Towards a Methodological Approach for the Definition of a Blockchain Network for Industry 4.0

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Abstract: The Industrial Internet of Things is expected to attract significant investments for Industry 4.0. In this new environment, blockchain has immediate potential in industrial applications, providing immutable, traceable and auditable communication. Blockchain gained prominence in the academy, being developed and evaluated in several application areas. However, no study has presented methodologies to definition blockchain networks in the industrial environment. To fill this gap, we present a methodology that presents paths to follow and important aspects to be analyzed for the definition and deployment of a blockchain network architecture. This methodology can help in the appropriate choice of platforms and parameters of blockchain networks, resulting in a reduction of costs for the factory and safety in meeting deadlines for industrial processes.

1 INTRODUCTION

Today, at the start of the fourth industrial revolution, the role of industrial networks is becoming increasingly crucial, as they are expected to meet new and more demanding requirements in any new operational context (Vitturi et al., 2019). A notable example in this regard is the widespread adoption of Industrial Internet of Things (IIoT), which requires a fast and reliable connection to all industrial systems and equipment, especially real-time systems. This scenario requires connectivity security even for the most remote field devices through adequate communication systems and interfaces.

Communication networks applied in an industrial environment are used to monitor conditions, manufacturing processes, predictive maintenance and decision-making. These networks have typical configurations, traffic and performance requirements that make them different from traditional communication systems generally adopted by applications in homes. Thus, industrial networks are designed to meet the requirements derived from their various fields of application, as well as the new scenarios generated by IIoT. The most critical requirements are: time, reliability and flexibility (Felser, 2005).

Unlike many network protocols and information systems already widely adopted in homes and businesses, Machine-to-Machine (M2M) communication protocols and Industrial Process Automation Systems (IPAS) are designed for specific industrial environments. IPAS are usually based on a five-level hierarchy, widely known in the automation field as the IPAS pyramid (Sharma, 2016). These systems are generally adopted for continuous industrial processes, such as oil and gas distribution, power generation and management, chemical processing and treatment of glass and minerals.

The vertical and horizontal integration of IPAS causes the traditional view of the IPAS pyramid to disappear. Systems, such as business management, and manufacturing, will change dramatically, while others will be replaced by applications that quickly emerge within the scope of IIoT platforms (Pérez-Lara et al., 2018). When integration is automated, all information can be collected and sent automatically from the various systems implanted in a factory to any of the parties involved. In this context, blockchain can decentralize or support decision-making in internal processes of a factory and external processes in a supply chain. This approach can make industrial automation systems fully decentralized and automated.

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Blockchain-based M2M communication can benefit the horizontal and vertical integration of IPAS, creating an immutable IIoT data flow from the control and production level to the decision-making levels (Wang et al., 2020). In addition, the inherent characteristics of blockchain in integration can ensure that industrial processes are auditable, generating greater confidence in decision-making. However, the incorporation of the entire blockchain network infrastructure to control processes in the industrial environment without careful analysis, can lead to a loss of time and resources, and even compromise time-sensitive industrial processes.

Given this research problem, this work aims to discuss several aspects related to the industrial environment in relation to blockchain. In view of this discussion, a methodology for the proper definition of blockchain networks in an industrial environment is presented. This methodology presents aspects of applicability, analysis, and parameters of blockchain networks according to specific contexts of the industry. This approach facilitates the deployment of blockchain networks, avoiding waste of resources or that the deadlines of industrial processes are compromised by the performance of the blockchain network.

The remainder of this article is organized as follows. Section 2 presents the background for understanding this work. Section 3 presents the related work. Section 4 presents blockchain issues and challenges in the industrial context. Section 5 presents the proposed methodology. Section 6 presents an application of the methodology in an industrial proof of concept. Finally, Section 7 presents conclusions.

2 BACKGROUND

Industry 4.0 refers to the revolution that transforms manufacturing systems into cyber-physical systems, introducing emerging information and communication paradigms.

2.1 Integration of Industry

One of the concepts of industry 4.0 is to have greater integration between processes and sectors in factories exchanging information in a faster and more efficient way for faster decision-making in order to increase productivity, decrease losses, optimize resources and lead to digital transformation. Therefore, integration is one of the pillars of industry 4.0 and aims to connect different areas, in order to extract information that will be used to make continuous improvements throughout the production process (Xu et al., 2018).

Each process of the factory dynamics generates and is supplied with data. In an environment without integration, there is the work of capturing all the information generated by one stage of the manufacturing process and supplying the next, this is often done manually, inefficiently and analogically. The lack of integrated systems also means that management levels have a much greater work of analyzing whether what is being manufactured really matches the demand received and whether suppliers and distributors are aligned with this production (Pérez-Lara et al., 2018).

