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Enhancing blockchain interoperability and intraoperability capabilities in collaborative enterprise-a standardized architecture perspective

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ABSTRACT

Collaborative Enterprise (CE) comprises of organizations that adopt digital platforms to achieve shared goals. In CE the prospect of Distributed Ledger Technologies (DLT) such as blockchain is reliant on its capability to integrate with other systems to improve organizational operations. But the inability for different blockchains to communicate with one another is an inherent issue as it puts a strain on the mainstream deployment of blockchains in CE. Therefore, this study presents a standardized architecture to support DLT interoperability and intraoperability within CE. A structural review was conducted after which design science research methodology was adopted to validate the architecture.

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1. Introduction

Blockchain was reported for the first time in 2008 alongside the cryptocurrency Bitcoin (Dimitrov and Gigov 2020), and is generally recognised as a possible disruptive technology that has recently received much attention as a promising innovation that could possibly play a significant role in facilitating commercial and technological capabilities for Collaborative Enterprise (CE) (Liu et al. 2019; Zamyatin et al. 2019). Blockchain is a novel infrastructure that decreases the dependence on centralised management and facilitates secure and direct transactions and agreements among different business partners (Khan et al. 2019; Zuo 2021). The deployment of blockchain is usually via a peer-to-peer (P2P) append-only ledger shared and distributed (Besançon, Da Silva, and Ghodous 2019), indicating the record of all data transactions is replicated across various network of clients or physical nodes (Jin, Dai, and Xiao 2018).

Blockchains such as Bitcoin, Ripple, Corda Ethereum and Hyperledger Fabric (Zeuch, Wöhnert, and Skwarek 2019) have gained much interest in Collaborative Enterprises (CE) due to their features such as immutability, transparency and decentralisation (Anthony Jnr 2021a). These characteristics make blockchains suitable for developing apps that

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require trustless and reliable exchange of data transactions (Jnr and Petersen 2021; Zheng and Lu 2021). More specifically, blockchain has the potential to address issues in CE such as security, scalability and interoperability by enabling efficient interactions between organisations adopting blockchain platforms to manage data securely to a variety of legacy systems towards improving the overall efficiency of CE business workflow (Gordon and Catalini, 2018). Regardless of many encouraging results, the present blockchain ecosystem is fragmented, as many blockchain platforms exist in silos and continue to run in complete isolation from one another.

Presently, there is fewer means by which blockchain-based systems can communicate or exchange data with external digital platforms (Dimitrov and Gigov 2020; Zamyatin et al. 2019). Additionally, in today's digital environment there is no unified standardisation in blockchain development, and this has resulted in the need for research regarding blockchain interoperability between digital platforms and intraoperability between chains that aids cross communication among blockchain platforms to enable retrieval or exchange of data between different distributed networks (Pillai, Biswas, and Muthukkumarasamy 2020). Hence, attaining blockchains interoperability and intraoperability remains an open issue in CE. As such, blockchain interoperability and intraoperability have become a crucial functionality to facilitate secure state transitions across diverse blockchains and support broad adoption of blockchain which is valuable for achieving the decentralised and distributed Web 3.0 (Liu et al. 2019). Furthermore, despite the interest in CE adopting blockchain, little research is available on the actual architectural styles, layers and patterns for enhancing blockchain interoperability and intraoperability capabilities in CE.

Existing approaches for blockchain interoperability and intraoperability are mostly focused on atomic token transfer between blockchain platforms. However, for large-scale industrial adoption blockchains, the scope of blockchain interoperability and intraoperability goes beyond just token transfers (Liu et al. 2019). Besides, ensuring blockchain interoperability and intraoperability without violating the underlying features of blockchain is also a challenge. Therefore, there is need for an approach that will safeguard the unique characteristics of blockchains and effectively manage the state change such as data append and validation procedure. Similarly, the cross-communication process of the integrating blockchain platforms should be compatible with the corresponding blockchain platform such as having similar consensus mechanism (Pillai, Biswas, and Muthukkumarasamy 2020). Researchers such as Zeuch et al. (2019) advocated for a universal method based on architecture that offers a generic description of blockchain properties and characteristics. Therefore, this study adds to the body of knowledge by:

- Presenting a standardised architecture that can be adapted for modelling of blockchain use in a range of CE scenarios for trusted data-sharing across two independent digital platforms through interoperation.
- Providing implications to stimulate a paradigm shift from closed blockchains to an open ecosystem where different digital platforms can interact with each other within the boundaries of blockchains.

As suggested by Borkowski et al. (2019), this study aims at providing an architecture for cross-platform asset or data transfers, confirming that such transfers are achieved in a trustworthy and decentralised manner. Where assets can be symbolised within blockchains in different ways such as native currencies (e.g. Bitcoin on the Bitcoin blockchain, or Ether on the Ethereum blockchain), and there are other types of assets commonly called tokens. The rest of the paper is arranged as follows. Section 2 outlines the literature review. Section 3 provides the method employed. Section 4 presents findings, and Section 5 highlights open challenges and recommendations for blockchain interoperability and intraoperability in CE. Section 6 is the discussion and implications, and finally Section 7 concludes the paper.

2. Literature review

This section offers findings from secondary sources as related to the state-of-the-art on blockchain interoperability and intraoperability in collaborative enterprise.

2.1. Current state of blockchain adoption in collaborative enterprise

Blockchain is a Distributed Ledger Technology (DLT) that promotes trust among users via the transparent recording of data transactions in a tamper-proof immutable and shared duplicated ledger (Jabbar et al. 2020). According to Biswas et al. (2020), in blockchain a NoSQL-based file type database ledger is distributed and held by every contributing peer, which can accept different unstructured data. Peer nodes are connected to each other in a P2P Transport Layer Security (TLS) maintained network. All data transactions are validated in a decentralised manner from initialisation to finalisation. The data transactions approval procedure is based on the deployed consensus mechanism (for instance maximum member peers vote), where votes are cast based on the predefined contract between issuer of transaction and receiver. A transaction is usually stored in a block together with other data transactions with appropriate encryption. Then, newly formed blocks are linked with the most recent block, forming chain of chronological immutable blocks (Biswas et al. 2020).

In Collaborative Enterprise (CE) the adoption of blockchain has seen an increase over the past decade. Blockchain such as Hyperledger, Ethereum, Corda, Tendermint, Polkadot and Cosmos (Jabbar et al. 2020) in recent times have surfaced as a possible solution that can be integrated in CE to improve traceability, access control, data availability and efficiency, and unification of information. Likewise, Zhang et al. (2017) stated that different blockchains are being employed in CE such as Bitcoin as a viable digital platform for enabling trustless transactions without the involvement of a central intermediary. In the Bitcoin platform, the DLT acts as a public ledger for all transactions of cryptocurrency in Bitcoins to support trustless finance between individual users, securing all their interactions cryptography. Due to the need for a more flexible DLT that can carter for more enterprise-driven services, Ethereum was developed as a substitute blockchain, providing users with a trustless and general platform that can support smart contracts beyond cryptocurrencies (Zhang et al. 2017).

Ethereum extends the abilities of Bitcoin blockchain by integrating smart contracts and is also being adopted in CE. Smart contracts are basically computer programs that directly maintain exchanges or reallocations of digital assets between two or more organisations such as CE based on certain agreements or rules determined between the involved individuals. The smart contracts in Ethereum support the development of decentralised apps (termed DApps), which are autonomously driven services cryptographically deployed on the blockchain to facilitate direct interaction among end users and providers (Zhang et al. 2017). Ethereum also imposes a payment protocol, whereby a fee is charged for memory storage capacity and each computational phase that is implemented in a transaction or contract. These fees are collected by block miners who execute, propagate and verify data transactions, which are then grouped into blocks. Just like in the Bitcoin-based blockchain, in Ethereum the mining rewards offer an economic incentive for miners to provide powerful hardware and energy to the public Ethereum platform (Zhang et al. 2017).

2.2. Interoperability and intraoperability in collaborative enterprises

Blockchain technology has surfaced as a disruptive technology that enables trust between untrusted distributed network nodes in the digital environment and is anticipated as a possible solution to several demanding problems faced across many domains such as collaborative enterprises. With the potential of offering traceability, transparency, resisting data tampering and trustability of digital platforms, blockchain has attracted substantial industrial attention and research studies (Pillai, Biswas, and Muthukkumarasamy 2019). Accordingly, different blockchains are being deployed within CE over the past years (Pang 2020). Nevertheless, digital platforms need to interact with each other, and thus interoperability and intraoperability are increasingly needed (Jnr 2020a, 2020b). Presently, practitioners in CE struggle with delayed communications, fragmented data and gapped business workflows caused by vendor-specific and incompatible blockchain systems, making it challenging to connect legacy digital systems seamlessly together to establish an end-to-end distributed network (Kamau et al. 2018; Song, Zacharewicz, and Chen 2013).

Interoperability refers to the ability of different Information Technology (IT) systems and software platforms to exchange data, communicate and utilise the data that have been exchanged (Jnr et al. 2021). A common goal of interoperability and intraoperability in CE is to enable cross-communication among different digital technologies (Lipton and Hardjono 2022). Generally, in CE interoperability refers to the ability of diverse information systems, applications or devices to connect in a synchronised manner across and within organisational boundaries to exchange and cooperatively access data among stakeholders to optimise enterprise operations (Khan et al. 2019; Xhafa and Ip 2021). Interoperability can be seen as the capability of two or more systems to offer service or accept service from other system and to use the service exchange effectively (Pillai, Biswas, and Muthukkumarasamy 2019). In CE, blockchains intraoperability has various potential benefits. First, well-communicating digital platforms can increase operational productivity and decrease time spent on managerial tasks. Likewise, interoperability among legacy systems within CE can also reduce data duplication that already exists, facilitate seamless access to pertinent longitudinal data and reduce overall enterprise information system cost (Gordon and Catalini, 2018).

Interoperability and intraoperability allow connected systems to exchange data consistently, effectively and accurately (Panetto and Boudjlida 2006; Song, Zacharewicz, and Chen 2013). It implies that the digital platform deployed within CE system must understand the functionality, which is available for other enterprise systems (Pillai, Biswas, and

Muthukkumarasamy 2019). Many approaches have been proposed to achieve interoperability as seen in Figure 1. According to Pang (2020) interoperability commonly comprises *foundational, structural and semantic intraoperability*. The *foundational intraoperability* ensures that data can be transmitted efficiently among different digital systems. *Structural intraoperability* involves the exchange that takes place when there is a well-defined data format within the connecting digital systems. Whereas *semantic intraoperability* ensures that the transaction data across digital systems are interpretable by all stakeholders involves (Pillai, Biswas, and Muthukkumarasamy 2019). Semantic intraoperability ensures dependency between distinct or similar blockchain for the purpose of exchanging or transferring value or data with assurances of verifiability or validity (Abebe et al. 2019).

Similarly, Pillai et al. (2019) stated that intraoperability comprises *integrated, unified and federated approaches*. The *integrated approach* aims to achieve a commonly agreed data structure format. The *unified approach* focuses on attaining a common format based on the semantic of the digital platforms, and the *federated approach* is achieved when connections are established accordingly among digital platforms.

2.3. Blockchain interoperability and intraoperability in collaborative enterprise

Blockchain is a novel technology, which can have a high influence on numerous organisations, such as supply-chain, healthcare, finance, energy and real estate (Besançon, Da

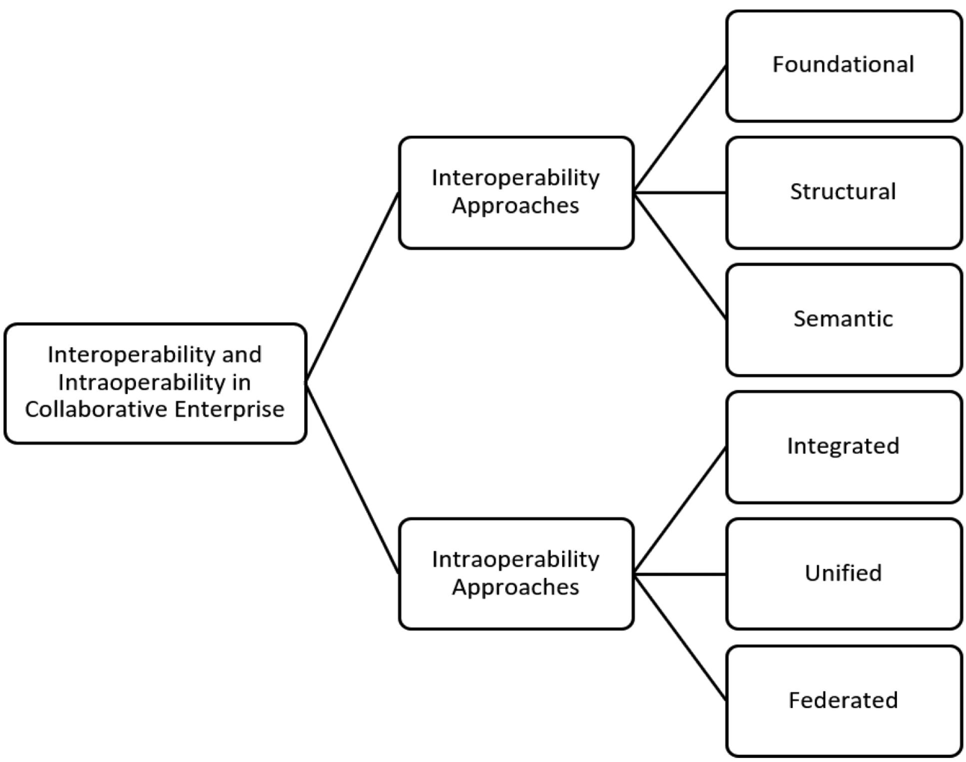

Figure 1. Interoperability and intraoperability approaches in CE.

