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ORIGINAL ARTICLE

Exploring interoperability of distributed Ledger and Decentralized Technology adoption in virtual enterprises

Anthony Jnr. Bokolo[1]

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Abstract
The breakthrough of Distributed Ledger Technologies (DLT) has enabled the emergence and implementation of a wide range of digital platforms in Virtual Enterprises (VE) which collaborate to provide digital services. DLT has the potential to revolutionize VE by offering transparent, decentralized, trustworthy, data provenance, reliable, and auditable features. Yet, the full deployment of DLT systems and digital platforms is still limited since some systems are operating in isolation. Hence, DLT interoperability is one of the challenges inhibiting widespread adoption of DLT platforms. DLT interoperability represents the ability for one distributed ledger platform to interact and share data with other legacy digital applications. It is inevitable to orchestrate these digital platforms fragments by introducing a cross-DLT platform integration to govern data usage within VE. Presently, already proposed approaches for DLT interoperability such as naive relay, sidechain, oracle solutions notary scheme, or relay chain are mostly not employed as they are either resource-intensive or too expensive to operate. Therefore, this paper presents a layered architecture that aids interoperability of DLT, and digital platforms based on IOTA Tangle. Design science method is adopted, and case demonstration is carried out to show how IOTA Tangle enable VE to provide an innovative virtual asset payment platform for seamless electric mobility as a service to clients. IOTA was employed as the DLT platform due to its data traceability, immutability, and tamper-proof features which allow for verification of integrity of data. IOTA offers flexibility and performance to support a reliable digital solution. Findings from this study presents a layered architecture that aids IOTA Tangle to make requests, inter-communicate, and share data via RESTful application programming interface as gateway with other external digital platforms deployed by VE to achieve an interoperable eco-system.

Keywords Information systems · e-business management · Disruptive technologies · Decentralized ledger technologies · Interoperability · Virtual enterprises

Extended author information available on the last page of the article

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1 Introduction

Digitalization has created a major shift on how organizations conduct business and prompted the development of Virtual Enterprises (VE) or virtual organization (Jnr and Petersen 2021). VEs are consortium of companies that come together to share core skills competencies, tangle, and intangible resources to better adopt to new business opportunities supported by deployment of digital technologies (Cardoso and Oliveira 2004; Camarinha-Matos and Afsarmanesh 2007). But VEs are faced with issues such as privacy, security, ownership, governance, and trust required to create successful collaboration (Camarinha-Matos and Afsarmanesh 2007; Jnr et al. 2021). This has led to deployment of digital technologies such as Distributed Ledger Technologies (DLT) to help address the stated issues. DLT is a distributed database that records data transactions on a Peer-to-Peer (P2P) network protocol principles and enables several members to manage their own duplicate copy of a common ledger synchronized simultaneously in all nodes without the need for authorization from a dominant entity (Domalis et al. 2021).

DLT enables independent untrusted nodes to create an agreement regarding the state of a shared distributed ledger (Ghaemi et al. 2021). DLTs employs different consensus mechanisms, supports collaboration, fosters transparency, and enforces strict security (Tenorio-Fornes et al. 2021). As such DLTs like blockchain, IOTA Tangle, Ethereum, Hyperledger have gained great attention in both academia and industry (Chen et al. 2020). Albeit, with the heterogeneity of sensors, equipment, and devices deployed in VEs the pursuit to address interoperability is mandatory for system synergies and data integration to exploit the full potential of DLTs (Alkadi et al. 2021; Henninger and Mashatan 2021). Also, the DLT landscape is mainly fragmented as newer heterogeneous distributed platforms have been developed over the years (Biswas et al. 2021). But, since each business has its own distinctive goals, there are different governance model for DLTs such as permissioned and permissionless being adopted (Beck et al. 2018; Pelt et al. 2021), posing constraints regarding DLT interoperability leading to incompatible vendor lock-in silos of digital assets and data which cannot be utilized by different enterprises within the networks (Ghaemi et al. 2021).

As such DLT platforms are not able to interoperate and co-operate with other systems. Thus, DLT interoperability is evolving as one of the essential features of distributed ledgers, but the understanding needed for realizing it is fragmented. This fact hinders different stakeholders from adopting DLT-supported platforms, resulting in the impediment of its wide-scale deployment information (Ghaemi et al. 2021). The isolation of different distributed ledger has resulted to asset and data silos, limiting the applications of DLT. DLT interoperability solutions are essential to enable data and asset transfer for deployment of innovative applications within VE (Anthony Jnr, 2021a). DLT interoperability can enhance advanced functionalities for future applications and revolutionize current DLT design principles. However, the actualization of cross-DLT applications involves much complexity concerning the range of underlying cross-DLT communication (Madine et al. 2021).

Currently, already proposed approaches for DLT interoperability such as naive relay, sidechain, oracle solutions notary scheme, or relay chain are mostly not employed as they are either resource-intensive or too expensive to operate. Likewise, notaries such as Binance and Coinbase mainly supports interoperability between Bitcoin and Ethereum DLT networks (Madine et al. 2021). DLT interoperability with digital system is completely not feasible and there are fewer studies that explore potential opportunities and use cases of DLTs and external digital platforms in VE context. Therefore, the key findings of the paper involves;

- Providing an understanding on recent DLTs interoperability in VE environment.
- Describe the application of IOTA Tangle and RESTful Application Programming Interface (API) for DLT interoperability.
- Design a possible scenario where DLT interoperability is applicable in VE context to provide virtual services to clients in VE environment.