As the processes are diverse and involve different agents in a factory, the concept of integration aligned to industry 4.0 was divided into horizontal and vertical integration. As shown in Figure 1, horizontal integration concerns the entire production chain, while vertical integration integrates the functions developed in the factory. To achieve the best results, there must still be an interaction between vertical and horizontal integrations to unite processes and optimize production as a whole.

For the factory, horizontal integration represents synchrony, loss reduction, and a saving of resources as the demand of suppliers is adjusted to the demand of customers. Besides, the higher quality of the products increases the consumer confidence index towards the factory, which generates customer loyalty. Also, with delivery control and distribution monitoring, it is possible to be sure that deadlines are met and also to generate data to predict more accurate deliveries.

Vertical integration creates a flow of data between all IPAS levels more quickly and efficiently, reducing the time for decision-making and improving the industrial management process. Therefore, vertical integration is in place when the employees, computers, manufacturing machines are linked with each other, communicate automatically with each other, and their interaction exists not only in the real world but also in virtual reality, in the model of the entire system.

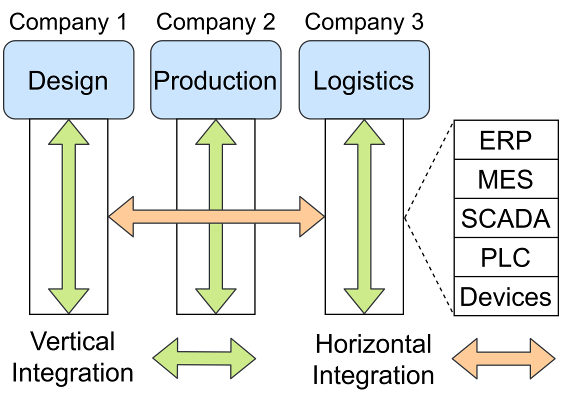

Figure 1: Horizontal and vertical integration of industry.

2.2 IPAS Hierarchy

IPAS comprises many devices, logically positioned at various hierarchical levels (see Figure 2) and distributed over large geographic areas (Sharma, 2016).

The field device level contains sensors and actuators. The process control level consists of Programmable Logic Controllers (PLC) and Distributed Control Systems (DCS) that provide an interface for Internet Protocol (IP)-based network communication. At the supervision level, the processes are monitored and executed by factory workers through systems such as Supervisory Control and Data Acquisition (SCADA). Finally, corporate and factory management levels make decisions based on production level data through the Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP).

At the top of the IPAS pyramid, the systems are asynchronous, while at the bottom of the pyramid the processes are mainly synchronous and critical in real time. At the bottom of the pyramid, control systems have evolved into a state where they are distributed and controlled by M2M communication. Blockchain can guarantee decentralized and reliable M2M communications, in which network nodes do not need a reliable intermediary to exchange messages.

2.3 Blockchain and Smart Contracts

The blockchain network is a decentralized P2P network, without failure points, whose transactions cannot be deleted or altered. Blockchain is highly scalable, and all transactions are encrypted, making them secure and auditable. As illustrated in Figure 3, at the heart of this technology, there are consensus algorithms, which are protocols designed to achieve reliability in a network of multiple untrusted nodes (Banerjee et al., 2018). Currently, there are two types of consensus algorithms:

- Crash Fault Tolerance (CFT): regular fault-tolerant algorithms, when it occurs to system malfunctions in network, disk or server crash down, they can still reach agreement on a proposal. Classic CFT algorithms include Paxos and Raft which has better performance and efficiency and tolerate less than a half of malfunction nodes;
- Byzantine Fault Tolerance (BFT): Byzantine fault-tolerant algorithms, besides regular malfunctions happen during consensus, it can tolerate Byzantine fault like node cheating (faking execution result of transaction, etc.). Classic BFT algorithm includes Practical Byzantine Fault Tolerance (PBFT), which has lower performance and tolerates less than one third of malfunction nodes.

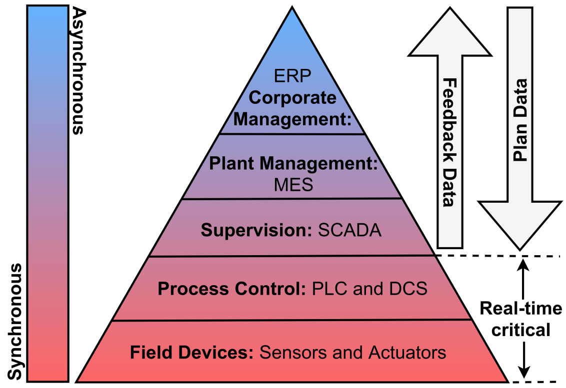

Figure 2: IPAS hierarchy levels.