Silva, and Ghodous 2019; Khan et al. 2019). As such, CE are adopting blockchain but are faced with difference issues such as the actualisation of an interoperable distributed network of blockchains and digital systems (Pillai, Biswas, and Muthukkumarasamy 2019). General blockchain interoperability is mainly associated with generic communication among blockchains, i.e. the transfer of arbitrary data/information from one blockchain platform to another blockchain platform or digital platform in a trustless and decentralised approach (Schulte et al. 2019). Blockchain interoperability will enable information obtained from external digital applications to make a change to the state of that digital application based on the data received. Blockchain interoperability aims to facilitate digital platforms to use the assets and data available on blockchains other than their primary blockchain network aiding greater range of digital ecosystem (Anthony Jnr 2021b; Ghaemi et al. 2021).

Blockchain intraoperability aims at one blockchain platform interacting with another to utilise its essential services such as data referencing, data verification and use of computational capacity of the entire blockchain network (Bhatia 2020). For example, different enterprises may need to exchange Litecoins with Bitcoins via cross-chain or intraoperable transactions to achieve blockchain intraoperability (Ding et al. 2018). Blockchain intraoperability provides a medium to bridge the gaps among numerous blockchain platforms without being locked-in to a particular technology. As suggested by Ghaemi et al. (2021), blockchain interoperability solution should consider the following design principles:

- The blockchain networks should be independent and may have different architectures.
- Every blockchain networks should be in full control of their data and assets.
- The data transfer protocol employed must be technology agnostic.
- The interoperability mechanism should not require substantial changes within the source and destination blockchain.
- The blockchain platform should be able to incorporate the mechanism with minimum effort.

However, digital platforms require the integration of different data interlinked from diverse sources and blockchains with different governance platforms (Pillai, Biswas, and Muthukkumarasamy 2019), so achieving blockchain interoperability and intraoperability remains a challenge. For instance, emerging blockchain platforms such as TradeLens, IBM Food Trust and Marcopolo employ permissioned/private-based systems like Corda and Hyperledger Fabric to create closed business consortia (CE). However, these existing private blockchain platforms are restricted within their closed consortia as assets and data cannot be communicated to external network. Thus, Corda, Fabric or other private-based blockchains do not provide any protocols or interface for interacting with external network which is essential for forming a consortium of enterprises termed as CE that cooperate to deliver digital services to clients (Anthony Jr, Majid, and Romli 2018; Ghosh et al. 2021).

Findings from Hardjono et al. (2018) on levels of blockchain interoperability and intraoperability in CE highlighted that interoperability needs to be achieved at the *technical* or *mechanical* level and *value* level. The *mechanical level* interoperability comprises the computer and network components such as the software and hardware that execute the technical blockchain modules as well as the communications elements. The *technical level* interoperability comprises transactions, cryptography, consensus algorithms, probes, protocols, signing, identities (identifiers), encryption, operating governance rules, etc. (Hardjono et al., 2018). On the other hand, the *value level interoperability* refers to the external blockchain system which includes constructs that render value as perceived in the real-world environment. The values can be fiat currencies, real assets, legal regimes, liquidity and regulations (Jnr, Majid, and Romli 2020) that all promote to form the concept of value as affixed to or attached to the constructs (e.g. tokens, coins) that are distributed in the blockchain platform and which are in turn applied by the systems and subsystems within the mechanical layer (Hardjono et al., 2018).

Hardjono et al. (2018) further argued that in blockchain intraoperability a concept analogous to peering policies must be established. This helps to specify the semantic compatibility needed for two blockchain platforms to exchange cross transactions, stipulate the domain protocols needed, state the technical-trust and delegation mechanisms to be utilised, and lastly describe legal agreements such as liabilities, service levels, penalties, fees and warranties for blockchain integration. Overall, blockchain interoperability and intraoperability in CE can be attained in three ways as seen in Figure 2.

As seen in Figure 2, blockchain interoperability and intraoperability in CE can be achieved between blockchain and other digital technologies utilised to develop a decentralised applications ecosystem (Besançon, Da Silva, and Ghodous 2019). Blockchain interoperability enables multiple blockchains to work collectively. For example, blockchain B1 manages sales report and permits a transaction when it manages the rules of B1's orchestrating the present state of B1. Likewise, blockchain B1 is interoperable/intraoperable with another blockchain B2 which manages supply chain and receives transactions from B2 if that transaction does not violate the predefined rules of B1. For convenience, B1 is the source chain since it shares data and B2 is the receiver called the destination blockchain. Blockchain interoperability and intraoperability in CE enable reading data from the source blockchain (B1) and writing on the destination blockchain (B2) further.

In such a model, data can be transferred and retrieved between two blockchains (B1, B2) that may be deployed in different organisation within the consortium without any notary for managing operational security and performance of the blockchain ecosystem. Hence, blockchain interoperability and intraoperability can be viewed as a smart feature that allows direct data exchange from one digital platform to another while retaining the core principle of the integrated blockchains (Imteaj, Amini, and Pardalos 2021). To this end, Imteaj et al. (2021) highlighted that the next generation of blockchain platforms will be driven by different digital systems that enable cross-communication mechanisms to improve enterprise capabilities and functionalities. But research in the field of blockchain interoperability and intraoperability in CE is still limited as there are fewer approaches which provide a practical solution that enables data transfer between different blockchains and digital platforms (Schulte et al. 2019).

2.4. DLTs that support integration with blockchain in collaborative enterprise

One of the most applicable use cases of blockchain technology is in organisational environments where multiple firms form a consortium (Ghosh et al. 2021), without any

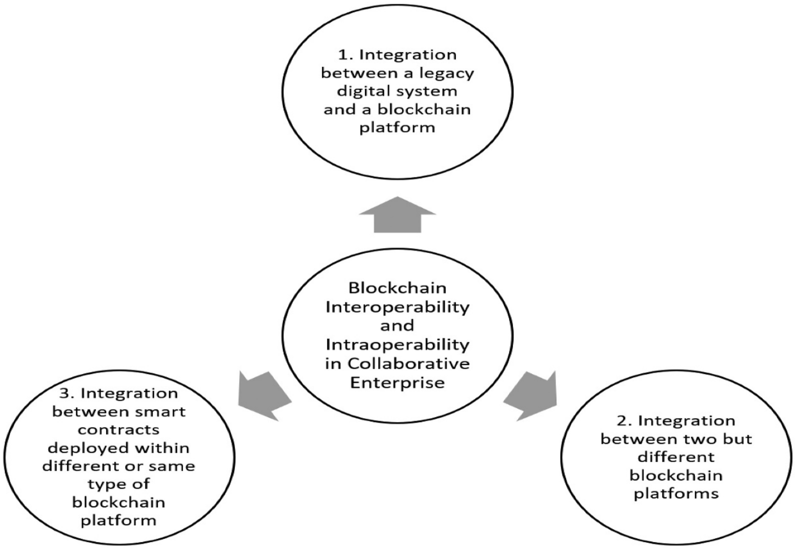

Figure 2. Blockchain interoperability and intraoperability in CE.

dominant trusted mediator's involvement termed as collaborative enterprise (Anthony Jnr 2021a). But CE are faced with issues such as blockchain interoperability/intraoperability when they adopt different blockchain platforms (Anthony Jnr 2021a). Blockchain interoperability generally involves the ability of transacting and sharing states across different digital platforms as previously stated. Blockchain interoperability can improve business use cases for blockchains adoption by providing portable assets transfer, improving payment and service delivery to clients (Qin and Gervais 2021). A recent survey classified blockchain interoperability/intraoperability into three mechanisms: *Cryptocurrency-directed, Blockchain Engines and Blockchain Connectors* (Belchior et al. 2021; Ghaemi et al. 2021) as seen in Figure 3.

Figure 3 depicts DLT interoperability and intraoperability mechanisms in CE. The first mechanism is the *cryptocurrency-directed* which are mainly industrial solutions that support interoperability across public blockchains. This mechanism emphasises asset interoperability and comprises sidechains, notary schemes, hash lock time contracts and hybrid approaches. *Sidechains permit* distributing transactions to a secondary blockchain, improve performance and deliver features that the main blockchain would not deliver. Sidechains also facilitate the representation of a token from the main blockchain to the secondary blockchain. Some widely adopted sidechain solutions in CE include the Zendoo, BTC Relay and RSK blockchain. *Hash lock time contract* mechanism facilitates cross-chain atomic operations utilising smart contracts. *Notary schemes* are decentralised or centralised entities that arbitrate token exchange such as cryptocurrency exchanges, and *hybrid mechanisms* combine features from previous mechanisms (Ghaemi et al. 2021).

The second mechanism is *blockchain engines* which facilitate designing customised blockchains that can integrate and provide reusable consensus, data, contract and network layers. An example of this comprises Cosmos and Polkadot which provide free interoperability. Blockchain engines cannot be deployed for

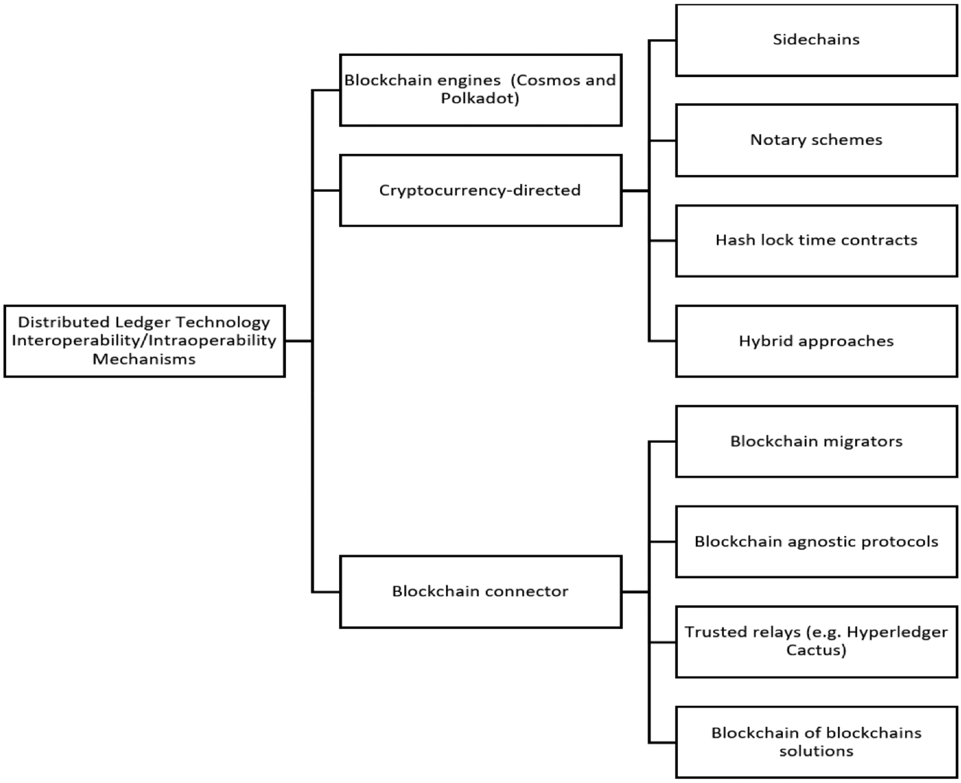

Figure 3. DLT interoperability and intraoperability mechanisms in CE.

running permissioned blockchains. It provides a blockchain networks which are interoperable by design (Ghaemi et al. 2021). The third mechanism '*blockchain connector*' comprises interoperability solutions which are not cryptocurrency-directed as in blockchain engine mechanisms. They include blockchain migrators, blockchain agnostic protocols, trusted relays and blockchain of blockchains solutions. Each of these blockchain solutions employed as blockchain connector is more applicable to different enterprise use cases. For instance, the trusted relays permit locating the target blockchains, often deployed in a permissioned blockchain ecosystem where trusted contractual arrangement among business collaborators employs cross-blockchain transactions.