Therefore, this study introduces a layered architecture for the design and development of stakeholders, technologies, and methods for interoperable DLT and legacy systems. The layered architecture facilitates DLT interoperability with external systems for seamless data communication, interaction, and sharing. A case is carried out to show how IOTA Tangle (based on a directed acyclic graph), and RESTFul APIs are deployed to enable virtual enterprises to provide an innovative virtual asset payment platform for seamless electric mobility as a service to clients. IOTA Tangle was selected as a supporting DLT due to its data traceability, immutability, and tamper-proof attributes environment to achieve an interoperable eco-system. Additionally, findings from this study identify open issues and recommendations for DLT interoperability. The rest of the article is organized as follows: Sect. 2 enumerates the literature review. Section 3 presents method and Sect. 4 describes the findings. Section 5 presents the issues and recommendation for DLT interoperability. Section 6 presents the discussion and implications, and Sect. 7 provides the conclusion, limitations, and future work.

2 Related Research

This section provides an understanding of DLT interoperability in VE environment.

2.1 Background of DLTs in Virtual Enterprise

A virtual enterprise is typically a multifaceted network of organizations collaborating to form a consortium that provide digital services to customers (Ghosh et al. 2021). VE involves a manifestation of dispersed collaborative networks of enterprises (Camarinha-Matos et al. 2009). VE have become progressively common due to organizations that collaborate and form alliances to provide digital services to clients allow organizations to be specialized and be adaptable within their business environments (Anthony et al. 2020; Jnr 2020a). As with all types of enterprises, virtual enterprises present both benefits and challenges. VE provides economic benefits to participating firms, better efficient operations, and a decrease in organizational costs (Cardoso and Oliveira 2004; Jnr 2020b).

Digital transformation of enterprise services can decrease administrative burdens, improve productivity of governments, minimize time and extra cost incurred by traditional business process to improve capacity, and eventually improve business quality (Anthony Jnr, 2021b; Domalis et al. 2021). Digital platforms such as DLT (for example Ethereum, Hyperledger Fabric, IOTA, Corda, etc.) are now being implemented in VE (Kazemi and Yazdinejad 2021). DLT comprises of decentralized database or ledger with multiple nodes and actors at various geographic locations (Farahani et al. 2021; Henninger and Mashatan 2021). DLT as a disruptive technology can improve different fields, e.g., supply chains, health sector, accommodation, retail, cryptocurrencies, finance and insurance, virtual enterprises, etc. (Madine et al. 2021). DLT enhances trust across a network of cooperating actors, such as in the case of VE, since each stakeholder has access to verifiable and transparent record about the status of the consortium (Henninger and Mashatan 2021). Basically, DLT consists of a set of nodes known as computers that stores the ledger data, a communication network used by the node(s) to receive data connections and possibly connect with each other, and a set of protocols that precisely define how the nodes can analyze, process, and securely store data.

Additionally, DLT may optionally be able to execute computer programs or stored procedures called smart contracts (Christodorescu et al. 2021). Smart contracts are routinely executed when predetermined conditions and terms are met. In VE smart contracts verify, enforce, or facilitate documents and business operations according to the agreement or terms of contract between partners in the consortium automatically making it independent of a main entity (Dima et al. 2021; Domalis et al. 2021). Smart contracts run on the DLT platform and can be utilized to develop custom decentralized applications (DApps). A DApp is simply a computer code deployed on a decentralized P2P network (Belchior et al. 2021). Smart contracts are invoked within the DLT platform as actions based on pre-defined governance rules performed when specific events are triggered. Ethereum was the first DLT platform to employ smart contracts which enables users to deploy applications via a dedicated programming language termed as Solidity (Dima et al. 2021).

DLTs can either be built permissionless or permissioned. A permissionless DLT is considered as a public DLT where no approval is needed to read and write data. A permissioned DLT on the other hand requires verification of the node users before processing of any data transactions. Nodes users need authorization to be able to access, read, and write data (Alkadi et al. 2021; Anthony Jnr, 2021a). Similarly, a DLT platform can also be public or private, where a public DLT allows anyone to join the distributed network, while a private DLT can belong to a single company or VE as such all the network nodes are governed by that corporation or VE (Jnr et al. 2020a; Alkadi et al. 2021). Using private DLT in VE requires some method of interoperability with external data sources such as open weather data, traffic data, currency exchange data etc.

2.2 Overview of DLT Interoperability in Virtual Enterprise

Virtual enterprises employ a series of different stakeholders, multifaceted global processes, activities, and systems to provide digital services to end-users. The adoption of DLT by VE offers a holistic inclusive approach for better interconnectivity and access to real-time data to optimize the delivery of digital services (Asante et al. 2021). Several enterprises envisioned a distributed multi-DLT and digital platforms ecosystem, in which different DLT and systems can collaborate with each other seamlessly to achieve different scenarios (Kazemi and Yazdinejad 2021). Presently, each DLT platform operates in isolation, thus its challenging to access external data, and each DLT platform executes data transactions only within its own ledger. Wegner (1996) mentioned that interoperability entails the capability of two or more computer software components to cooperate regardless of differences in execution platform, language, and interface.