Blockchain can be permissionless or permissioned (Wüst and Gervais, 2018). In the permissionless network, transactions are validated by public nodes. In a permissioned network, transactions are validated by a group of nodes approved by the blockchain owner, providing a more scalable and faster approach, but it is more centralized. Permissionless systems are open for all nodes to participate and thus provide a more decentralized approach where the trade-off is speed and scalability. Generally, permissionless network, to increase network security and stability, consensus algorithms apply a mining process that requires effort from participants. For a permissioned network, where all nodes are known and configured individually, there is no inherent need to incentive miners.

A smart contract is a computer protocol intended to digitally facilitate, verify, or enforce the negotiation or performance of a contract. Ethereum, Hyperledger (Fabric, Sawtooth), and Corda are popular smart contract platforms that are contributing significantly to the generation of Decentralized Applications (DApps) (Voulgaris et al., 2019). As illustrated in Figure 3, DApp query the blockchain network through a network node that executes the smart contract for the ledger access. A decentralized oracle network (DON) is used to establish a reliable connection with the external blockchain. External communication follows the rules of a protocol that encourages all nodes to tell the truth and punishes them for lying.

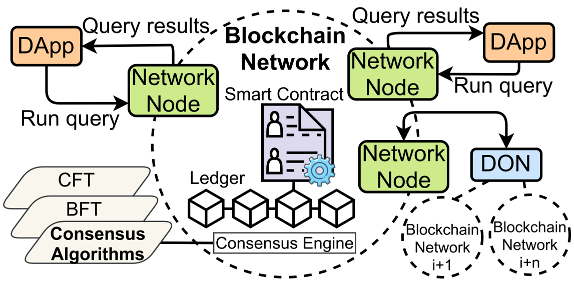

Figure 3: Blockchain-based smart contracts operation.

3 RELATED WORK

Blockchain can increase the automation and security of industrial processes. In this sense, following the protocol of (Kitchenham, 2004), a research was carried out to identify methodological solutions for the integration of blockchain in the industrial context. The results of this review showed that several articles propose methods to facilitate the blockchain development process. Through research and situational method engineering, the work (Fridgen et al., 2018) proposes a method for the development of blockchain use cases. The work (Wessling et al., 2018) proposes an approach to decide which elements of a system can benefit from the use of blockchain. In the work (Jurgelaitis et al., 2019), a method based on Model Driven Architecture is proposed, which can be used to define and specify the structure and behavior of the blockchain. Finally, the work (Bettín-Díaz et al., 2018) presents a methodology for integrating blockchain into the food industry supply chain, in order to understand the product life cycle.

As can be seen in recent related work, the main objectives are to understand how to relate the product process to the functioning of the blockchain and to analyze the benefits of this integration. Thus, despite a great theoretical context presented by the related works and the discussion of some aspects related to blockchain structure and technologies, it is not presented in depth how to define, develop, configure and deploy blockchain architectures and networks in practice. Another important aspect is the metrics and scenarios for evaluating such approaches. As seen in recent studies (Fan et al., 2020), performance evaluations are often based on metrics like transactions per second on the blockchain network. However, these metrics do not take into account delays generated by encrypting data and creating transactions on IIoT devices that can have a greater influence on performance and affect the timelines of time-sensitive processes.

It is understood, therefore, that the problems presented may make it difficult or even impossible to deploy a blockchain network in an industrial plant. In this context, this work seeks to fill this research gap, presenting a methodology for implementing blockchain networks in the industrial environment. Unlike related works, this proposed methodology presents paths to follow and important aspects to be analyzed during the study for the definition of a blockchain network. In addition, the methodology presents important parameters and technologies to assess the performance of the blockchain network in order to identify the feasibility of implementing this technology in time-sensitive industrial scenarios.

4 BLOCKCHAIN ISSUES AND CHALLENGES IN INDUSTRY

Despite the advantages that blockchain can offer, its adoption is a challenge mainly for traditional industries due to the difficulty in accepting changes and also the high costs. The final cost of deploying a blockchain includes not only the costs related to the software and hardware, but also the cost of the time required to understand the underlying business processes and to define precise smart contracts. In this new context, the general agreement in the blockchain-based IIoT ecosystem requires that all stakeholders commit to investing and using this new technology.

