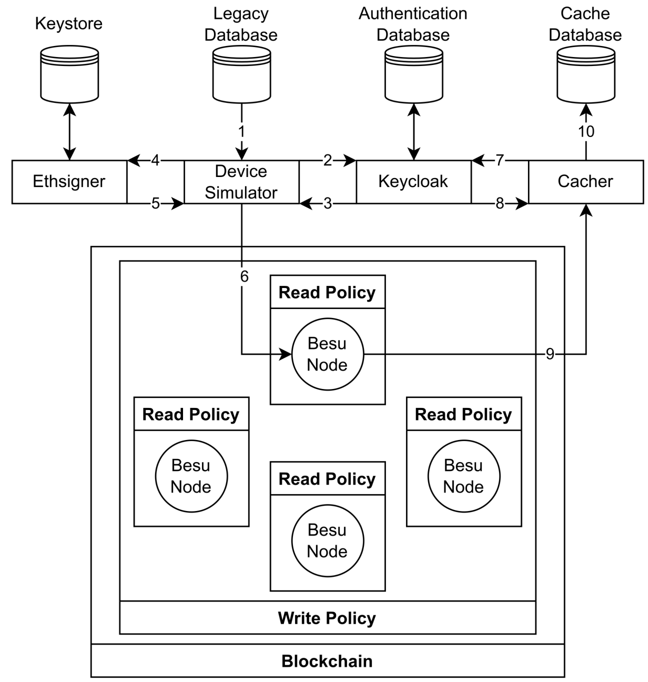

Fig. 2. Simplified architecture.

C. Limitations

Even if the system represents an improvement over the existing solution, it is subject to some limitations.

The system is affected by the GIGO problem, as it relies on oracles (i.e., sensors) to collect on-field data. Thus, proactive data manipulation is possible by tampering with or displacing the sensors. This risk can be mitigated by leveraging the Narrowband-IoT technology and the cooperation of the Internet Service Provider [5]. Moreover, the blockchain system prevents retroactive data manipulation, a guarantee that currently used centralized solutions cannot provide.

Due to the scalability trilemma, centralized solutions are more efficient than blockchain ones. Thus, we decided to store in blockchain only tracking information and those negative events that may compromise the health of the batteries. Consequently, jammers could be used to disrupt the communication between the monitoring sensors and the blockchain network, preventing the registration of negative events.

Finally, even if the system enables the assignment of responsibilities, smart contracts do not have legal value by themselves, and traditional contracts are necessary to legitimate them [8]. Nonetheless, we believe that companies are likely to accept their responsibilities even without legally binding agreements, as long-term cooperation is their main objective.

IV. System Design

This section discussed the main choices made while designing the system. The obtained architecture is represented in Fig. 2.

A. Framework Selection

Permissioned blockchain platforms answer common industrial needs: they limit network access to selected members and are efficient and flexible. Many permissioned blockchain frameworks are available in the market, and some comparative analysis of the main solutions are available in the literature [6]. As a result, we focused on Hyperledger Fabric [17], Hyperledger Sawtooth [26], Hyperledger Besu [13], and Quorum [25]. Based on the assessment of the performance of the frameworks [6], we decided to discard Sawtooth. Sawtooth's performance might be sufficient for our use case, but we preferred to adopt more efficient frameworks. We discarded Hyperledger Fabric, which does not offer any official implementation of Byzantine fault-tolerant consensus protocols [6]: true decentralization and security are key factors for our use case. Both Quorum and Besu are Ethereum-based, which means we can leverage many of the tools developed for the Ethereum blockchain. However, we discarded Quorum as it is supported by ConsenSys only, whereas Besu is supported by the Hyperledger consortium (which includes ConsenSys). Moreover, Besu's community is more active on Github [6], which is relevant for technologies that must be used in the long term.

B. Smart Contracts

In Besu, data can be stored in logs or in contract storage. Smart contracts can directly access contract storage to persist their state. However, persisting data in contract storage is expensive [11]. Logs are cheap forms of storage that are populated each time a smart contract emits an event, but they cannot be directly accessed by smart contracts. We decided to keep smart contracts simple and efficient. In particular, we used smart contracts only to check permissions and emit events. Thus, we used blockchain to order transactions and moved any additional logic off-chain. In particular, we duplicated blockchain data in a relational database (indicated as cache database in Fig. 2) through an event listener. Such a database stores the state of the blockchain and is updated by off-chain smart contracts. The consistency of the system is preserved, as the total order of transactions enforced by the blockchain guarantees that all the honest peers reach the same state [8].