Interoperability was defined by IEEE as the capability of two or more components or systems to exchange information and to utilize the exchanged information (Margaria et al. 2021). Accordingly, interoperability is the capability of two or more systems or components to cooperate regardless of differences in interface, language, and implementation platform (Dinh et al. 2019). DLT interoperability requires that disparate DLT systems and digital platforms can communicate with each other, and be able to access, exchange, and share, information (Koens and Poll 2019; Wang and Nixon 2021). There are different types of interoperability as suggested in the literature (Lohachab et al. 2021), in VE as seen in Table 1.

Table 1 depicts the types of interoperability in VE. Therefore, practitioners and researchers are concerns of how consortium such as VE can achieve DLT interoperability. For instance, the smart contracts running in Ethereum cannot connect with external digital systems, as the smart contract is only able to access, read, and modify the state data of the hosting DLT (Sober et al. 2021). Authors such as Asante et al. (2021) stated that issues related to DLT interoperability can be solved by adopting intermediate links between DLTs and data sources.

The emergence of research in DLT interoperability started in 2016 (Ghaemi et al. 2021), aimed at allowing systems to connect health and opens the possibility of exchanging data to provide better services to stakeholders (Anthony et al. 2019; Jnr et at., 2020b). In DLTs, interoperability means connecting and integrating DLTs with multiple external systems to access data and act on that data by modifying the state of DLT platform or the state of the external digital platforms without compromising the decentralization and trustworthiness of the DLT infrastructure (Wang and Nixon 2021). DLT interoperability is achieved when data saved in one DLT platform is referable reachable, and verifiable by another digital platform in a compatible manner (Belchior et al. 2021). In VE environment interoperability measures the ability to achieve interoperation between software, systems, processes, data, and business entities within the consortium. Interoperability helps to facilitate cooperation, communication, and coordination among different enterprise processes and units (Belchior et al. 2021). DLT interoperability in VE comprise of three main categories.

The *first entails the interoperability between different DLTs* refers to the ability of a source DLT to change the data state of a target DLT (or vice versa). This is mostly enabled by cross-DLT or cross-DLT transactions, involving a composition of heterogeneous and homogeneous DLT systems (Belchior et al. 2021). *The second interoperability category comprises of different DApps deployed within the same DLT platform* and *the last category comprises of interoperability between DLT, and*

Table 1 Types of interoperability in virtual enterprise

Interoperability Types	Description
Syntactic interoperability	Also referred to as structural interoperability focuses on enabling computer systems with different data structure to work in a common compatible format. Mostly syntactic interoperability can be achieved by using a common architectural design among computer systems with incompatible data structures. In the context of this study syntactic interoperability involves the ability of data to be accessible and reused by different stakeholders in VE by focusing on the issues caused by distinct representations, purposes, and methods.
Semantic interoperability	This refers to the information model and data model employed by different computer deployed which manages the operational procedures within the enterprise. Besides, there may be different semantic employed by computer systems due to legacy procedure employed or incorrect information used among the systems. Hence, semantic interoperability provides a structure for interconnecting or integrating semantically different data models ensuring that the meaning of data exchanged between systems provider and requester have a common data meaning. Semantic interoperability is linked whether the platform-specific semantics can be maintained across DLT.
Specification interoperability	Aims to broaden the semantic interoperability of computer systems by extending several enhancements in terms of higher-level of system integration. Specification interoperability aids in the method of information hiding and decrease in the reliance on low-level interoperability. Besides, specification interoperability expands the range of employed programming languages. Without the specification interoperability semantic interoperability will not be able to specify the differences in data properties.
Organizational Interoperability	As in VE there are various companies that collaborate to support the running of DLT platforms. However, these enterprises are currently employing different DLT networks according to their personal enterprise needs. Organizational interoperability aimed at developing techniques that can aids cooperation among VE. Though the organizational interoperability cannot be exclusively achieved without improving individual enterprise specification, as well as semantical and structural interoperability.
Platform interoperability	This refers to the technical interoperability. It involves the technical processes that enable integration among DLTs. This is because DLTs employ different consensus mechanisms which offers flexibility in VE selecting DLT framework. Enterprises are faced with various issues in terms of platform interoperability since there are different platforms developed for specific DLT networks, such as Hyperledger, IOTA Tangle, Ethereum, and so on, each having different versions or platforms requirements. This difference may result to drawback for developers in developing cross-DLT and digital platform integration. Thus, platform interoperability facilitates cross-platform communication without requiring prior extensive knowledge of any specific DLT platform. Therefore, heterogeneous digital platforms can be federated when platform interoperability is achieved to develop innovative DLT applications which can be utilized in VE and other domains.
Network interoperability	This type of interoperability will provide a method for facilitating seamless end-to-end connectivity between computer systems in heterogeneous DLT networks. This is because DLT employs different distributed networks and heterogeneous infrastructure that comprises of multi organizations which provides digital services.
Isolated interoperability	This comprises of isolated computer systems that have no means of establishing connection with other systems. This type of interoperability comprises of standalone computer system at the local level that can be manually integrated for the purpose of data interaction and extraction among the isolated systems.

other digital platforms deployed to facilitate VE operations. Additionally, findings from the literature (Ghaemi et al. 2021; Madine et al. 2021) suggest that for DLT interoperability to be successful the following have to be observed;

- The solution architecture should facilitate various types of DLT systems, such as private or public DLTs e.g. (Ethereum, IOTA, Hyperledger Fabric, etc.).
- The integrated external systems must not trigger a major disturbance to the DLT infrastructure that will require modification of the smart contract procedures or requiring frequent forking for new intercommunication within the network.
- The end-users should be involved in any manual processing.
- Any dependence on off-chain communications with external digital systems shall be minimal.
- The integration should not negatively impact the security or performance of the DLT networks.
- The DLT platforms such as IOTA should be in full control of their data and assets.
- The data transfer protocol employed should be technology-agnostic. Such that the interoperability solution needed should not require substantial changes in the destination and source networks.
- The DLT infrastructure should be able to integrate with digital system solution with marginal effort.