In addition to the problem of investment in infrastructure, there is another problem of investment in staff qualification. Automation engineers and technicians are familiar with the use of ladder logic and do not understand the scripting language, so they feel comfortable working with today's easy-to-use, reliable, proven functional and necessary industrial process control systems. Therefore, while new technologies allow for higher levels of scalability, traceability, integration, manufacturing capacity and autonomous collaboration with other systems, the lack of skills and understanding to explore IIoT and blockchain will bring challenges.

According to (Khan et al., 2017), industrial automation is becoming complex gradually, and the data generated in manufacturing alters to big data. Robots, sensors, actuators, switches, industrial devices, and M2M communication are the ore of big data in Industry 4.0. Heavy usage of IIoT brought an immense commute in the era of industries. Industry 4.0 is a blend of modern smart technology and systems which creates a deluge of data, which is quite challenging to handle with classical tools and algorithms. Therefore, in addition to the problems of investment in infrastructure and qualification of the professional team, there is a significant challenge in the transfer and storage of large amounts of IIoT data between the various systems of the IPAS hierarchy.

Recently, big data analysis tools have been proposed for Industry 4.0, which aim to facilitate the cleaning, formatting, and transformation of industrial data generated by systems by different levels of IPAS hierarchy (Rehman et al., 2019). However, localization and data processing becomes a significant challenge, as the centralized communication architectures used have high network traffic and high latency, due to the large volume of IIoT data. For decentralized communication architectures, the impact on network traffic and latency is greater due to the consensus among nodes of a blockchain network.

In the vast majority of recent approaches to cyber-physical systems, the blockchain network is deployed from the level of process control devices in the IPAS hierarchy, allowing integration between synchronous and asynchronous systems. However, in this new context, synchronous IIoT applications acquire new features (data encryption, transaction creation, generation and storage of public and private keys) that can negatively influence the energy consumption of IIoT field devices that are deployed for long periods of time (Barki et al., 2016). Thus, new encryption schemes and techniques or new lightweight, efficient and robust encryption algorithms must be designed with the aim of reducing energy consumption in IIoT devices.

Some recent work, through the results of experimental evaluations, points out that there are problems related to the high and variable blocking time when changing a state in the blockchain network, from the request (made by a requesting client device) to a blockchain node to the commit of the transaction which is the confirmation among all blockchain nodes that the state has been inserted or changed in the ledger (Pongnumkul et al., 2017). These results show that the problem is due to the standard operation of the blockchain and its consensus algorithms. Thus, defining fast and reliable consensus algorithms is the key to enabling critical, real-time process controls for IIoT devices. However, seeking the low latency and reliability of a consensus algorithm at the same time is a challenging task. The problem is further compounded by slower and less reliable wireless connectivity compared to wired connections assumed in traditional consensus algorithms.

The communication delay is very sensitive in the lower layers of IPAS, and can mainly influence the monitoring and control of processes. Monitoring, carried out at the supervisory level by shop floor operators, is less sensitive, however, deadlines from data collection to visualization by HMI cannot be changed, with risks of compromising the entire product process. At the process control level, the control performed by PLC is highly sensitive, with low latency and strict deadlines, here a single deadline break can compromise the entire production process chain. Blockchain-based solutions that guarantee execution, control, monitoring and decision-making without influencing the real-time systems deadlines, can provide a breakthrough in industry 4.0 (Garrocho et al., 2020).

In order not to affect the time and strict deadlines of industrial process control systems, some approaches store IIoT data outside the blockchain network and reduce latency with new paradigms. Recent works in the literature apply concepts of fog and edge computing in M2M communication approaches, in which gateways are used close to field devices as a communication bridge for IIoT data collection and IIoT data hashing only for storage on the blockchain network (Wang et al., 2020). However, gateways can increase the delay in delivering sensor and actuator data to higher levels of IPAS, compromising decision-making.

In addition to the problems of high and variable block time, other evaluations have shown that some blockchain platforms such as Ethereum do not allow parallel operations (Schäffer et al., 2019). However, serial execution seems to be necessary: smart contract sharing state and smart contract programming languages have serial semantics in the current operation of the Ethereum system and its four testnets. Although several works in the literature present new ways to enable miners and validators to execute smart contracts in parallel, this is still an open problem in this area of research.

Finally, with IIoT devices in constant motion, communication with the blockchain network will face high dynamism and, consequently, large amounts of connectivity failures (Lucas-Estañ et al., 2018). This scenario will contribute to the reduction of communication opportunities with the blockchain network, increasing the communication delay between IIoT devices and blockchain network. Also, if the process control is in the blockchain network or higher layers, production may be compromised.