C. Simplified Architecture

Blockchain adoption is challenging if blockchain-based solutions cannot process all the data required by production systems. For this reason, we used some production data to evaluate the performance of our system. We decided to implement many of the features that would be present in a production environment to obtain meaningful results. In particular, we created a blockchain network of four nodes using the IBFT 2.0 consensus algorithm. The data stored in the blockchain is also persisted in the cache database. The cache database solves two issues: legacy application integration and query offloading. On-chain data is not encrypted, as data sharing is the objective of adopting blockchain technology. Besu offers three layers of permissioning: node permissioning, account permissioning, and API permissioning. Node permissioning regulates peering. Only connections to other nodes of our system are allowed. Account permissioning regulates which accounts can update the ledger. We generated and granted permissions to a few thousand accounts representing IoT devices. API permissioning authorizes selected devices to invoke a node's API methods. We used Keycloak and the OpenId Connect Client Credentials grant to restrict access to known clients. It is important to underline that account permissioning can be enforced at the network level, while node and API permissioning can only be enforced at the node level. Thus, Byzantine nodes cannot perform unauthenticated write operations but can answer unauthenticated read attempts. Such a limitation is common to all blockchain systems, which may limit the adoption of the technology. We used multiple clients to persist production data in the blockchain and Ethsigner to handle the private keys safely, enabling the integration with low-end IoT devices. In the future, such devices will be replaced by newer ones that are equipped with cryptographic modules.

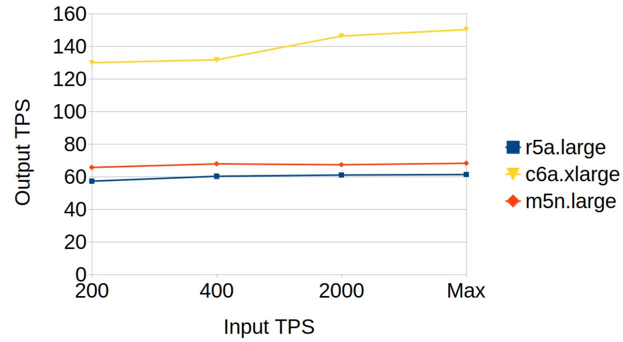

Fig. 3. Performance evaluation with multiple AWS instance families

D. Performance Evaluation

We tested our system on different AWS instance families to evaluate the impact of various factors, including the RAM size, the number of CPUs, and the network bandwidth. We used Hyperledger Besu v21.1.0 on all four nodes, as versions v22.7.4 and v22.7.6 turned out to be unreliable due to frequent crashes. We connected a single client to each node. A coordinator service instructs the clients on the workload to submit and synchronizes their interaction with the blockchain. We used workloads of 1600 transactions (400 per client) that we submitted to the blockchain at different input rates. We measured the number of transactions processed per second (TPS) from when the coordinator submits a workload to the clients to when the last client completes the task. We used three types of instance families: AWS r5a.large instances are memory-optimized, AWS m5n.large instances are general purpose with large bandwidth, and AWS c6a.x large instances are compute optimized. The results of our performance evaluation are shown in Fig. 3.

AWS c6a.xlarge instances offer the best performance: such instances are equipped with four vCPUs, which is twice as much as the other two instance families. AWS m5n.large instances have slightly better performance than r5a.large instances, but we believe such a difference is a consequence of the different types of processors leveraged by the two families. Thus, the additional network bandwidth offered by m5n.large and the additional RAM provided by r5a.large instances may not improve the performance of our blockchain system. This result indicates that the bottleneck of our system is the number of vCPUs in the current configuration.

All the machines we used are rather cheap, and we believe better results could be obtained with better-performing instances. Nonetheless, the obtained performance is sufficient to satisfy the efficiency requirements of our use case.

V. Conclusion

This study analyzed the application of blockchain technology to a multinational company-inspired electric vehicle supply chain. We discussed the economic impact of the technology and designed a permissioned system based on Hyperledger Besu. Future developments may focus on integrating the Interplanetary File System to improve the system's scalability in terms of storage requirements. Moreover, additional efforts will be made to create a production-grade blockchain solution, as well as integrating the sustainability issues in the solution [32].

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