Overall, DLT interoperability aims to enable digital platforms to use the assets and data available on DLT other than the distributed network (Ghaemi et al. 2021). This promotes the creation of value-added services to VE (Anthony Jnr et al. 2021). Furthermore, DLT interoperability solution is envisaged to support heterogeneous DLT and diverse systems to interact and share data (Madine et al. 2021). Therefore, this study is more aligned with the third category of DLT interoperability in VE and platform interoperability (see Table 1), to support conflate digital application portability and flexibility. As platform interoperability has the potential to address DLT scalability towards creates innovative business opportunities as argued by (Belchior et al. 2021).

2.2.1 Existing Interoperable DLTs in Virtual Enterprise

Due to development of different DLT platforms deployed in VE such as Ethereum, Hyperledger, Bitcoin, or IOTA Tangle which utilize different data formats achieving interoperability across these platforms with external digital systems is important for data integration. This will facilitate enterprise transition from deploying isolated DLT platforms to networks of interoperable DLT platforms and systems to unlock the potential of DLTs. Additionally, standardization can help VE to achieve interoperability. Existing open solutions assisted by international regulating alliances, groups, or private associations (such as., IEEE, IEC, W3C, OMG, OneM2M, OASIS ETSI ITU-T, ETSI, etc.), are available to support standardization of digital technologies. These associations provide suggestions to achieve an interoperable digital eco-system of architectures, IoT devices, services, and systems. Some of these standards are neutral and adhere to cross-domain support, but some standards only apply to certain technologies (Farahani et al. 2021).

DLT interoperability facilitate secure state data transitions across different digital platforms, either heterogeneous or homogeneous (Lohachab et al. 2021; Wang, 2021). Findings from the literature suggest that prior studies focus on cross-DLT communication for asset transfer or asset exchange, such as AMHL, Tesseract, Xclaim, Herlihy, etc. Another DLT is Interledger created as a protocol for enabling communication across different DLT ledgers by utilizing payment channels (Antal et al. 2021). Irrespective of these standards to promote DLT interoperability, these standards are more applicable for public-to-public DLT interoperability mostly to aid exchange of asset transfer, payment channel and cryptocurrency. Also, findings from Ghosh et al. (2021) highlighted that DLT such as Fabric Channels, Chainspace, Omniledger, and Atomix aids interoperability between different modules of the same DLT platform.

Enterprises such as IBM Food Trust, Marcopolo, TradeLens, etc., utilize private (permissioned) DLT platforms such as Corda and Hyperledger Fabric to create their own VE (closed consortia of industries). But these DLTs (Corda, Fabric, or other private DLT) do not provide integration or communication protocols for connecting with external digital platforms which is essential for building consortia of digital service in VE (Ghosh et al. 2021). However, some DLT based platforms which enable enterprises to interact with clients have been developed, such as BlockV that ensures fairness and supports ridesharing and ArtChain an art marketplace platform based on blockchain (Ghosh et al. 2021). There is need to explore how DLT interoperability can be achieved with external digital systems in VE.

2.2.2 Consensus Mechanism and Operability of DLTs

DLTs such as blockchain employs verification, also termed as mining, which is usually executed using a consensus mechanism or algorithm that comprises of the rules that network nodes must employ when authenticating data transactions (Hardjono et al. 2019; Lai et al. 2021). Consensus demands that participating nodes get a positive response from all other member nodes by confirming the specified transaction. As no centralized body verifies data transactions, all data transactions are completely secure and accurately validated based on the consensus protocol. Consensus algorithms aims to guarantee consistency within the DLT platform (Wang and Nixon 2021). Consensus algorithms necessitate all network peers in the distributed ledger to achieve mutual agreement concerning the distributed ledger's state (Lima 2018). This ensures the reliability and trust among all participants within the distributed network. Basically, consensus algorithms make sure that each new block in the chain is the only authenticated version agreed upon by all nodes (Dima et al. 2021; Farahani et al. 2021; Meier et al. 2021).

Presently, many consensus algorithms have been developed. The most widely employed ones are Proof-of-Work (PoW), Proof-of-Stake (PoS), Proof-of-Authority (PoA), Delegated Proof-of-Stake Consensus (DPoS), Practical Byzantine Fault Tolerance (pBFT), etc. (Dima et al. 2021; Lan et al. 2021). DLTs such as Bitcoin employs PoW protocol where the participating network nodes are needed to resolve a tough cryptographic problem that involves computational resources (referred to as mining) (Dima et al. 2021). The miner or node user who manages to unravel the challenge will eventually update the data state of the DLT and get rewarded. Besides, other consensus protocols, such as PoS and PoA are being deployed to resolve increased costs and scalability constraints of PoW. In a PoS consensus protocol, participants vote with their stakes implying that every user has some chance per second of creating a valid transaction and this chance assigned to the user is proportional to their profile`s balance. Whereas in PoA, which employs a less decentralized architecture, only specific validators or stakeholders can create new transactions. Validators can be chosen according to the DLT platform's governance rules (Dima et al. 2021).