Existing state-of-the-art blockchain infrastructure is architectured in a way that it functions as a standalone digital platform (Pillai, Biswas, and Muthukkumarasamy 2019). It is designed as a network of node contributors or stakeholders who decide the operability of the system based on an established protocol which governs the value and the consensus pattern. This means facilitating interoperability is a medium to exchange value from one blockchain platform to another digital application. However, verifying data from another platform is difficult because each platform's value is distinctive, and there are not well-functional standardisation approaches that classify crypto assets' value (Pillai, Biswas, and Muthukkumarasamy 2019).

2.4.1. Cross-network communication protocols

Many promising blockchain developments are actively creating inter-blockchain protocols to develop a network of blockchain ecosystem. The cross-network communication protocol that supports integration with blockchain platform in CE is seen in Figure 4. A well-known trusted cross-network communication protocol/relay mechanism is *Hyperledger Cactus* which is the latest Hyperledger project trying to connect clients to various blockchains, where transactions are approved by trusted validators. Hyperledger Cactus aims at delivering multiple use case scenarios for enterprises through a trusted consortium (Ghaemi et al. 2021).

Another cross-network communication protocol from the Hyperledger project is *Hyperledger Fabric* which provides foundation for deploying blockchain-based solutions using plug-and-play components for adoption in private enterprises. Others include *One Network* (blockchain in supplychain), *Overledger* open enterprise network of DLT networks) and *Blockchain Terminal (BCT)-hubs* (relaychain-parachain, hub-zone, parent chain-sidechain) that support the capabilities on several BCT-architectures, for instance performing swift payments (via *Ripple*), inclusion of corporate units in a mutual platform for transactions visibility (*Tradelens*) or secure correspondence (*Telegram*) (Dimitrov and Gigov 2020). Overledger provides an identical solution by creating a multi-ledger system for the inclusion of different blockchain-projects to achieve interoperability. Overledger include data from existing digital platforms in CE via the use of standard file formats (e.g. Extensible Markup Language (XML), JavaScript Object Notation (JSON)), which entered

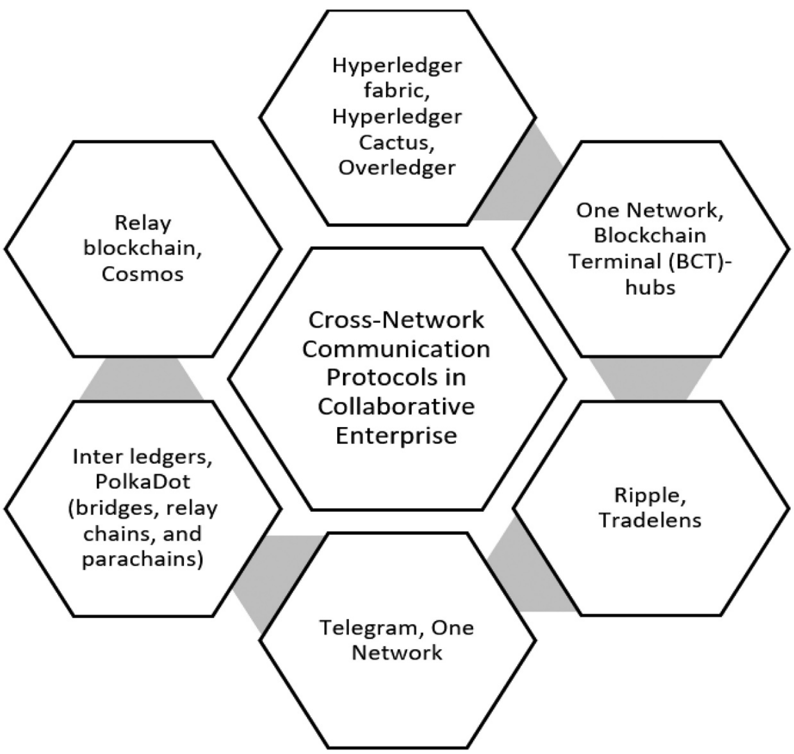

Figure 4. Cross-network communication protocols in CE.

the blockchain platform through application layer (see the method section). It is supported by BPI (Blockchain Programming Interface) and API (Application Programming Interface) (Dimitrov and Gigov 2020).

Likewise, *Hyperledger Fabric* is designed in response to changes in the widespread usage and flexibility of blockchain in CE. Hyperledger Fabric employs a permissioned network that supports up to 15,000,000 transactions per minute. Also, the transfer of data between users, applicants and customers is implemented via communication with a remote procedure calls (RPC) framework. Another blockchain platform is *One Network* which offers interoperability solution while depending on a simple interface. It employs a Proof of Authority (PoA) consensus mechanism that provides access to different types of data from users according to privacy conditions. It features a smart approach when selecting different blockchain-implementations through the integration of existing blockchain infrastructures (Hyperledger Fabric, Ethereum). One Network is important for adoption in organisations where different targets are set based to the hierarchical status of the administration and each section within the enterprise receives different access level to the blockchain platform. *Inter ledgers* is another DLT protocol utilised for payments across various payment networks. It helps to achieve blockchain interoperability in companies based on data generated from IoT devices and available information systems (Dimitrov and Gigov 2020).

Next is *Polkadot* and *Cosmos* which facilitate cross-network communications between different blockchains, termed *zones* in *parachains* and *Cosmos* in Polkadot, through a central blockchain Polkadot is a more common multi-blockchain platform based on the Proof of Stake (PoS) consensus algorithm (Schulte et al. 2019). The Polkadot platform topology comprises bridges, relay chain and parachains. Polkadot employs the PoS interface contract by using the Proof of Authority (PoA) consensus algorithm and changing it into a PoS algorithm with logic to resolve who are the decision-making authorities based on conditions such as DOT tokens employed for governance and staking (Johnson, Robinson, and Brainard 2019). Polkadot aims to offer a platform for blockchain interoperability managed by a principal relay blockchain which authenticates transactions taking place in the so-called parachains (Schulte et al. 2019).

The relay chain arranges consensus and transaction delivery between blockchain platform and process transactions. Whereas parachains receive and connect two blockchains with their consensus. Parachains are blockchains which can be specialised for specific purposes and applications. Relay blockchains facilitate interchain integration of parachains by employing message-passing protocol which aids parachains to share their security, thereby reducing the entry difficulties for new blockchain platforms (Schulte et al. 2019). Cosmos is another blockchain aimed at achieving generic blockchains interoperability capabilities for enterprises. Similar to PolkaDot Cosmos is deployed between multiple blockchains known as zones. The Cosmos zones are all executed based on the PoS consensus algorithm termed '*Tendermint*'. One zone, so-called the Cosmos hub, works as the main communication blockchain across other zones. The *Cosmos hub* maintains all committed block headers executed in the other zones and similarly the zones maintain all blocks in the hub. By deploying Merkle proofs, zones can validate each other by sending messages to other blockchains to enable interchain communication (Schulte et al. 2019).

Overall, Polkadot and Cosmos enable cross-network communications through a decentralised networks such as every transaction sent to the main blockchain is authenticated by a group of validators. Polkadot needs all contributing networks to adapt to a common consensus protocol to attain inter-network operations. Whereas Cosmos allows contributing blockchain platforms to plug in to the central hub maintaining their initial consensus protocol. Though, Cosmos requires all contributing network nodes to conform with the *Inter-Blockchain Protocol (IBC)* to achieve blockchain interoperability. Cosmos and Polkadot are also not interoperable with one another, making existing blockchain network pairs to select and execute the same protocol for shared interoperability (Abebe et al. 2019). Lastly, PolkaDot and Cosmos do not support interoperability between blockchains with different consensus mechanisms (Schulte et al. 2019). As discussed in this section, existing cross-network communication protocols that support integration with blockchain in collaborative enterprise are mostly based on exchange of token, assets and data between two blockchains, aiming to achieve blockchain interoperability/intraoperability. However, there is need for an approach that goes beyond blockchain to seamlessly integrate with blockchains with different consensus mechanisms and with legacy systems.

2.5. Blockchain interoperability/intraoperability solutions in collaborative enterprise

Blockchain provides a verifiable way to track and manage digital transactions. This makes this technology valuable for digital asset and data management in collaborative enterprises. Many researchers and industries are actively examining multiple blockchain protocols, architectures and solutions that allow blockchains interoperability to enable the exchange of transactions (Pillai, Biswas, and Muthukkumarasamy 2019). To facilitate blockchain interoperability/intraoperability in CE, cross-communication solutions/techniques such as notary schemes, sidechain, hash-locking and relay are being employed. A few of these techniques are shown in Figure 5.

Figure 5 illustrates blockchain interoperability/intraoperability solutions in collaborative enterprises. Each of this is discussed below.

2.5.1. Notary scheme solutions

Notary Scheme Solutions is the technologically easiest way to enable most cross-chain operations between two blockchains using notary mechanisms (Buterin 2016; Qin and Gervais, 2021). Notary schemes employ a centralised architecture based on a trusted third party which is responsible for carrying out asset transfer/exchange when both participants of a transaction across different blockchains mistrust one other and their information/data is asymmetric (Pang 2020). The trusted third party utilised by notary schemes can be a particular notary or a conglomerate of notaries executing a multi-signature digital wallet (Bhatia 2020). In this technique the notary is responsible to authenticate that an action occurred in one blockchain and transfer this information to another blockchain without requiring any underlying implementation. One of the disadvantages of this technique is that it requires the partners involved to trust the notary (Scheid et al. 2019). It is highly complex, may face a single point of failure and tends to centralise due to the presence of a trusted third party (Bhatia 2020).

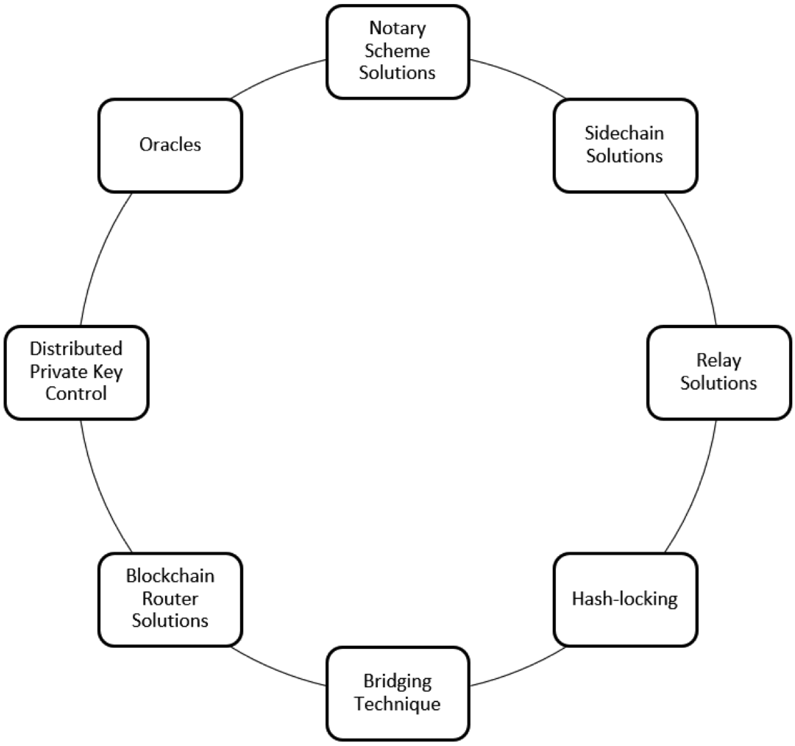

Figure 5. Blockchain interoperability/intraoperability solutions in CE.

2.5.2. Sidechain solutions

A sidechain is a blockchain that validates assets or data from another blockchain. For example, Ethereum is a sidechain for Bitcoin (Buterin 2016). This is technically attained by employing Simplified Payment Verification (SPV) which utilises block headers and Merkle trees to authenticate if a transaction occurred in another blockchain without having to download the entire ledger (Scheid et al. 2019). The sidechain or new blockchain is linked to the (mainchain) parent blockchain via a two-way peg (Pillai, Biswas, and Muthukkumarasamy 2019; Qin and Gervais, 2021). The two-way peg connectivity is utilised to transfer data/assets between mainchain and sidechain, i.e. cryptocurrency or tokens with no need for an exchange (Bhatia 2020; Pang 2020). The sidechain gets assets, cryptocurrency or token from the parent chain via transactions sent to a unique address, digitally locking the assets on the parent chain to support use on the sidechain (Pang 2020). Pegged sidechains are then capable of using the assets with a customised version of the parent chain protocol and can easily transmit the assets in return to the parent. This form of blockchain interoperability is restricted to only assets transmitted in a 1-to-1 relationship with no rise in the quantity of total assets (Dagher, Adhikari, and Enderson 2017). Sidechains can run independently and can have execution different from the parent blockchain. Sidechains provide the capability to authenticate and process information about the state of other blockchain (Scheid et al. 2019). Sidechains are known to be useful in performing instantaneous transactions at a higher volume and speed and are employed for micropayments use cases in CE (Pillai, Biswas, and Muthukkumarasamy 2019). Additionally, to achieve full interoperability, smart contract capabilities are needed to create a sidechain (Scheid et al. 2019).