5 METHODOLOGICAL APPROACH

The problems become challenges for the definition of a blockchain network in the industrial environment. Therefore, this work presents a methodological approach (see Figure 4) divided into three layers: the first layer has to do with applicability and parts involved; in the second layer, the analysis of aspects involving the industrial process is presented; finally, the third layer presents the steps for the development, testing, deployment and monitoring of the blockchain network. Each layer step is presented below:

0. **Has the Team Knowledge of Blockchain Technologies Involved?** As simple as it may seem, this is a baseline and It is important that professionals involved in defining the blockchain network have a thorough understanding of the technologies involved. Unlike cloud architectures and others, blockchain needs more attention due to its distributed characteristics, which can lead to a waste of time and resources;

1. **Are Blockchain Technologies Suitable?** Blockchain characteristics are not be applied in some cases. An applicability survey will ensure that blockchain technologies will attend and preserve all functional and temporal requirements. Example: blockchain databases are based on key/value for shorter response times; the data replication between blockchain nodes makes data with large volumes unsuitable for storage; smart contracts do not generate external calls;
2. **Has Agreement with Horizontal Parts, Partners and Stakeholders?** If the blockchain is to be used for horizontal integration, all parties involved must comply with the inherent characteristics that the blockchain will apply in its internal processes. All horizontal elements will have to invest in this new approach. Thus, contracts establishing partnerships are essential to prevent one of the elements of the supply chain don't accept such changes after the implementation of the blockchain network;
3. **What Are the Real-time Requirements that Must Be Met and How Critical Are They?** Industrial processes are time sensitive and may require tight deadlines of 100 ms for communication. In this case, fewer interactions with the blockchain network are desirable. More important process information can be chosen for on-demand storage, while less relevant information can be left out of the blockchain network. Another alternative is to deploy a device that monitors other devices that are time sensitive, retrieving information and reporting to the blockchain network;
4. **Where Blockchain Will Be?** The positioning of blockchain network nodes can influence communication latency. In this context, edge computing approaches can be applied: depending on the case, the blockchain network can be placed as a new communication layer and the devices are just DApps; in other cases, the blockchain network can replace existing communication, making each device a blockchain node. Turning a device into a blockchain network node may represent greater investment, but it also represents less latency as element will be removed from communication;
5. **Is the Fault Model and Blockchain Compatible?** Failure model analyses is critical step especially if the process is time sensitive. In some industrial processes the mobility is small, while in other processes the mobility can be extreme. The main problem may be the loss of connection, either due to characteristics of the industrial environment, or due to limitations of wireless communication technology. In this context, it is important that there is a failure model so that the system tolerates the lack of connectivity to the blockchain network and continues to function normally;
6. **Which Type: Permissionless or Permissioned?** For horizontal integration, both suppliers and customers can participate in the communication, significantly increasing the number of elements in the network. In this case, permissionless blockchain networks like Ethereum are the best choices, but time-sensitive processes will not be able to use this type of network because of the poor performance they provide. As for vertical integration, communication is internal and therefore all elements are known and reliable. In this case, permissioned blockchain networks like Hyperledger Sawtooth or Fabric are the best choices, providing times and latency closer to real-time systems;

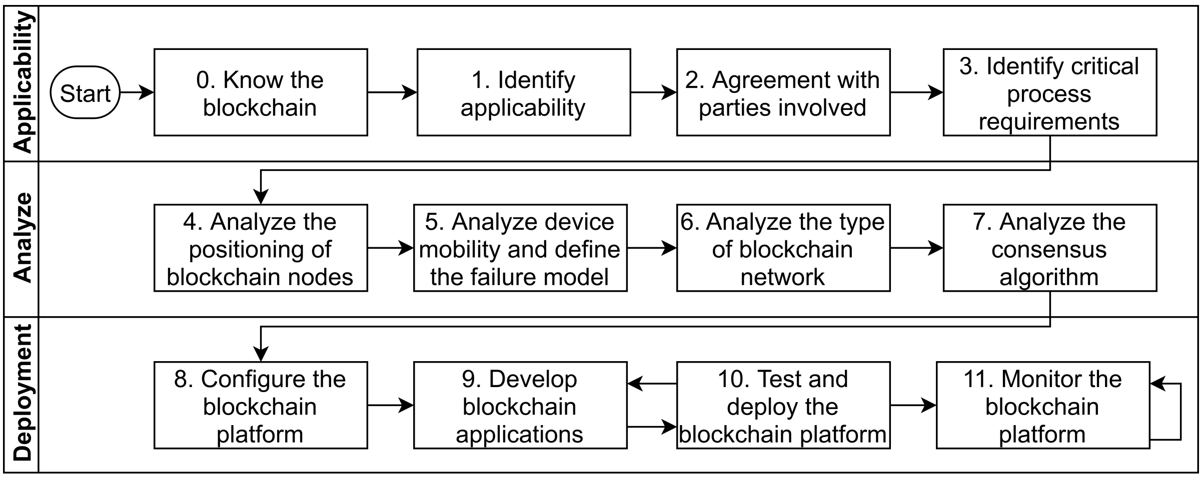

Figure 4: Blockchain network definition methodology for the industrial environment.