PoA consensus protocol is an Ethereum sidechain-based platform. The PoA is aimed at allowing a cross-chain data transferring process between Ethereum to a side chain based DLT while providing interoperability and scalability between other DLT platform. PoA offers a bridging capability which aids stakeholders to transfer their non-changeable tokens from one DLT to another easily, which offers a solution to improve communicate between two arbitrary stand-alone DLT platforms (Wang, 2021). On the other hand, PBFT provides mechanism of achieving consensus between node users within the distributed network which may have flawed nodes, either providing ambiguous data or not responding. PBFT is based on a functional algorithm that assumes that nodes are dishonest. Thus, this consensus mechanism depends on trusted nodes within the DLT system (Asante et al. 2021). In this research IOTA Tangle based on Directed Acyclic Graph (DAG) protocol is employed to facilitate collaboration of trusted and non-trusted stakeholders in VE. IOTA Tangle is employed as it the decreases cost and performance requests of digital application. More discussion on the application of IOTA Tangle is presented in the methodology section of this paper.

2.3 Exiting DLT Interoperability Solutions

A DLT interoperable approach comprises of uniquely distributed data ledger where data transaction execution may span across multiple heterogeneous platforms. This helps to support data recorded in DLTs to be reachable, referenceable, and verifiable by other external computer systems in a semantically compatible approach (Wang, 2021). Currently, the full actualization of DLT interoperability is still in the theoretical phase and has had little practice, since successful inter DLT interoperability requires at least two DLT platforms to freely exchange data (Wang, 2021). To realize DLT interoperability paradigm there has been a recent development to facilitate DLT platforms interoperability with the goal of developing a decentralized network that allows independent distinct DLTs with different governance policies to interact with one another (Kazemi and Yazdinejad 2021; Lumineau et al. 2021).

Although, there are many digital tokens developed on top of the Ethereum system that are interoperable with other DLTs because they are built by smart contracts that follow the same set of Ethereum token specifications. Also, Hyperledger Cactus permits specifying business logic plugins that connects to private and public DLTs capable of conforming with legal regulations and frameworks (Belchior et al. 2022). Conversely, there are other digital tokens developed on distinct DLTs which are not interoperable such as the instance between Bitcoin and Ethereum networks (Christodorescu et al. 2021). Accordingly, this sub-section discusses prior DLT interoperability solutions developed in the industry and literature as seen in Table 2.

Based on the reviewed suitable approaches for DLT interoperability. Several approaches can be employed to support DLT interoperability as discussed (see Table 2). With relays, the state of one DLT is replicated within another DLT, which facilitates callers of the relay contract to validate the presence of a data transaction on the source DLT (Sober et al. 2021). However, relays have associated costs incurred since on-chain authentication is quite expensive, and ledgers (blocks) must be continuously relayed. All the reviewed approaches, except for hash-locking mostly depend on a centralized body for validating the transactions and ensuring assets and data are transferred fairly. Protocols such as the Interledger protocol and the notary scheme requires at least one DLT network which instinctively trusts another entity. Although the reviewed approaches maintain the integrity of data communicated across DLTs, notary-based approaches including Polkadot and Cosmos utilize complex mechanisms to ensure integrity verification, thus making them inefficient.

Besides, all reviewed categories have limited scalability, except Polkadot and Cosmos which directly confront this limitation with the notion of parallel blockchains. Also, other framework-independent solutions would be able to offer cross-chain communication to support DLTs such as Ethereum with Hyperledger Fabric. In theory, all approaches are independent, except for notary scheme because they depend on a specific ledger (block) header structure (Madine et al. 2021). In this study RESTful APIs are employed to provide data from external systems as they serve as bridges between DLT platforms and external data sources. These APIs can facilitate query of data from external data sources and also re-directs data or asset state to DLT platform or smart contract. Furthermore, to ensure the integrity and authenticity of the data "IOTA Tangle" is employed as discussed in the methodology section of this paper.

2.4 Prior DLT Interoperability Approaches

DLT interoperability is a promising and extensive research domain. Several efforts from both academia and industry have been carried out to improve interoperable DLT protocols and architecture which allow cross-DLT exchange between different distributed networks to expedite the exchange of data transactions as seen in Table 3.

To the best of the author(s) knowledge, none of the discussed studies in Table 3 investigated cross-DLT interoperability solutions that are capable in integrating with external digital systems towards enhancing data sharing across architectural-independent and domain-neutral DLT environment with no end-user intervention and point of centralization. Prior interoperability paradigms such as HTLC mainly employs a solution for ensuring the integrity of data transactions, but do not offer a wide range of abilities and use cases. Conversely, there is need for study that can offer secure, adaptable solutions, and cost effective to address complexity enterprises operations such as in VE. Therefore, IOTA Tangle and RESTful APIs are employed in this study as further discussed in the next section.