2.5.3. Relay solutions

Relays are direct solution for enabling blockchain interoperability without relying on trusted mediators to offer information about one block chain to another; the blockchain platforms essentially take on the task of accomplishing that themselves (Buterin 2016). Relays are especially powerful, and they can be utilised for atomic swaps, asset portability or any other complex use cases effectively without restriction (Buterin 2016). Although relays are constrained by the consensus time of the original blockchain which in turn decelerates cross-chain processes (Qin and Gervais, 2021). Relay offers a method where a 'blockchain A' actively listens to and retains a record of part of the information, for example, block header from a different 'blockchain B'. This is valuable for a light client to validate block headers belonging to 'blockchain B' by applying a standard authentication procedure (Pillai, Biswas, and Muthukkumarasamy 2019).

2.5.4. Hash-locking

Hash-locking is a technique that facilitates interchange of digital assets or transactions between two or more partners in blockchains without an intermediate (Pillai, Biswas, and Muthukkumarasamy 2019). This technique uses a hash time locked logic which employs a time lock on the transaction so that both requirements are completely met; if not, the transaction cannot be completed (Pillai, Biswas, and Muthukkumarasamy 2019). Thus, one drawback of this technique is that the deployed blockchain needs to be compatible with a specific type of smart contract, so-called Hash TimeLock Contract (HTLC) (Scheid et al. 2019). Also, hash locking is merely applicable for atomic processes and can be integrated with relays technique as an effective option to move assets from one blockchain to another (Buterin 2016). HTLC is mostly used to make digital payments routable throughout multiple payment channels and is also appropriate for cross-blockchain atomic swaps. For instance, two companies want to make a transaction but have their assets on different blockchains. By employing hash-locking method it is possible to support exchanges even if there is no direct link between the transaction companies (Pang 2020). HTLC does not require any trust via the routing path since the whole transaction value is collateralised (Qin and Gervais, 2021).

2.5.5. Bridging technique

The bridging technique, also referred to as gateways, is an intermediate mechanism that aims to provide interoperability between digital platforms. The gateways connect different data standards via middleware. The gateway can be extended with the help of plug-ins to carry out conversion between the protocol employed by sending platform and the protocol used by the receiving platform (Pillai, Biswas, and Muthukkumarasamy 2019). Bridging interoperability solutions provide a connection between two blockchains to exchange/transfer assets. This technique is different from other solutions such as sidechains and notary schemes as it does not require any main blockchain. Mostly smart contracts or other software modules are employed as a bridge to link two blockchains.

Although most bridging technique support asset exchange, most others facilitate mainly asset transfer (Bhatia 2020).

In collaborative enterprises environment, bridging supports communication between blockchains such as Polkadot with legacy digital platforms or commercial blockchains which deploy their own consensus mechanisms such as Ethereum, through breaking and break-out gateway contracts. These gateway contracts support Ethereum to receive and forward messages/information from external digital platforms into Ethereum smart contracts. Bridging employs light client block proofs (basically Ethereum light clients) to ensure in the absence of information of the current blockchain state that transactions are executed as anticipated or that a certain part of the state has a specific piece of data in it (Johnson, Robinson, and Brainard 2019).

2.5.6. Blockchain router solutions

Johnson et al. (2019) mentioned that Wang et al (2017) initially proposed a blockchain router to manage cross blockchain communication. In this solutions blockchain node are employed as a router to foster communication between different blockchain platforms. All communications across the blockchains platforms are routed through the blockchain router and the sub-blockchains connect via a cross-blockchain communication protocol. Also, all contributors in the blockchain router carry out a specific role such as '*validators*' who concatenate, verify and forward blocks, '*nominators*' who are responsible to contribute funds to validators which they trust, '*surveillants*' who monitor the entire blockchain router operations and report possible malicious behaviour. Besides, there are '*connectors*' who enable the flow of data/information across sub-blockchains and '*the router*' which sends and receives data/information, performs transactions, signs results and collects the results into blocks to be forwarded to the validators.

Each connector manages a full node for a particular sub-blockchain, and delegates stake supported by a variation of the Practical Byzantine Fault Tolerance (PBFT) consensus algorithm to enable validators' voting rights (Johnson, Robinson, and Brainard 2019). However, the node architecture or structure of the platform of the node working as a router needs to be modified so it can act as a router to facilitate interoperability among blockchain platforms (Bhatia 2020). Also, Routing is also reliant on the available collateral and as such, even if utilised, would not likely be adequate to make payment channels fully functional on a large scale. This is because more complex and longer routing paths would raise the transaction costs and changing between various paths may result in affecting users' privacy (Qin and Gervais, 2018). Presently various projects are working towards improving routing complexities and barriers within the routing channel networks.

2.5.7. Distributed private key control (DPKC)

Distributed private key control is another technique that manages the private keys of data/digital assets via the distributed nodes and connects the original blockchain assets to another blockchain to achieve the interconnection of various assets within the blockchain ecosystem. Distributed private key control helps with distributed control right from orchestrating and separating the ownership and usage right of assets and control transfer of digital assets from the original blockchain safely within a decentralised system (Pang 2020). For example, in the 'fusion blockchain project' an implementation is achieved across two essential phases for digital assets management which includes lock in and lock out. In the phase of 'lock in' the key is partitioned and saved in a distributed manner. The digital asset is then transferred to the specified account on the original blockchain and validated by the fusion node to accomplish the distributed management of usage and control rights. The same is similar for the 'lock out' phase.

DPKC technique is similar to the notarial solution, although users always have the access to control the assets, only employing the distributed storage approach to save digital assets key, which, to some degree, prevents the integrated risk faced in the notarial man-based machine system. Additionally, account locking is not required to employ two-way securing. Since all transactions are transferred into the original blockchain network after which the authentication node is recreated without altering the attributes of the original blockchain. DPKC technique enables each participating blockchain platform to access the original blockchain easily and with a reduced threshold, decreasing the cost of integrating blockchain access, enabling the platforms to be extensively applicable and easy to achieve. But, due to not changing the original blockchain's features, blockchain interoperability development needs to be adapted to the features of the original blockchain. Also, development of DPKC technique is challenging and awaiting validation from the original blockchain takes a longer time leading to low operating proficiency (Anthony Jnr 2021b; Pang 2020).

2.5.8. Oracles

An oracle is an agent or computer program that supports the transfer of data from external sources to the blockchain platform for on-chain usage. This is accomplished using smart contracts that add data/information about real-world scenarios to the blockchain platform. Once such data is transmitted within the blockchain platform, this data can be utilised to automate processes based on real business use cases. Technically oracles are similar to smart contracts but are required to be trusted because they are managed by a trusted third party via cryptographic verifications. Overall oracles are mostly easy to deploy with blockchain platforms, and they provide data feed with external cases. But one of the limitations of this technique is that oracles do not create actual blockchain interoperability with other blockchain platforms. It only supports blockchains interoperable with non-blockchain based systems such as external digital platforms (Hewett, van Gogh, and Palinczki 2020).

Moreover, most oracles deployed in enterprises need a smart contract within the blockchain to function as the front end to communicate with other smart contracts within other blockchains. Accordingly, it is challenging to develop an unbiased and dependable oracle that is concurrently open to multiple blockchain platforms, as developers cannot merely implement an oracle smart contract for each blockchain since synchronising the implementation of those oracle contracts entails blockchain interoperability. This constraint, in turn, inhibits DApps deployed in enterprises from expanding their business models across several blockchains. For example, a call-based contract implemented on Ethereum forces developers to employ the option of adopting Ether only, not other cryptocurrencies (Liu et al. 2019).

Evidence from the literature suggests that blockchain interoperability and intraoperability are very complex and challenging. A variety of solutions have been proposed to achieve blockchain interoperability, but practically most of these do not really adhere to decentralisation (Pillai, Biswas, and Muthukkumarasamy 2019). Thus, for easy operations of blockchain interoperability, novel protocols, frameworks and architectures are needed. For example, multichain can interconnect to Bitcoin but has restricted functionalities (Imteaj, Amini, and Pardalos 2021). While cross-network communication protocols such as Polkadot and Cosmos support cross-chain transactions and allow developers to make communication with other blockchain platforms. Polkadot's relay chain and Ethereum 2.0 beacon chain facilitate message passing via a management chain. Another approach involves direct communication through hardware integration using Transport Layer Security (TLS) as implemented by enterprises such as NEC, or through smart contracts utilising atomic function calls, as suggested by Ethereum private sidechains (Johnson, Robinson, and Brainard 2019).

Overall, most of the blockchain interoperability and intraoperability solutions are based on sidechain approach since it is the most practical to be employed in a spectrum of business use cases. But it requires changes in the operation of the target blockchains as most blockchain platforms do not support destroying or locking of tokens. To overcome this restriction, some projects combine different techniques. For instance, Interledger integrates sidechains with notary scheme to achieve blockchain interoperability. Besides, most work focus on the blockchain interoperability by connecting blockchain platforms through a hub or gateway deployed in a separated enterprise ecosystem, thus resulting in secluded blockchain platforms (Scheid et al. 2019). Nevertheless, if the blockchain types are different such as private/permissioned, permissionless/public, it may prevent actualisation from performing blockchain interoperability for cross-chain communication. Therefore, there is need for an approach that supports blockchain interoperability and intraoperability. Hence, this study presents a standardised architecture to facilitate blockchain interoperability and intraoperability capabilities in CE (see section 3.2).

2.6. Related works of blockchain interoperability or intraoperability

Over the past decade a few studies have investigated blockchain interoperability and intraoperability. One of these studies was conducted by Ghaemi et al. (2021) who developed a publish-subscribe oriented architecture to support blockchain interoperability. The study further implemented a prototype platform to depict the feasibility of the architectural design which was evaluated using various publisher and subscriber distributed networks, for instance Hyperledger Besu, an Ethereum client, and other two different versions of Hyperledger Fabric. Imteaj et al. (2021) examined blockchain interoperability based on the perspective of interdependent networks. Mostly, the study proposed a high-level architecture view for blockchain interoperability and presented a design philosophy for blockchain interoperability. Also, a comparison of current blockchain schemes was presented. Bhatia (2020) examined various interoperability approaches for blockchain provided for blockchain systems to be adopted by researchers and industries. The study identified some interoperability solution types that can be employed to support the interaction of standalone ledgers with systems deployed in the outside world.

Furthermore, Pillai et al. (2020) investigated how cross-chain interoperability can be achieved among blockchain-based applications using transactions. The researchers argued that the lack of applicable inter-blockchain communication is an issue that impacts the adoption of blockchain and suggested that to promote multiplatform blockchain, a mechanism is needed to improve the connection and communication between blockchain platforms in a distributed approach. Besides, Pang (2020) developed a new consensus protocol termed Multi-tokens Proof of Stake to aid blockchain interoperability architecture. The new protocol helps to improve the token network impacts within a blockchain ecosystem. Findings from the study provide an analytical model to evaluate and verify that the new consensus protocol can provide and improve security as compared to a conventional single-token Proof of Stake (PoS) consensus mechanism.

Another study by Abebe et al. (2019) explored how to facilitate enterprise blockchain interoperability using trusted data transfer. The authors focused on providing an understanding towards interoperability grounded on a communication protocol which archives trust from the core network consensus protocol. An architecture was also provided in the study for use and demonstrated as a proof-of-concept for trustworthy data exchange between two enterprise networks (supply-chain trade finance), each deploying Hyperledger Fabric blockchain. Similarly, Borkowski et al. (2019) proposed a deterministic cross-blockchain token transfers (DeXTT) approach to simultaneously record token transfer among different number of blockchains in a decentralised approach. A reference implementation was provided utilising Solidity to test the performance based on the number of contributing nodes and cost requirements analysis of transferred tokens. Johnson et al. (2019) researched on how sidechains can promote interoperability by reviewing the approaches that key players in the blockchain ecosystem have applied to improve cross-chain transactions and communication between sidechains. Findings from the study present a summary of cross-chain and sidechain technologies employed in the literature.