7. **Which Consensus Method/Approach?** The choice of the type of blockchain network can directly affect the choice of the type of consensus algorithm. For the permissionless blockchain network, the most appropriate distributed consensus is based on effort. Examples of such algorithms are the BFTs. In permissioned blockchain networks, where nodes are identified, the use of a vote-based consensus algorithm is relevant, as the nodes involved trust each other, thus being able to reach an agreement through a voting process. Examples of such voting algorithms are the CFTs;
8. **Which Parameters Must Be Configured?** The configuration of the blockchain platform is related to the desirable parameters: define whether the platform will perform the serial or parallel processing of the blocks; define timeouts for DApps and blockchain network; set manual or automatic key sharing; define the number of nodes in the blockchain network; define the types of metrics to be evaluated, which allow analyzing the performance of the blockchain network;
9. **Which Blockchain Apps Must be Developed?** The development of smart contracts and DApps are based on analysis of industrial process characteristics. The smart contract can be used as: communication intermediary; registration of information; etc. DApp is the means of relating directly to the industrial process, however, many devices are like black boxes (in which the code is closed). In this case, the ideal is to monitor data from these devices, or to design new embedded devices;
10. **The Blockchain is Tested? Deploy It!** During development, the blockchain network must be deployed in test mode. This means that a consensus simulation is performed in order to facilitate development and testing. Thus, an alternation is made between testing and development. The injection of data simulating the industrial process over long periods of time is necessary to assess the long-term performance of the blockchain network. After the tests, the production mode is deployed, in which the chosen consensus algorithm comes into action in all blockchain nodes;
11. **Are the Blockchain and All System Performing?** With the blockchain network in production mode, monitoring the status of each blockchain node should be performed in order to assess the performance of: processing, memory, network latency, consensus latency, etc. All nodes must have similar performance, otherwise, a hardware or software problem must be identified and corrected. Corrected the problem, the blockchain node re-incorporates the blockchain network and updates its database with the newly inserted blocks.

6 PROOF OF CONCEPT

The Dynamic Railway Scale (DRS) is one of the most used resources in iron ore plants, in which wagons are weighed in motion. Generally the PLC of a DRS are closed boxes and the cost of maintenance is expensive. Developing of an open source PLC for DRS would bring hardware and software openness, cost reduction and flexibility. However, the ease of making changes to the control logic becomes a point of attention with regard to the integrity of the data measured by the DRS and, consequently, the measurement result may not be reliable due to the changes made.

To solve this problem, it is proposed to apply the blockchain to the immutable record of any change in the control logic or change in the calibration coefficients in the DRS, making the system transparent and auditable. Thus, through this DRS system, the methodology proposed in this work will be demonstrated. Table 1 shows the DRS case study using our methodology and Figure 5 illustrates the organization of PLC devices in the DRS system.

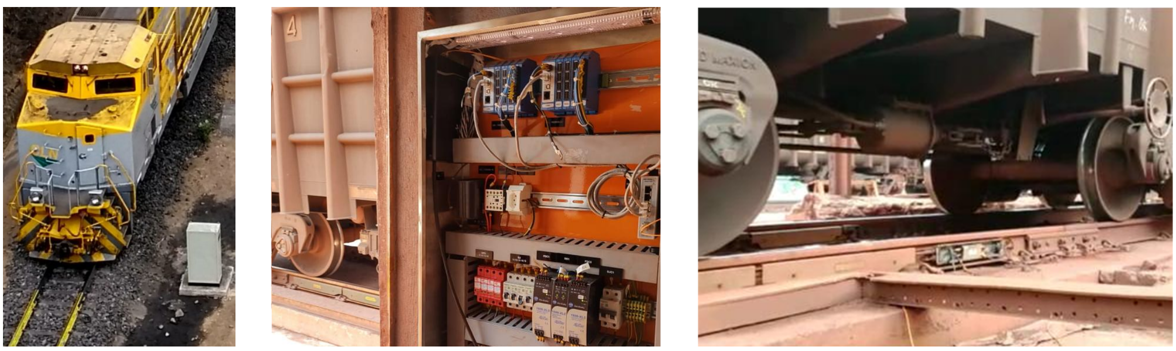

Figure 5: DRS system environment and equipment.