Table 2 Existing DLT interoperability solutions mostly employed in VE

DLT Interoperability Solutions	Description
The Chain-Based Interoperability	The chain-based interoperability approach mainly aims to improve interoperability among public DLTs, particularly for the applications of cryptocurrencies in enterprises. The chain-based utilizes token swaps, for example crypto-coin swapping, to exchange data among different DLT platform. According to Wang (2021) this approach comprises of *sidechain, notary scheme, and hash-locks*.
Sidechains	Sidechains was proposed by Back et al. (2014), as secondary chains connected to blockchains through a two-way peg procedure. This approach involves locking the transferred data on the mainchain till they are generated in the sidechain (Alkadi et al. 2021). Sidechains are suggested as alternatives for improving the scalability of blockchain and processing of transactions simultaneously with the main DLT (Lohachab et al. 2021). The primary goal of the sidechain is to expand the functionalities of interoperable DLT networks to support the transmission of data between interlinked blockchain networks in a decentralized approach to ensure synchronization of tokens among two chains (Hewett et al. 2020). Sidechains may deploy their own consensus mechanism via a two-way peg which completely differs from the main DLT protocol employed (Wang, 2021). Thus, all data transactions associated with sidechains are mainly rooted in a locking data transaction in the main DLT. The sidechain approach provides an alternative to sharding technique by entirely relying on the data stored on the side chain and incorporating the data with the main chain only when locking and unlocking data transactions. Thereby offering improvements to the underlying DLT by taking over some of the transitioning load (Antal et al. 2021). Although, generating and managing sidechains is complex as it is designed to interlock two chains only. Connecting more “N” DLTs requires constructing “N-1” sidechains which eventually reduces the scalability of this approach (Alkadi et al. 2021).
Notary Scheme	Notary schemes provides centralized data and assets exchanges between multiple DLTs. This DLT interoperability approach is the most convenient and easiest to employ. Although it is susceptible to centralization associated security risks and possible single point failures (Alkadi et al. 2021). Notary schemes employ a third trusted body as an intermediary between DLTs. Hence, the notary’s role is to validate the integrity and correctness of exchanged data to guarantee consistency among DLT. One substantial advantage of notary schemes is that it requires no additional change and is easy to deploy in enterprise (Wang and Nixon 2021). An example on the application of Notary scheme is deployment of Ripple’s ILP protocol. Notary scheme is mostly employed for cryptocurrency exchange and is the most adopted as a common solution in industries that use DLT.

Table 2 (continued)

DLT Interoperability Solutions	Description
Hash-locking	This is another technique that helps DLTs to exchange data and assets without requiring a trusted third party. Hash-locking employs a digital signature verification and Hash-Time Locked Contracts (HTLCs) to achieve interoperability among DLTs. This approach is employed to facilitate cryptocurrency ecosystem among trustless parties for off-chain transactions and atomic swaps (Alkadi et al. 2021; Christodorescu et al. 2021). Overall hash-locking approach via HTLC aids locking of collateral funds or assets on both distributed ledgers to form a universal payment channel and issues the collateral funds as part of a final payment automatically at the payment channel's termination time or manually by the participants (for instance in case of manual channel termination or a disagreement) (Christodorescu et al. 2021). The hash-locking method employed puts a time lock on data transactions so that both agreements are fully met (Wang and Nixon 2021). The tokens are lock up for a certain time on one DLT platform. The receiving user can unlock the tokens utilizing a secret which is communicated with him/her by the sender. However, this approach requires distributing a secret between the receiver and sender which may have some associated security risks. Besides, it requires the sender and receiver to be online during data transfer duration. This is similar to the one-time password (OTP) as such it provides a robust interoperable solution for future development (Alkadi et al. 2021).
Atomic Cross-chain	An atomic cross-chain or swap is one method that supports users of different DLTs to exchange their data or assets in a trustless manner. In this approach data exchange is carried out using atomic swapping procedure that is employed to ensure consistency and integrity among different DLT networks. The term "atomic" is derived from database management systems, where an atomic data transaction or atomicity is restricted to a set of binary outputs (for instance, either 0 or 1). Hence the concept of atomic swap is adapted to a multi-DLT scenario as an atomic cross-chain swapping procedure. Generally, atomic swap is employed to achieve interoperability among multiple DLT systems (Madine et al. 2021; Wang and Nixon 2021). To attain the atomic procedure, the token transfer course must be in a self-governing and synchronized manner among the involved DLT without the support of a centralized body. However, an atomic swap often facilitates token exchanges mainly rather than data transfers. Also, this approach mainly requires a counterparty (of another DLT) who is eager to swap these tokens (Wang, 2021). Additionally, atomic token swapping procedures are not adequately self-inclusive to carry out tasks of decentralized applications (DApps) as the executable mechanisms in DApps may require more complex actions other than basic token transfers.

Table 2 (continued)