Liu et al. (2019) proposed an hyperservice aimed at achieving programmability and interoperability among heterogeneous blockchains. The proposed approach is driven by two pioneering designs: a programming framework that aids developers to develop cross-chain systems in an integrated programming model and a secure blockchain-based cryptography protocol that verifiably realises those applications in blockchains. Scheid et al. (2019) presented a novel solution called Bifröst which is a modular blockchain interoperability API. The solution helps to save and retrieve data on several blockchains by employing a notary scheme that supports blockchain connectivity. Findings from the study reveal that the approach is well modular and currently executes seven adapters to support common blockchain implementations, including Stellar, Ethereum and Bitcoin. Ding et al. (2018) presented a framework to facilitate blockchain interoperability termed InterChain to accomplish asset transfer among blockchains. The approach aids secure and scalable interoperability between blockchains and can be easily expanded to other systems of cross-chain transactions. Jin et al. (2018) designed a novel architecture for supporting interoperability amongst multiple blockchains based on different blockchain layers. Findings from the study present challenges that are needed to be addressed to achieve blockchain interoperability.

Evidently, blockchain interoperability and intraoperability aim to address isolated and fragmented blockchain platforms that exist. Yet, existing studies only address limited functionality required to accomplish blockchain interoperability. At first, to achieve blockchain interoperability, digital assets such as native currencies or tokens were traded based on centralised exchanges (Borkowski et al. 2019). According to Pillai et al. (2020) research on blockchain interoperability aimed at facilitating the transfer of value from one blockchain platform to another is mostly theoretical and not practically validated on a large scale. Additionally, existing approaches are customised for either private or public blockchain through third-party gateways. *Therefore, this current study provides evidence on blockchain interoperability and intraoperability and presents a standardised architecture to facilitate blockchain platforms to cross-communicate between different digital platforms as presented in section 3.2.*

2.7. Existing blockchain interoperability architectures

The attainment of blockchain interoperability presents a challenging and complex issue that affects the wider adoption of blockchain in CE. Therefore, architectures are being developed to support blockchain interoperability as seen in Table 1.

Findings from Table 1 present current blockchain interoperability architectures. But there are fewer studies that design architectures for blockchain interoperability and intraoperability simultaneously. Hence, there is need to develop blockchain interoperability and intraoperability architectures as current architectures are more aligned to blockchain interoperability and not blockchain intraoperability. As suggested by Bhatia (2020), a standardised architecture enables blockchain platforms to interact with different distributed ledgers and with external legacy platforms deployed within CE to provide digital services towards meeting the needs of today's society.

3. Method

3.1. Data collection approach

This study employs design science research methodology (DSRM) as proposed by Peffers et al (2007), which concerns the design of artefacts aimed at addressing identified problems. A DSRM approach employing use case scenario in information systems was used for investigating the condition where boundaries of evidence are not evidently defined. Therefore, a case scenario approach has been considered as suitable for finding out the real situation of an occurrence. Besides, DSRM is a suitable method as this research addresses the inadequate interoperability and intraoperability of blockchain by designing a meaningful artefact in the form of a standardised architecture. DSRM based on use case scenario was employed to capture a more contextual, holistic and complete understanding of how blockchain is being adopted in CE domain. Use case scenarios will be collected which have been less employed in blockchain interoperability and intraoperability literature, as such use case scenarios are adopted to help to confirm the internal validity of findings (Anthony et al. 2019; Perrons and Cosby 2020). Use case scenarios mostly offer a good understanding of the dynamic aspects, underlying the relationship among different components (Anthony, Petersen, and Helfert 2020; Junior, Majid, and Romli 2018).

The design science research methodology process employed is shown in Figure 6. In this study the data for the use case scenario on renewable energy trading were collected via a series of document reviews involving primary data from technical reports and secondary data from the real cases on blockchain interoperability and intraoperability from 2013 till 2022. Also, multiple secondary sources (as seen in Table 1) were used essentially to gather qualitative data on the components for each layer of the developed

Table 1. Existing blockchain interoperability architectures.

Author(s), year, and contributions	Architecture layers	Methodology employed	Context	Countries
Antal et al. (2021) provided a complete overview of DLT examining the issues, provided alternatives or solutions and their use for achieving decentralised applications.	• The protocol and network tier • The scalability tier • The interoperability tier	Literature review	Defined a three-tier-based architecture for DLT systems to systematically categorise the infrastructure solutions and startup strategies.	Romania
Asante et al. (2021) Explored adoption of DLT in supply chain data management.	• Application layer • Smart contract layer • Incentive layer • Consensus layer • Network layer • Data layer	Literature review	Provided a roadmap for present and future researchers who focus on supply chain security management to achieve the integration of DLT.	United Kingdom (UK), Iraq
Farahani et al. (2021) presented a holistic reference architecture as well as fundamentals, current advancements, and issues in blockchain.	• Device layer • Data layer • Network layer • Consensus layer • Contract layer • Application layer	Experiment (performance evaluation)	Progressing the convergence of IoT blockchain	Iran, Germany, the United States of America (U.S.A.)
Lohachab et al. (2021) designed a layered architecture for the efficient development of methods and protocols for interoperable blockchains.	• Gateway layer • Message cache layer • Distributed ledger layer • Consensus layer • Access layer • Virtual-chain layer • De-application layer	Literature review	Presented in-depth taxonomy and insight on blockchain interoperability and open challenges.	Australia
Reegu et al. (2021) developed a blockchain-based architecture for interoperable health data.	• Organisational layer • Blockchain layer • Storage layer	Literature review	Recommended an interoperable electronic health record platform based on blockchain.	Saudi Arabia, Jordan
Jabbar et al. (2020) designed an architecture for data access management and exchange across different users via a decentralised trusted third party for achieving data integrity.	• Frontend layer • Blockchain layer • Backend layer	Experiment (Execution time and cost effectiveness)	Provides roadmap for further work on dynamic data interoperability and integrity verification in a decentralised domain.	Qatar, France, Tunisia
Abebe et al. (2019) proposed an architecture to aid enterprise blockchain interoperability utilising trusted data transfer.	• Governance layer • Sematic layer • Syntactic layer • Technical layer	Experiment	Aimed to offer an understanding towards interoperability grounded on a communication consensus protocol.	India

(*Continued*)

Table 1. (Continued).

Author(s), year, and contributions	Architecture layers	Methodology employed	Context	Countries
Besançon et al. (2019) proposed an architecture aim to effortlessly connect blockchains and decentralised technologies.	• Application layer • Platforms and second layer solutions • Processing layer • Distributed databases • File storage • Communication layer	Conceptual/ theoretical	Discussed the impact of the architecture for the video game enterprise. Also propose a new data representation of blockchain gaming assets to enhance data exchanges.	France
Chen et al. (2019) proposed a blockchain integrated energy application framework.	• Data center • Service provider • Energy monitoring company • Grid enterprise • Green energy generator • User • Participating Network • Inter-chain communication	Conceptual/ theoretical	Employs an application model for blockchain platform towards integrated energy exchange to solve the interoperability issue of integrated energy systems.	China
Lan et al. (2021) introduced TrustCross, a privacy-preserving cross-blockchain platform to facilitate confidential interoperability among blockchains.	• Application layer • Cross-chain interaction layer • Blockchain layer • Basic layer	Experiment (processing time, memory overhead latency of cross-chain transaction)	Provided insight on how to encrypt cross-chain communication data within relay chain domain and employ access management to safeguard user privacy.	China
Jin et al. (2018) presented a novel architectural model to aid interoperability from different blockchain layers.	• Application layer • Contract layer • Consensus layer • Network layer • Data layer	Experiment (Impact of input data size and CPU utility)	Provided a roadmap of issues needed to be resolved for blockchain interoperability.	China
Qin and Gervais (2018) presented a report on blockchain interoperability, scalability and sustainability.	• Application layer • Blockchain layer • Network layer • Hardware layer	Conceptual/ theoretical	Suggested that security and trust are important to achieve scalability of permissionless-based blockchains	UK

standardised architecture. This approach was employed to arrive at conclusions that are mostly in conformity and reproducible as possible (Anthony 2018).

3.2. Developed standardised architecture

Blockchain interoperability and intraoperability embody the ability to share both transaction data and digital assets across different networks. Also, blockchain interoperability and intraoperability enable secure and seamless execution of smart contracts among various permissionless, permissioned, public, private or consortium-based blockchains (Pang 2020). A blockchain interoperable architecture is a structure of different blockchain platforms and associated digital platforms, each integrated to

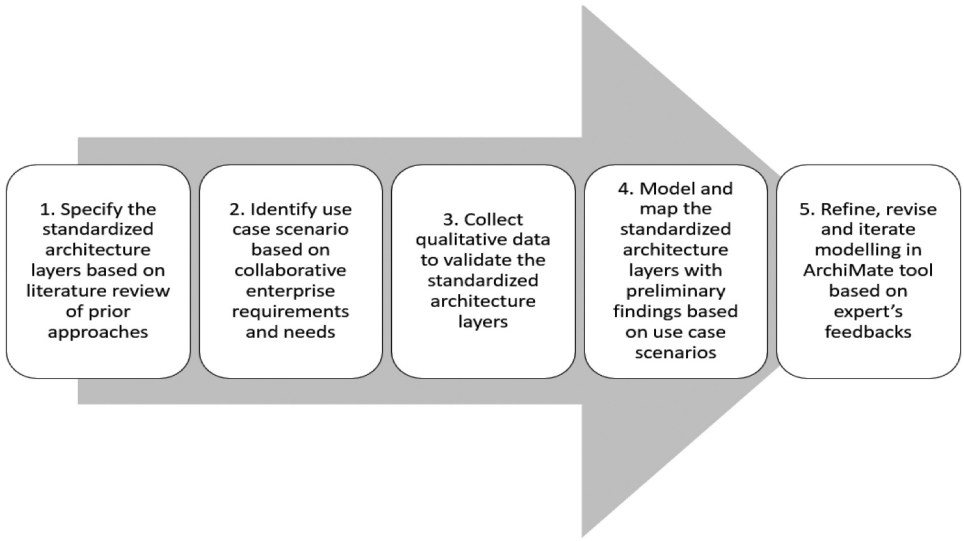

Figure 6. Design science research methodology process employed in this study.

a distributed data ledger. In this architecture data transactions may span across multiple blockchain platforms and data saved in one blockchain platform is accessible and verifiable by another blockchain platform or digital platform in a semantically compatible means (Hardjono et al., 2018). Accordingly, in this study a standardised architecture is developed grounded on secondary data as seen in Table 1 (architecture layer), for blockchain interoperability and intraoperability across CE as seen in Figure 7.

Figure 7 depicts the standardised architecture to facilitate blockchain interoperability and intraoperability with blockchain platforms and legacy digital platforms within CE comprises data layer, network layer, transaction layer, consensus layer, trust layer, application layer, enterprise layer, interoperability layer and intraoperability layer. Each layer is discussed below.

3.2.1. Data layer

One of the most vital tasks in blockchain platforms is to handle data generated that include managing block structure, modelling storage and transaction format. Data management is important in the blockchain ecosystem, and this necessitates the need for data layer. Therefore, this layer comprises different *storage model, block structure, transaction format, data layers* and *different transaction format* which are needed for enabling information exchange between multiple blockchains. For example the data format of Ethereum and Bitcoin is not similar which leads to impediments of transaction between Ethereum and Bitcoin. Thus, the data generator layer is important. A middleware can be used with a *data generator* to facilitate direct collaboration among multiple blockchains (Imteaj, Amini, and Pardalos 2021), to integrate the transaction format without depending on relays. On the other hand, a transaction translator can be employed in translating data transaction from a certain format to a common format.

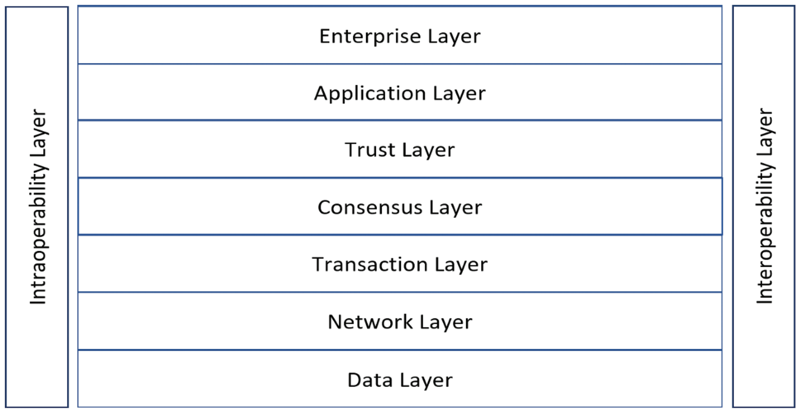

Figure 7. Developed standardised architecture.

3.2.2. Network layer

The network layer includes the storage and peer-to-peer network utilised within the blockchain platform (Anthony Jnr 2021a). The main aim of the network layer is to manage communication among the participating nodes. To achieve blockchain interoperability and intraoperability protocols such as *gossip protocol, P2P protocol* or preferably a combination of gossip protocols and P2P is commonly used (Imteaj, Amini, and Pardalos 2021). Additionally, gossip protocol enhances the communication effectiveness and aids distributed fault-tolerance (Jin, Dai, and Xiao 2018).