Table 1: Definition of the blockchain network for the DRS system through the methodological approach.

0. Has the Team Knowledge of Blockchain Technologies Involved? Yes. In this case, the iron ore miner maintains academic and professional agreements with a prestigious university and its graduate program in computing and engineering. Its employees are trained in engineering and computing subjects. Blockchain is one of research lines of this program, where this proof of concept is one of the prototypes under development.
1. Are Blockchain Technologies Suitable? Yes. The main objective will be to monitor operations (for example, changes to control logic, calibration parameters, and weighing) performed by PLC of the DRS ensuring log records on the blockchain. Using an IIoT device (in our case, Raspberry Pi 4 board) the monitored data is recorded on the blockchain network through an intelligent contract. Data sent to the blockchain network does not take up much storage space (about 0.5 kB each transaction). Thus, the blockchain network is used as an immutable storage system for DRS operations.
2. Has Agreement with Horizontal Parts, Partners and Stakeholders? Yes. As the company only needs to record all the control information of the DRS system in order to guarantee traceability and greater reliability in its wagon measurements, the integration is only vertical between the levels of process control and supervision of the IPAS pyramid. The agreement is done in level of system permissions that was done with success.
3. What Are the Real-time Requirements that Must Be Met and How Critical Are They? Industrial processes are usually time sensitive. In this specific case, all logics (represented by structured text or ladder diagram) for controlling the industrial process that are sensitive to time, continues to be executed directly by the PLC and not by a smart contract on the blockchain network. Therefore, the strict time requirements of the DRS system are not compromised. Then, all real-time requirements are in conformity.
4. Where Blockchain Will Be? Due to the constraints of external connectivity to the DRS environment, all blockchain components are deployed directly to each DRS device avoiding conflicts between legacy PLC and blockchain network. The aim is to reduce communication latency by applying concepts of edge computing. Therefore, DApps communicate directly with the Rest API of the blockchain deployed on the IIoT device, with no communication network delay. The reduced number of devices and the low cost of hardware that is supporting blockchain system make the investment low by the company.
5. Is the Fault Model and Blockchain Compatible? Yes. As shown in Figure 5, the control devices of the DRS system are installed close to the rails and protected from rain and sun. Therefore, there is no mobility on the devices or on blockchain nodes that are deployed on the devices. In addition, a communication failure model is defined, in which Rest APIs are deployed in all blockchain nodes, ensuring continuity of operation in case one of the Rest APIs stops working.
6. Which Type: Permissionless or Permissioned? Permissioned. The integration is vertical between the levels of process control and process supervision of the DRS, and all devices are known and reliable. Therefore, the best choice is a blockchain network with permission. The Hyperledger Sawtooth has fewer internal components and better performance compared to other platforms.
7. Which Consensus Method/Approach? CFT type algorithm. Considering that the platform chosen was Hyperledger Sawtooth and the type of network is permissioned, consequently the choice of the consensus algorithm will be a CFT type algorithm. In this case, the Raft algorithm is defined for consensus.
8. Which Parameters Must Be Configured? Looking for less delay in block processing, a parallel processing parameter is defined; due to the characteristics of the embedded systems, key sharing is performed manually on each node; three blockchain nodes are defined: two for the monitoring of the PLC of the DRS; and one for a workstation that represents a blockchain network HMI device. Each node in the Sawtooth network is configured to generate metrics and send them to the workstation that has Influxdb (https://www.influxdata.com/products/influxdb/) and Grafana (https://grafana.com/).
9. Which Blockchain Apps Must be Developed? DApps for monitoring and Smart contracts for receiving transactions and secure access. DRS DApps are designed to monitor PLC operations and submit this data to the blockchain network. HMI DApps are designed to monitor changes in the blockchain network and provide visualization to a shop floor operator. Smart contracts are developed to receive transactions from DApps, validate access to the device using keys and store this new state (with control logic, parameters and execution information) on the Sawtooth blockchain network.
10. The Blockchain is Tested? Deploy It! As DApps and smart contracts are developed, the Hyperledger Sawtooth platform's non-consensus development mode is used. Block simulations with transactions that represent control information are submitted to Sawtooth nodes and their behavior is evaluated by the HMI workstation using Grafana. After performance testing and analysis, the consensus is changed to Raft, and each hardware receives its respective actors.
11. Are the Blockchain and All System Performing? Yes. With the Sawtooth network and all other systems in place, the performance monitoring of each device is performed through Grafana on the HMI workstation. Any problem, a blockchain node can be interrupted and, after correcting the problem, the node can be deployed again and communication with the Sawtooth network is restored with all blocks being recovered.