DLT Interoperability Solutions	Description
Cross-chain Communication	Presently, each DLT platform works as an isolated system, and it is difficult to acquire external data as each DLT executes data transactions independently. Cross-chain communication protocols are crucial to achieve DLT interoperability. Cross-chain communication entails the transfer of data between one or more DLTs. A cross-chain communication approach refers to the method in which a pair of DLTs (consist of both intra and inter DLTs) interconnect to achieve a consistent status and synchronization among DLTs. A cross-chain scenario can comprise of different DLT systems, e.g., Ethereum and Bitcoin. This approach aims at accessing or exchanging functionality and data which is available in other digital systems. It typically comprises of two chains usually two chains (source and target). The source chain usually refers to the DLT that originates the data transactions, and the data transaction is sent to the receiving DLT (Belchior et al. 2021). However, a cross-chain communication approach mainly focuses on homogeneous DLTs, such as intra-chain scenario, for instance, Zendoo, Interledger protocol, etc. In most cases, it is difficult to achieve a cross-chain communication protocol, since different DLTs may deploy different network models, block sizes, consensus protocols, hashing algorithms, and confirmation times (Wang, 2021).
Blockchain of Blockchains	Generally, DLT interoperability aims to create a generic communication scheme between DLTs, e.g., transmitting arbitrary data across DLTs in a trustworthy and decentralized manner (Wang, 2021). Blockchain of blockchains approach is a model that integrates different blockchains in an approach analogous to sidechains called bridges. In blockchain of blockchains approach each blockchain is linked to other blockchains across different distributed network either directly or through hubs (Rajnak and Puschmann 2020). However, this approach requires the interconnected blockchains to have the similar architecture. Besides, this approach entails additional transaction fees which may inhibit scalability on a global level (Alkadi et al. 2021; Belchior et al. 2022).
Trusted Relay/Relay Chain	Trusted relay is a decentralized method that aids validators from source and target chains to authenticate, sign, and deliver data transactions between two DLTs. Sometimes, a trusted third party is used to perform the tasks of the decentralized verifiers. Trusted relays involve trusted parties that redirect data transactions from a source DLT to a target DLT, aiding end-users to specify arbitrary business logic (Belchior et al. 2021). To achieve DLT interoperability between different DLTs such as blockchain platforms. Relays are usually employed on smart contracts running on a target DLT i.e., the DLT which requires data from a source DLT platform. For example, Cactus implements multiple trusted third party to issue data transactions in several DLTs (Alkadi et al. 2021). Relay chain was first developed in the chain fibers scheme, which suggests the notion of cross-chain data exchange across a single relay chain and several similar chains grounded on decoherence and transaction latency to manage data transactions of multiple components of the system. Subsequently, different DLT systems including Cosmos and Polkadot have been improved on this basis, improving the original DLT architecture, facilitating DLTs to exchange assets and data within a variety of heterogeneous DLTs. Although trusted relay approach supports cross-chain integration to a specified extent, it does not address data privacy issues (Lan et al. 2021).

Table 2 (continued)

DLT Interoperability Solutions	Description
Oracles	Oracles are technological solutions for addressing complex computational issues in distributed ledgers. Oracles can be seen as mechanisms that offer a secure connection between DLT platforms and external digital platforms. Oracles acts as a trusted network of entities or third-party body for DLTs. Thus, oracles can be utilized to provide integration from via different URLs, InterPlanetary File System (IPFS), or components responsible for operating more complex algorithms. Accordingly, oracles are responsible for ensuring data authenticity through authenticity proofs. The required data can be retrieved from external digital services and published back to the distributed ledger via callback transaction (Antal et al. 2021). Although, oracles are faced with issues which impacts direct response or requests issued by node users during mining operations. This is an issue in VE, and it leads to DLTs not able to access dynamic changing data such as stock prices, weather, etc. Also, oracle-based system may be prone to man-in the-middle attack or data tampering. Besides, oracles re-establish trusted third parties and the concept of centralization which is seen as an issue (Henninger and Mashatan 2021).
Open Digital Asset Protocol	Open Digital Asset Protocol (ODAP) is seen as the first cross-chain integration protocol for handling multiple digital systems and assets for cross border data transactions. It leverages data or asset profiles (such as the data schema of an asset) and via gateways. The ODAP was proposed by the Internet Engineering Task Force (IETF) mainly to support asset and data transfer protocol that is deployed between two gateway systems. The process of transmitting data or an asset among DLTs is analogous to an atomic swap that locks data or asset within DLT and creates its representation in another digital platform (Belchior et al. 2022).

3 Method

3.1 Design Science Method

This research adopts the design science methodology by using case demonstration approach. Design science research is a problem-solving approach that has its roots in sciences and engineering as a problem-solving method (Peffers et al. 2007). It aims to deliver answers to design-based issues by forming innovations that describe the technical ideas, capabilities, practices, and products via which the design, analysis, administration, implementation and use of information systems can be effectively and efficiently accomplished (Hevner et al. 2004). In design science the solution is built as an innovative artifact which comprises deploying a set of actions to create an artifact. Thus, design science develops and assesses artifacts aimed to address associated issues (Hevner et al. 2004). To develop an artifact, design science method defines two processes to build and evaluate (Jnr et al. 2020b). Thus, design science methodology is employed to report how the IOTA Tangle enable VE to build an innovative virtual asset payment platform for seamless electric mobility as a service to clients. Each of the phase employed in design science approach is briefly discussed below;