3.2.3. Transaction layer

The transaction or processing layer is in control for verifying transactions executed by the smart contracts initiated by collaborating enterprises. It also includes data mining process (Anthony Jnr 2021a). The transaction layer is included to enforce data integrity and to manage critical game mechanism such as validating integrity of transactions and stopping fraud). This is executed by blockchains which support smart contracts such as *Hyperledger Fabric, Ethereum and Electro-Optical System (EOS) blockchain*. The developer selects the specific blockchain deployed within this layer based on the enterprise use case. For example, as stated by Besançon et al. (2019), to achieve better throughput over security decentralisation Hyperledger or EOS can be employed instead of Ethereum to handle the blockchain's smart contracts.

3.2.4. Consensus layer

The consensus/trust or verification of transaction layer comprises consensus mechanism or incentive mechanism that can be employed for verifying transaction within the distributed network (Anthony Jnr 2021a). The trust layer is of great importance to guarantee the consistency of states for a blockchain platform (Jin, Dai, and Xiao 2018). This is important for achieving blockchain interoperability and intraoperability to verify transactions to guarantee the reliability of blockchain states (Bokolo 2022). The consensus algorithms can be categorised into two groups: Nakamoto consensus, which incorporates *Proof of Stake (PoS), Proof of Work (PoW), Proof of Location (PoL), Proof of Elapsed Time (PoET)*, etc. and other contemporary consensus algorithms such as *Practical Byzantine*

Fault Tolerance (PBFT). To achieve blockchain interoperability and intraoperability via cross-chain communication, the consensus algorithms assess if valid data are shared and committed from the source chain. Also, the consensus algorithms can validate if data have been altered or not on the destination chain (Bokolo 2023; Imteaj, Amini, and Pardalos 2021).

3.2.5. Trust layer

This layer comprises the trust or governance employed to administer data and transaction exchange among the blockchain platforms and digital platforms (Anthony Jnr 2021a). Thus, to enable blockchain interoperability and intraoperability between multiple blockchains there is a need to deploy a *smart contract* that would govern and hold all the transaction policies, rules, and agreements (Dagher, Adhikari, and Enderson 2017; Imteaj, Amini, and Pardalos 2021; Tan et al. 2021). In CE context the smart contract is prepared based on the consent of all participated nodes (organisations involved in the consortium), within the distributed network for trust. Smart contract can be seen as a computer protocol which will auto-execute and auto-verify once it is invoked (Carter et al. 2020; Khan et al. 2019; Pillai, Biswas, and Muthukkumarasamy 2020). It has the advantages of real-time accurate execution, update and less human intervention (Bokolo 2022; Jin, Dai, and Xiao 2018). Thus, the smart contract is activated during a transaction between source and destination blockchains/digital platforms (Chen et al., 2019; Imteaj, Amini, and Pardalos 2021). To extend the contract layer to enable blockchain interoperability and intraoperability scenarios, a smart contract should be triggered by two conditions from both blockchain platforms separately (Jin, Dai, and Xiao 2018).

3.2.6. Application layer

The application layer includes all *centralised and decentralised digital platforms* (DApps) deployed within CE to support organisational business operations (Anthony Jnr 2021a). This layer helps to carry out the interoperable actions with blockchain platforms (Imteaj, Amini, and Pardalos 2021). The application layer also captures platforms that provide graphical user interface (GUI) to partners within the CE that uses legacy digital platforms to integrate with blockchain platforms (Besançon, Da Silva, and Ghodous 2019; Lan et al. 2021; Lohachab et al. 2021; Qin and Gervais 2018). Lastly, Application Programming Interfaces (API) are used in this layer as gateways to process access to facilitate blockchain interoperability and intraoperability (Jnr et al. 2021).

3.2.7. Enterprise Layer

The enterprise layer is incorporated as the layer that comprises all the organisations and stakeholders involved in CE consortium (Anthony Jnr 2021a; Reegu et al. 2021). The organisations involved in the CE manage the governance of the smart contracts (Jnr and Petersen 2021), which is an independent platform business logic deployed on all the network peers of the interoperating blockchains, enforcing network rules for data transfer and acknowledgement across all enterprises. The decisions on what data can be granted access and transfer criteria are employed locally by the governing partners within the CE consortium.

3.2.8. Interoperability and intraoperability layers

The interoperability and intraoperability layers comprise different techniques, mechanisms or protocols employed to enable cross-chain and cross-platform interactions within blockchains and digital platforms deployed within CE.

4. Evaluation via use case scenario

4.1. Deployed blockchains within the standardised architecture

Blockchain platform maintains an immutable, distributed ledger that comprises a history of what has happened on the blockchain. Immutability aids records/transactions to persist the life of the blockchain and can facilitate data integrity over time. Additionally, blockchain integrate access control procedures for ensuring data privacy. The blockchain platform deployed within the developed standardised architecture is seen in Figure 8; 'transaction layer' is discussed below.

4.1.1. Ethereum

The advantages of blockchain can be achieved in collaborative enterprise through the deploying of Ethereum, a prominent application platform for developing blockchain-based systems (Dagher, Adhikari, and Enderson 2017). Ethereum was built as an application that could execute programmed applications on blockchain via smart contracts (Lipton and Hardjono 2022). Therefore, it creates a wide range of decentralised platforms which open the infrastructure to the prospect of tokens and digital assets with the capability to decentralise and tokenise not only cryptocurrency but also other digital assets within the blockchain ecosystem (Pillai, Biswas, and Muthukkumarasamy 2019). Analogous to Bitcoin, Ethereum can also be utilised by CE for cryptocurrency in the form of Ether (Ethereum's currency). Moreover, Ethereum allows CE to create permissioned or private blockchains that can be controlled and managed by a reduced set of partners or organisations for increased control and privacy (Dagher et al. 2018).

Ethereum supports the ability to scale which is important in CE environment, and scaling is achieved through 'Sharding'. Every node within the Ethereum network processes by downloading, computing, storing and reading all transactions in the history of the blockchain platform to support write and upload of new transactions (Johnson, Robinson, and Brainard 2019). Ethereum is employed in this study (see Figure 8, transaction layer) due to its maturity, and it is presently the most widely adopted smart contract platform. Also, it offers high utility via shortened block intervals and smart contracts (Dagher et al. 2018; Jin, Dai, and Xiao 2018). Ethereum transactions utilise Solidity coding scripts to perform required functions automatically (Zhang et al. 2017), referred to as smart contracts (see Figure 8, trust layer).

4.1.2. Hyperledger Fabric

Hyperledger Fabric is an open-source permissioned blockchain developed mostly for enterprise business cases. The design of Hyperledger Fabric is highly configurable and modular which supports customisation for each specific business case (Abebe et al. 2019). It maintains smart contracts based on general-purpose programming languages such as

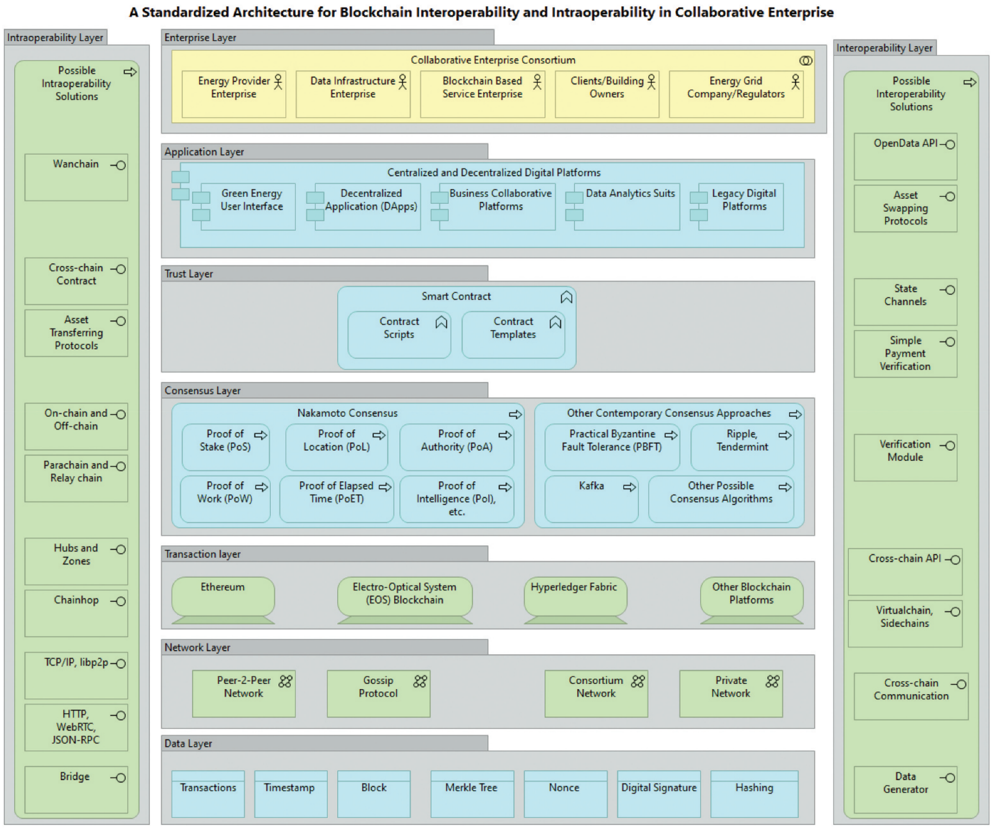

Figure 8. Evaluation of the architecture based on energy trading use case.

Java, Go and Node.js. Unlike other blockchains that mostly support smart contracts coded in non-standard and domain locked programming languages which makes it difficult to execute smart contracts that involve a Turing-complete language (Ghaemi et al. 2021).

4.1.3. *Electro-Optical System (EOS)*

Electro-Optical System (EOS) is an open-source blockchain platform that is developed to support developers to build decentralised apps referred to as DApps. EOS was introduced in 2016 by Block.one, a software firm focusing on blockchain technologies. The distributed network is based on a cryptocurrency called EOS.

4.1.4. *Other blockchain platforms*

Additionally, there are other blockchain platforms that can be employed in CE such as *R3 Corda* which is an open-source DLT platform which was released in 2015 by R3, a consortium financial institution known for its emphasis on ease of integration and interoperability with legacy applications. Another blockchain platform is *Ripple* which aims to connect digital asset exchanges banks, corporates and payment providers through RippleNet with almost-free worldwide transactions with no chargebacks. *Quorum* is another blockchain developed to manage use cases needing high-throughput and high-speed handling of private transactions, within a permissioned set of participants. *Stellar* is a blockchain platform that better connects people, payment systems and banks in getting funds across borders. *Hedera hashgraph,* a blockchain platform, is a well-scalable public-based network utilised to deploy innovative and scalable decentralised products that relies on asynchronous Byzantine Fault Tolerance (aBFT) consensus protocol. *IBM blockchain* is a private, decentralised network that is being adopted by enterprise who are less risk hesitant. It connects more to legacy technologies and enterprise cloud system seamlessly as compared to other decentralised networks. *Tezos* is an older blockchain platform that aids smart contracts and other decentralised applications in maintaining exchange cards that are attached to digital assets.

4.2. Modelling of use case scenario

The applicability of the developed standardised architecture was evaluated to facilitate blockchains interoperability and intraoperability with blockchain platforms and legacy digital platforms within CE are shown as seen in Figure 8.

Figure 8 depicts findings from the evaluation based on a use case scenario modelled within the developed standardised architecture in *ArchiMate modelling tool*. The modelling illustrates findings of the standardised architecture employed within an inter-organisational collaboration for *energy trading use case*. Further discussion of the findings is shown in Table 2, showing the architecture layers, digital components and description.

5. Blockchain interoperability and intraoperability challenges and recommendations

Blockchain interoperability and intraoperability allow enterprises such as CE to exchange data between multiple blockchain platforms that may be developed with different consensus protocols/mechanisms, etc. Without CE achieving blockchain interoperability and intraoperability data would be restricted only in a single blockchain platform. However, enabling blockchain interoperability and intraoperability is not a straightforward process since there are several challenges such as increased raise in the risk of attack due to variant access control, consensus protocols, algorithms, or service discovery within the underlying cross-chain communication that may impact CE goal of achieving blockchain interoperability and intraoperability. Overall, the most critical issues in blockchain interoperability and intraoperability areas are privacy and security, governance and discoverability (Imteaj, Amini, and Pardalos 2021). Other open challenges that impact blockchain interoperability and intraoperability are discussed below.