6.1 Scenarios and Metrics

Two DRSs are separated by a distance of 200 meters. Each DRS has a PLC that is monitored by a Raspberry Pi 4 (Quad core Cortex-A72 1.5 GHz, 4 GB of RAM). A third device is a workstation (Intel Core i5-4200 2.60 GHz, 8 GB of RAM) for monitoring. Thirty executions were carried out in each scenario:

- *Tranquility*: sending to the blockchain network of changes in control logic or calibration parameters in the PLC of the DRS is considered. Thus, delays involving only one transaction from each device to the blockchain network were assessed;
- *Stress*: sending to the blockchain network of all executions and measurements performed by the PLC of the DRS is considered. Thus, delays were assessed by sending 1000 transactions from each device to the blockchain network.

An Ethernet/IP network with a rate of 100 Mbps is used for communication between the three devices. The following metrics were measured:

- *Submit*: total IIoT board delay for preparation (hash generation, payload encoding) and transfer of the transaction to the blockchain network;
- *Latency*: total delay from Rest API until confirmation that the transaction has been confirmed by all blockchain nodes;
- *Query*: total delay in querying a transaction to blockchain network and decoding the payload.

6.2 Results

The operations delays (submit, latency, and query) found in the DRS blockchain system successfully established from the methodology are illustrated in Figure 6. There is a slight increase in the time of the stress scenario compared to the tranquility scenario. This increase is related to a greater number of transactions submitted to the blockchain network, which generates a longer processing time to create the transaction, send data in the communication network and process the transaction between the blockchain nodes.

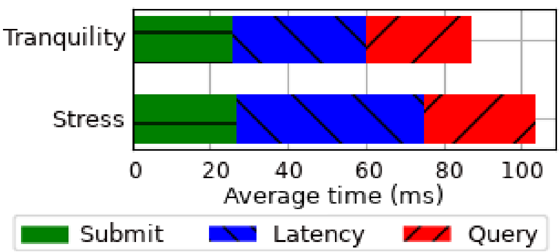

Figure 6: Total time of blockchain operations.

In addition to the total time of each scenario, Figure 7 show the time and standard deviation of each operation, which represents the variability of the data. Considering the behavior of the latency operation in the stress scenario, it is possible to observe an increase in time in this scenario. The 1000 transaction load has a greater effect because the operations are replicated between the 3 nodes of the blockchain network, generating a delay related to processing and consensus time between the validator nodes.

The standard deviation for submit operation is quite small, because this variation is only related to interruptions caused by the board's processor and message forwarding over the network. The high variation in latency operation is related to consensus and load replication between nodes on the blockchain network. Finally, the average variation of the query operation is related to message forwarding and receiving over the network, query processing on the blockchain network, and decoding the message on the IIoT board.

Therefore, although the latency operation has a short execution time, in the industrial scenario, the standard deviation of this operation can make the system unsafe. The variability of the data makes the system unstable, especially in the scenario of stress. Each time an operation is performed, it will result in a high degree of unpredictability for its conclusion. This variation in time in the stress scenario can affect the fulfillment of the deadlines by which tasks must be completed. In industrial systems, this time is not suitable for processes where it can delay decision-making and compromise system time constraints.

So, for the tranquility scenario, the average execution time and the standard deviation of blockchain operations can guarantee a time of around 100 ms. However, in the stress scenario, data variability makes communication inaccurate. Therefore, the application of blockchain for M2M communication in time-sensitive IIoT applications, has its operation affected by the amount of interactions to be carried out on the blockchain network. However, this problem does not affect the DRS system, as the blockchain network is used only for monitoring, and the process control that is time sensitive remains on the PLC of the DRS.

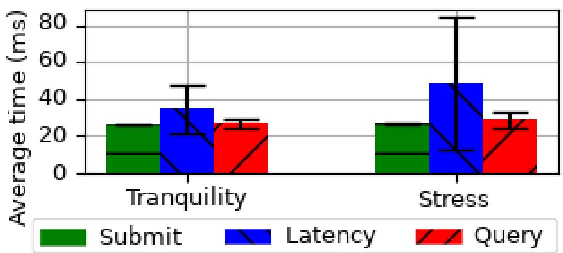

Figure 7: Time of operations with standard deviation.

7 CONCLUSION

Blockchain has the ability to revolutionize the industry. In this context, we present a methodology for defining blockchain networks for the industrial environment. This step-by-step methodology is easy to follow and to be applied in the industry as well as outside the industrial environment. In this approach, aspects related to the strict and specific requirements of industrial processes were addressed. As a future work, we intend to extend the studies and discussion of the methodological approach, incorporating new distributed ledger technologies such as Tangle and Hashgraph.

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