5.1. Guarantee of atomicity

The assurance of atomicity for blockchain interoperability operation is a difficult task. For blockchain interoperability, atomicity signifies that any transaction that is performed on the chains requires to be either entirely successful or unsuccessful simultaneously for both chains (Imteaj, Amini, and Pardalos 2021). For example, in a scenario comprising two different companies within the CE (namely E1 and E2) that have different blockchains and they aim to transfer digital assets, both transactions should be either successful or unsuccessful as the transaction occurs (Jin, Dai, and Xiao 2018).

Table 2. Findings from the use case scenario in the standardised architecture.

Architecture Layers	Digital Components	Description
Enterprise Layer	• Energy provider enterprise • Data infrastructure enterprise • Blockchain based service enterprise • Clients/building owners • Energy grid company/ regulators	• This layer comprises the collaborative enterprise consortium that all come together to contribute their knowledge and tangible/intangible resources in providing energy trading to clients.
Application Layer	• Green energy user interface • Decentralised Applications (DApps) • Business collaborative platforms • Data analytics suits • Legacy digital platforms	• Captures all the deployed centralised and decentralised digital platforms (DApps) used within all enterprises involved in the CE consortium. The aim is to enable seamless interoperability and intraoperability of all these digital platforms to aid providing renewable energy trading. Besides, most of the applications may be legacy systems being utilised within each enterprise.
Trust Layer	• Contract scripts • Contract templates	• *Smart contract* is a computer code which are executed based on a pre-defined codes which make it viable to develop decentralised which can communicate with blockchain platforms and also support storage on the blockchain (Khan et al. 2019). As seen in Figure 8, smart contracts comprise of *smart contract scripts* and *contract templates* deployed without end-user oversight or action which aids to ensure security and reliability of transactions among blockchain platforms.
Consensus Layer	• Nakamoto consensus • Other contemporary consensus approaches	• These are possible consensus mechanisms that can be employed by the deployed blockchain platforms to manage the governance and operation such as PoS, PoL, PoW, PoET, PoI, PoA, PBFT, Kafka, Ripple and Tendermint. A few of these consensus mechanisms are already discussed in the literature (Antal et al. 2021; Belchior et al. 2021; Farahani, Firouzi, and Luecking 2021; Imteaj, Amini, and Pardalos 2021; Qin and Gervais 2018).
Transaction layer	• Ethereum • EOS blockchain • Hyperledger Fabric • Other blockchain platforms	• This layer captures all the blockchain platforms that are interoperable and intraoperable within the CE that are employed to facilitate enterprise operations as discussed in section 4.1.
Network Layer	• P2P network • Gossip protocol • Consortium network • Private network	• This layer comprises different network topology being employed within the CE. • In the *P2P network* computers run similar protocol and hold a duplicate copy of the ledger of transactions without a middleman via machine consensus. • A *gossip protocol* relay new information (termed gossip) regarding the transactions. A collaborative record of gossip events is managed as the contributors keep adding data about their prior gossip to every recent gossip message. • The *consortium network* is a blockchain in which several companies manage the blockchain platform. This helps enterprises to find solutions together and save development costs and time. Consortium networks are also referred to as federated blockchains. • In a *private network* only, a particular enterprise has authority over the distributed network.

(*Continued*)

Table 2. (Continued).

Architecture Layers	Digital Components	Description
Data Layer	• Transactions • Timestamp • Block • Merkle tree • Nonce • Digital signature • Hashing	• *Transactions* are new data relating to business operations mostly governed by consensus mechanism. • *The timestamp* is a small data recorded in each block as a distinctive serial and whose central function is to define the precise moment in which the block data has been mined. The timestamps are utilised for storing records of information on a computer or online displaying when specific information was created, deleted, modified or exchanged. • *The block* are data structures in the blockchain database, where transaction information is permanently recorded. • *A Merkle tree* is a data structure that is utilised to encode blockchain data in a more securely and efficiently. • *A nonce* is abbreviated as 'number only used once' which is a number included to encrypted block or a hashed within a blockchain. The nonce can also be seen as the number those miners are solving to get cryptocurrency. • *Digital signatures* are a basic structure block in blockchains they are mainly used to validate the legitimacy of transactions. • *Hashing* is a cryptographic procedure of utilising a procedure to map data of any size to a predetermined length. It helps to validate the integrity and authenticity of different types of input.
Interoperability Layer	• OpenData API/Cross-chain API • Asset swapping protocols • State channels • Simple payment verification • Verification module • Virtualchain • Sidechains • Cross-chain communication • Data generator	• This layer comprises different such as *OpenData API* and *cross-chain API*, where API refer to application programming interfaces which can be seen as Middleway which provide access to data. API allow CE to save and retrieve arbitrary data on deployed blockchain platforms. API were employed in prior studies such as Pillai et al. (2020) where the authors adopted API with Ethereum platform to help in management of digital wallets to subscribe events across a blockchain network to monitor transaction. Similarly, Ghaemi et al. (2021) employed the Hyperledger Fabric contract API to provide interface for developing applications and smart contracts. • *Asset swapping protocols* facilitate users to use smart contracts to easily exchange cryptocurrency or digital assets from one blockchain to another. • *State channel* is a technique that deploys predefined rules such as smart contracts for off-chain transactions designed to allow users make transactions across multiple blockchain without committing all the transactions to the blockchain. • *Simple payment verification* aids a lightweight client to validate that a transaction is integrated in blockchains such as Bitcoin without downloading the complete blockchain. • *Verification module* is a mechanism that enables user verification without requiring the swap of any private data. • *Virtualchain* validates that the transfer transactions are authorised by the same principal and authenticates that the last-known state on the sender blockchain is consistent with the consensus hash announced on the receiver blockchain. • *Sidechains* are mechanisms that allow digital assets and tokens from one blockchain to another securely and can support the moving back to the original blockchain when required. It offers a more efficient and scalable approach. • *Cross-chain communication* between blockchains aids various protocols to validate data and transactions without the involvement of a central third-party service. • *Data generators* aid direct collaboration among multiple blockchains, to integrate the transaction format.

(*Continued*)

Table 2. (Continued).

Architecture Layers	Digital Components	Description
Intraoperability Layer	• Wanchain • Cross-chain contract • Asset transferring protocols • On-chain and off-chain • Parachain • Relay chain • Hubs and Zones • Chainhop • TCP/IP, libp2p • HTTP, WebRTC, JSON-RPC • Bridges	• *Wanchain* is a stand-alone blockchain that support cross-chain transactions and inter/intraoperability across different blockchains. • *Cross-chain contract* is a blockchain bridge comprising of a set of well-written computer code incorporating smart contracts that aid users to transfer crypto assets, tokens, smart contract actions or orders, or data across blockchains. • *Asset transferring protocols* enable the transfers of digital assets from one blockchain platform to another. This technique aids digital assets to be burned from the source blockchain and reconstructed on the destination blockchain. Mostly, integration mechanisms, hash-time-locks and digital signatures are employed to achieve cross-blockchain transactions in a distributed manner (Pillai et al. 2021). • *On-chain transaction* are transactions that occur and are regarded as valid when the blockchain is modified to reflect the transaction within the public ledger. *Off-chain transaction* receives the transaction value outside of the distributed ledger chain. Thus, it can be implemented utilising multiple methods. • *Parachains* are customised specified blockchains that are incorporated within the Kusama (KSM) and Polkadot (DOT) distributed networks. Parachains are the heart of Kusama and Polkadot can be adapted for several business use cases and feed directly to the main blockchain, known as *Relay chain* which is the main chain that is utilised by the Polkadot distributed network that allows public blockchains and specified blockchains to integrate within a unified network. • *Zones* are standard heterogenous blockchains whereas *Hubs* are blockchains particularly developed to connect different Zones together. Zone creates an Inter-Blockchain Communication Protocol (IBC) connection with a Hub, to routinely access, send and receive data to every other Zone that is linked to it. • Chainhop is a solution that enables the transfer of one data asset such as coin across two or more blockchains platforms. • Transmission Control Protocol/Internet Protocol (*TCP/IP*) is a standard internet communications protocol that allows digital platforms to communicate remotely. Also, *Libp2p* is a network framework that allows developers and enterprises to deploy decentralised P2P applications. • HyperText Transfer Protocol (*HTTP*) is an application-level protocol that sends data to the TCP/IP protocol stack that is then routed across the network. HTTP enables web browsers to communicate with web servers and is employed by some legacy digital systems that are integrated with blockchain platforms employed in CE. • Web Real-Time Communication (*WebRTC*) is one of the most common protocols that provide the framework for real-time data communications and is employed based on its wide area application coverage and improved security (Yilmaz, Barak, and Ozdemir 2020). It is used with Bitcoin in enterprise environment. • JSON-Remote Procedure Calls *(JSON-RPC)* is employed as a data exchange protocol that aids a client (for example a blockchain platform) to communicate with a server (such as a local blockchain node) by listening to responses and issuing commands. It is used within the Web3, Ethereum and Bitcoin network. • *Bridges,* also known as cross-chain bridges, integrate two blockchain platforms and permit users to send cryptocurrency/digital asset from one blockchain chain to the other. For example, if an enterprise has Bitcoin but intends to spend it with another enterprise that adopted Ethereum within the CE consortium, bridges can help in achieving this goal.

5.2. Performance efficiency

Maintaining a stable cross-chain communication that accelerates data exchange process for blockchain interoperability and intraoperability is mostly a challenging process as the performance of all chain may be affected during integration. The effectiveness can be accessed and established by analysing the blockchain interaction times per second (Jin, Dai, and Xiao 2018). The consensus algorithm that involves transaction validation, digital asset/data commitment speed at the destination blockchain, verification module, smart contract and efficient cross-chain communication are regarded as the necessary factors for enhancing blockchain interoperability and intraoperability (Imteaj, Amini, and Pardalos 2021).

5.3. Retaining evolvability and lessening integration complexity

Presently, the implementation of blockchain technology is mostly complex, and this could be a barrier to adoption for some organisations. Many digital platforms are developed with the assumption that data are easy to exchange. However, in blockchain-based platforms data are immutable and challenging to modify. An important consideration when developing blockchain platforms is ensuring that data utilised into the blockchain platform can enable evolution where needed. For this to be achieved the data must often be available from a variety of deployed digital platforms. Findings from the literature (Zhang et al. 2017) suggest that methods such as the abstract factory pattern can be employed in Ethereum contracts to enable evolution while reducing the impact on external digital platforms.

5.4. Security and privacy maintenance

The cross-chain mechanism employed to achieve interoperability and intraoperability raises security risks that could undermine the entire blockchain ecosystem security. The cross-chain method introduces more security threat than specific blockchain operations. Data transmission procedure of cross-chain comprises three phases. The first phase entails the shared data leaving the source chain. The second phase involves when data leaves source chain and presently in transit, and lastly the third phase involves the shared data which reach the destination chain (Jin, Dai, and Xiao 2018). Specifically, to improve security across several blockchains the following need be to be satisfied such that first the shared data gotten from a random node are required to be committed on the source blockchain to be reliable (Imteaj, Amini, and Pardalos 2021).

Next the transferred data while in transit cannot be altered, and a signature checking protocol can be integrated, and finally a final commitment should be recorded on the destination blockchain after the transferred data reach the destination blockchain without any temper (Zhang et al. 2017). Also, to minimise the data leakage and confidentiality, blockchain fine-grained access control can be employed (Imteaj, Amini, and Pardalos 2021). Regarding privacy, within the CE if an organisation asks for the erasure of their shared personal data, there are no efficient processes to address that request (Imteaj, Amini, and Pardalos 2021). Thus, privacy measures should be explored in future blockchain platforms.

5.5. Friendliness to platform developers

As an inherent technology, the blockchain ecosystem entails considerable efforts with contribution from a community of platform developers. At the high level, the blockchain interoperability and intraoperability should offer friendliness to draw more enterprise system developers to join the blockchain community/ecosystem. But the inadequacies of platform-transparent by design can result in a considerable loss of universality (Jin, Dai, and Xiao 2018).

5.6. Management of diversification

Blockchain interoperability and intraoperability may be faced with diversification in terms of usage scenarios or consensus mechanisms employed by different organisations within the CE consortium due to their diverse business models. Furthermore, several open-source blockchain platform source codes are available that could be modified by changing some code (Imteaj, Amini, and Pardalos 2021). Likewise, blockchains adopted in CE have different transaction formats which is one of the bottlenecks impeding information exchange among different blockchain platforms. For example, Bitcoin and Ethereum are different in transaction format which limits direct transaction transmission between Bitcoin and Ethereum (Jin, Dai, and Xiao 2018).

Over the years, blockchain ecosystem exhibits considerable diversification in both consensus mechanism design (e.g Ethereum and Bitcoin running on different consensus protocols (i.e. PoS and PoW) and usage use cases owing to their distinct purposes, leading to the immense discrepancies. Further, a trustworthy cross-chain consensus protocol should be available to maintain the diversification of blockchains so that no existing protocol of each system is needed when a new blockchain platform joins within the blockchain ecosystem (Jin, Dai, and Xiao 2018).

6. Discussion and implications of study

6.1. Discussion

Blockchain is basically a mathematical structure for saving data in a manner that is nearly difficult to fake, making it useful way to dependably share a broad range of useful information in enterprise domain (Perrons and Cosby 2020). In recent years, blockchains have gained much adoption in several industries and this has led to the blockchain environment being fragmented, with several incompatible blockchain infrastructures. In enterprises such as the finance domain, blockchain is most notably known as the infrastructure underlying cryptocurrencies such as Bitcoin (Perrons and Cosby 2020), but this digital technology is being adopted in other sectors such as in collaborative enterprises domain. Blockchain is characterised as being highly resilient, decentralised and provides a secure log of transactions (Gagnon and Stephen 2018), making it a suitable technology to improve collaborative enterprise operations in maintaining the cooperation between consortium members. Blockchain has developed as a promising infrastructure that could possibly play a significant role in providing technological and commercial resources that CE will need to digitalise their organisation process. But, irrespective of the potential of this technology to potentially improve the sustainability and productivity of

CE, blockchain is still evolving, and is faced with a few barriers which negatively impact its widespread adoption in CE such as the lack of interoperability, intraoperability and standardisation among blockchain platforms.

Interoperability refers to the capacity of several software systems and information technology platforms to communicate and exchange data effectively, accurately and consistently as well as to accurately utilise the exchanged or shared data. Blockchain interoperability and intraoperability aim to connect different blockchains by exchanging assets and information. Although blockchain interoperability projects started as early as 2016 (Ghaemi et al. 2021), one of the initial contributions in the domain of blockchain interoperability is the atomic cross-chain protocol suggested by Tier Nolan in 2013 (Nolan 2013). This protocol permits users of several cryptocurrencies to exchange their digital assets in an atomic way (Qin and Gervais, 2021). Beyond the trading of digital assets other solutions such as Cosmos, Polkadot and Block Collider aim at integrating blockchains in a more traditional approach, e.g. by facilitating communication between smart contracts positioned within different blockchains. Findings from the literature suggest that a further notable contribution in the domain of blockchain interoperability is blockchain Relay, which is a smart contract deployed within Ethereum to confirm Bitcoin transactions. Blockchain Relay via smart contract acts as bridge between Ethereum smart contracts and Bitcoin blockchain enabling clients to make payment with Bitcoin for utilising Ethereum DApps (Qin and Gervais, 2021).

There are fewer works that examined blockchain interoperability and intraoperability in collaborative enterprise domain. To add to the body of knowledge both in the practitioner domain and in academic literature, this current study provides evidence from the literature and qualitative data on the state of the art of blockchain interoperability and intraoperability in CE. A standardised architecture was developed to provide a tool that depicts how blockchain interoperability and intraoperability can be achieved within CE to possibly unlock the full potential of blockchain technology. Findings from this paper provide practical experience on how a network of blockchains such as Ethereum and Hyperledger Fabriccan be adopted by different enterprises (within a consortium). The findings also shed new light on blockchain interoperability and intraoperability by providing a novel architecture as seen in Figure 7 to store, retrieve and migrate data on different blockchains based on different interoperability and intraoperability solutions/ techniques.

To enable scalability of the standardised architecture, the intraoperability and interoperability layers are included to support enterprises to create innovative blockchain-based business model that is transparently driven by the interaction and integration with several blockchains, e.g. Ethereum, Hyperledger, Bitcoin. Similarly, in the framework EOS can be employed which aims to enable programmers to incorporate blockchain technology in different business cases, and EOS is much better than other blockchain platforms based on its improved scalability handling more dozens of transactions per second. Thus, this standardised architecture allows CE to plan and deploy interoperable and intraoperable applications that support a variety of business use cases which are not well addressed in the literature. In addition, 'Sidechains' are mainly applied for enhancing the scalability of the main blockchain or for adding extra functionality to the main blockchain (Bhatia 2020). Also, unlike the open permissionless blockchains that have scalability issues, Hyperledger Fabric, which has low transaction confirmation latency and facilitates high transaction throughput, can be employed (Abebe et al. 2019). Analogous to Dagher, Adhikari, and Enderson (2017), findings from this study advocate for the usefulness of smart contracts to be utilised to automate business tasks and accomplish access control for CE members. Findings from this study as seen in Figure 8 also employ APIs (OpenData API and Cross-chain API) as used in prior study (Dagher, Adhikari, and Enderson 2017), to connect to the Ethereum private/public blockchains.

6.2. Theoretical implications

With blockchain adoption being increasingly embraced in industry and academia, many blockchain platforms are being developed worldwide. These blockchains are mostly incompatible and isolated with each other, leading to digital assets and data fragmentation and silos. Blockchain interoperability and intraoperability mechanisms can revolutionise this governance and operational challenges of managing cross-platform communication by enabling digital asset and data transfers between heterogeneous and homogeneous blockchains. In CE environment, the adoption of blockchain plays an important role in governing business process by automating data management, data access and authentication processes, aiding data aggregation from external sources via APIs within the enterprise consortium. Blockchain interoperability and intraoperability open possibilities where digital assets and data can be moved from one blockchain platform to another via different governance mechanisms or enabling accessing information from one blockchain inside another blockchain platform without any further effort required from the adopter of the blockchain platform (Buterin 2016).

As a primary goal, this article seeks to provide interoperability and intraoperability solutions to promote interaction and integration between blockchains. In this study, a standardised architecture was developed to enable blockchain interoperability and intraoperability solutions within CE. The architecture consists of vertical and horizontal layers that facilitate data and digital asset transfer between blockchain platforms, enabling data not to be locked within a specific blockchain platform. Additionally, smart contracts are deployed within the architecture to facilitate inter-organisational collaboration for energy trading between organisations that deploy heterogeneous blockchains. As suggested by Borkowski et al. (2019), the architecture can be employed for several number of blockchains and autonomously synchronise data transactions across different blockchain platforms in a decentralised manner. More specifically, a comprehensive perspective is introduced to guide the design and development of blockchain interoperability and intraoperability which is scarce in the literature.

Moreover, findings from this study provide a modelled use case on the potential of blockchains to illustrate how diverse blockchain solutions could possibly interact with each other. The findings (as seen in Figure 8, Table 2) provide a viewpoint of a blockchain network which comprises different enterprises deploying both private and public blockchain platforms that need to communicate and talk to each other in a seamless way. Theoretically, this study contributes to the literature on blockchain by describing a generalised form of cross communication among blockchain platforms that has the potential for extensive use in different enterprise scenarios such as energy trading across multiple digital platforms. Within the standardised architecture each blockchain transaction is validated based on the corresponding blockchain platform's consensus algorithm.

Thus, the developed standardised architecture does not alter any decentralised operation of the blockchain design but initiates possible interoperability and intraoperability cross-communication solutions transactions for exchange of data (block) between blockchain platforms.

6.3. Practical implications

The goal of actualising digital transformation of enterprise process and diverse business requirements has led to many isolated permissionless and permissioned blockchain platforms which have been developed over the years. Currently, organisations such as collaborative enterprises adopt different blockchain solution, which has resulted in vendor lock-in, incompatible silos of data and digital assets, which cannot be exchanged across the distributed networks. Blockchain interoperability and intraoperability solutions are proposed as approaches to enable digital asset and data transfer from one blockchain platform to another. However, achieving blockchains interoperability and intraoperability is challenging as different blockchain platforms usually achieve a consensus regarding the order of transactions using different protocols.

Respectively, the blockchains' core network and their authentication mechanisms can be different from one another as each blockchain platform has independent algorithms and is in full control of their digital assets and data. Besides, achieving interoperability and intraoperability solutions should not necessitate significant changes in the inherent blockchain platforms, and it should be usable with minimum effort for current blockchains. This study aims to address this problem by proposing a standardised architecture to promote blockchain interoperability and intraoperability solution based on findings from the literature and qualitative sources. This article offers a simplified solution to address cross communication between blockchain-based platforms and external digital platforms. The architecture does not alter the heterogeneous nature of different blockchain platforms. This study attempts to fill a significant gap in the deployment of blockchain platforms in collaborative enterprise.

Practically, this paper addresses the problem of data and digital asset transfer in different blockchain platforms via the developed standardised architecture for interoperability and intraoperability attainment. The implementation of blockchain technology can be complex, and the standardised architecture presented in this study may require significant technical expertise and resources to implement effectively; as such this could be a barrier to adoption for some organisations. Therefore, the standardised architecture is developed as a reference architecture to provide guide and best practice on how CEs can implement blockchain with existing legacy applications. In addition, this study demonstrates the usefulness of the architecture for energy trading across business consortium providing digital services to clients offering a unified interface between the conglomerates. The modelled use case presented in this paper as seen in Figure 8 and Table 2 provides practical guidelines as a reference Archi-model for practitioners and policymakers in CE domain who are interested in practical application of blockchain in industrial areas. Also, this paper provides evidence that promptly responds to the call from the literature to improve blockchain adoption by supporting data standards that aid interoperability and intraoperability between different digital platforms.

6.4. Managerial implications

Blockchain is recognised as the distributed ledger technology that intelligently employs different techniques such as distributed consensus algorithm, cryptography, P2P and smart contract. With the potential of consensus, transparency and immutability, it has gained a substantial industrial and research attention. Specifically, it holds a huge potential for increasing the trustworthiness of data across digital platforms in collaborative enterprises. For example, CE can leverage blockchain to facilitate transaction settlement among consortium members to reduce operational expense and enable businesses to track their enterprise progress in a more economic and resilient way. To fulfill different needs there are ever-growing blockchain platforms being developed, each of which stores and processes data separately. Integration of various blockchain platforms is required to provide better services and greater value in the future blockchain landscape and creates a new paradigm of creating connections between isolated blockchain platforms (Jin, Dai, and Xiao 2018). Ideally, a mechanism is established where generic data can be exchanged to enable synchronously or asynchronously communication between various blockchain platforms through request and reply procedures, etc.

Similarly, to achieve blockchain interoperability and intraoperability different scripting languages, network models, confirmation times, block sizes, frequency of forks, consensus mechanisms, header sizes, etc. (Schulte et al. 2019), therefore, a foremost managerial challenge is to enable cross-blockchain token transfers to facilitate the reliable authentication of arbitrary data and digital asset from one blockchain platform to another. Although findings from the literature (see section 2.6, 2.7) provide evidence on preliminary solutions employed to support cross-chain interoperability, these approaches are not scalability or do not concretely define how to realise both blockchain interoperability and blockchain intraoperability. Blockchain interoperability and intraoperability can be achieved by formalising model specifications for intercommunication between architecture layers. In this work, a standardised architecture is developed and applied to an energy trading use case to support interconnections between blockchain platforms.

7. Conclusion

The DLT philosophy aims at enabling a set of untrusted independent nodes to establish an agreement on the condition and state of a shared distributed ledger. Blockchain is a type of DLT which is primarily well known for applicable use cases in cryptocurrencies for example Bitcoin and Ethereum (Ghaemi et al. 2021). But due to different blockchain platforms deployed across enterprise environment there is need to enable seamless interoperability and intraoperability to realise the full potential of blockchain technology. Therefore, this paper develops a standardised architecture which comprises different layers to facilitate integration across different blockchain networks to reduce the fragmented blockchain landscape. Data from a qualitative approach via use case scenario were carried out to demonstrate a proof of concept based on a real energy trading use case scenario enabling different DApps to communicate, exchange data and use the data that have been transferred. Findings from this study present the current state of blockchain adoption in CE, interoperability and intraoperability in CE, and blockchain interoperability and intraoperability in CE. More importantly, the findings present DLTs that support integration with blockchain in CE, blockchain interoperability/ intraoperability solutions in CE and blockchain interoperability and intraoperability challenges and recommendations.

Furthermore, blockchain interoperability and intraoperability is an essential emerging research area, and there are many exciting domains for further research. Future research direction aims to employ the developed architecture in other domains such as in smart city environment connecting two different blockchains networks that provide digital services driven by open data and digital assets. This will serve as a roadmap for further research in interoperability and intraoperability issues within the blockchain ecosystem. Another limitation is the limited applicability of blockchain infrastructure in the development of innovative digital services due to the inability of different blockchains to communicate with one another. This is due to these blockchain systems using different communication protocols and different vendors. This has put a strain on the mainstream deployment of blockchains in CE and may limit the potential impact of the standardised architecture. As such future work will investigate how to address this important issue. Although most of the possible interoperability and intraoperability technologies suggested within the standardised architecture (see Figure 8) are still in the early-stage development, more research is needed to be employed in other domains. Lastly, the standardised architecture will be further evaluated using a different research approach to further validate the practical use of the artefact in a real-life environment. Primary data will be further collected using survey questionnaires from practitioners to validate the usefulness of the developed architecture.

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