Table 3 Prior studies on DLT interoperability approaches

Authors, year and Contribution	Aim	Key Findings
Belchior et al. (2022) developed a fault-tolerant middleware for blockchain interoperability.	A HERMES fault-tolerant middleware was proposed that connects blockchain systems based on the open digital asset protocol.	Overall findings from their study suggest that cross-chain data transactions can be attained firmly with HERMES, as far as the gateways are conforming with legal frameworks.
Alkadi et al. (2021) researched blockchain interoperability in unmanned aerial vehicles networks-based systems.	The study provided a review on cross blockchain approaches to underline the latest developments in the field.	Findings provided a continuum of scenarios related to unmanned aerial vehicles networks that may influence the possibilities of cross-blockchain approaches.
Belchior et al. (2021) carried out a review on blockchain interoperability.	The study aims to reveal that blockchain interoperability has a much wider continuum than cross-chain asset and cryptocurrencies transfers.	Findings provide support for technologies, open challenges, use cases, standards, and future directions in blockchain interoperability.
Domalis et al. (2021) proposed a conceptual approach to achieve an interoperable and trustable decentralized service for cross-border eGovernance mainly citizen-centric.	An artificial intelligence-based solution was introduced that facilitates stakeholders to contribute to a decentralized network.	Supported efficient service delivery and data exchange to promote an efficient, cost-effective, secure, and interoperable service.
Ghaemi et al. (2021) designed a pub-sub oriented architecture to enhance blockchain interoperability.	The study also proposes an innovative blockchain interoperability approach for permissioned blockchains based on publish and subscribe architecture.	The study tested different subscriber and publisher networks, such as Hyperledger Besu, an Ethereum client and two distinct types of Hyperledger Fabric.
Ghosh et al. (2021) explored how to utilize public-private blockchain interoperability within closed consortium.	A decentralized architecture gateway was provided as an interface for public and private blockchain which supports interoperation.	A use case of Hyperledger Fabric and Ethereum comprising of three service providers that creates a consortium was formed for cloud technology provisioning.
Kazemi and Yazdinejad (2021) developed an automatic benchmark support for multi-blockchain interoperability-based platforms.	The study explored the security and efficiency requirements of interactions among heterogeneous blockchains. In realization of multi-blockchain approach in achieving an interoperability platform that aims at connecting different blockchains.	Provides understanding on the trade-offs between different interoperability platform and their appropriateness for different system domains.
Lan et al. (2021) examined how to enable confidential interoperability within blockchains based on trusted hardware.	The study provided a privacy safeguarding cross-chain system that enable confidential interoperability among blockchains.	The key contribution aimed at encrypting cross-chain exchange of data based on the relay chain with the support of trusted implementation environment and utilizing fine grained access mechanism to protect end-user privacy.
Lipton and Hardjono (2021) conducted research on intra-and interoperability of blockchain.	Provided an overview of intra-and interoperability of blockchain.	Findings from the study recommended employing automatic market makers for intraoperability and atomic swaps and gateways for interoperability.

Table 3 (continued)

Authors, year and Contribution	Aim	Key Findings
Lohachab et al. (2021) conducted a review on interconnected blockchains towards the role of interoperability between different blockchains.	A layered architecture was developed for efficient development of methods and protocols for interoperable blockchains.	Findings also provides taxonomy and insight into the state-of-the-art of on interconnected blockchains.
Madine et al. (2021) developed an application-level interoperability for blockchain systems.	The study proposed an application-based cross-chain interoperability service which support blockchain infrastructure for architecture to share data and inter-communicate.	The study employs a decentralized platform as a distributed translation layer that can communicate with multiple blockchain systems.
Wang (2021) carried out a systematic review on the current development of blockchain interoperability by investigating practical schemes and general principles to achieve interoperable blockchain applications.	Discussed several challenges and potential directions to improve blockchain interoperability.	Findings from the study provided the state-of-the-art discussion to address interoperability of blockchains.
Wang and Nixon (2021) provided discussion towards an architecture for blockchain interoperability based on trusted services.	The proposed interoperable architecture offers robust arbitrary support for blockchain systems based on Byzantine fault tolerance protocol.	Findings from the study provides an effective cross-chain transmission protocol to aid interoperable operations and atomic swaps between various blockchain systems.

3.1.1 Problem identification and motivation

This first phase aims to identify and define the research issue to be resolved and it intends to show the significance of the current study. Accordingly, this research aims to investigate interoperability of distributed ledger and decentralized technology adoption in virtual enterprises.

3.1.2 Specifying the objectives for a solution

The purpose of this next phase is to indicate the objectives for the solution to be described, which entails a definition of how IOTA Tangle can be employed to support interoperability with DApps to address the problems described in the previous phase.

3.1.3 Design and development

This phase entails the design and development of the layered architecture that facilitates interoperability of DLT. This phase describes how the layered architecture aids the collection, processing, and usage of data within VE. This phase is described in Table 4.

3.1.4 Demonstration and evaluation

The demonstration phase is merged with the evaluation phase in this study as a single phase. Hence, in this phase, the layered architecture described in the previous phase is employed to demonstrate a case of "IOTA Tangle" to support interoperability as seen in Fig. 1. The modelling case scenario is shown in Fig. 1 is also the artifact of the evaluation phase which demonstrates the usefulness of the presented layered architecture.

3.1.5 Communication

The last phase includes the writing, documenting and reporting of the findings from the case demonstration to other researchers and practitioners interested in interoperability of DLTs to improve VE operations.

3.2 Employed DLT Approach

Although several approaches have been suggested to support DLT interoperability, practical architectural frameworks are scarce and limited. Particularly, current approaches are often lacking standardization to provide DLT interoperability capabilities for use cases scenarios. Therefore, a layered architecture is presented based on enterprise architecture modeling. The layered architecture helps to show how interoperability is achieved with DLT and external digital platforms. Architectural models seem like a baseline to understand how DLT (IOTA Tangle via directed acyclic graph) can interoperate and form synergies with external digital systems via APIs deployed with VE. Furthermore, DLTs are grouped based on how the infrastructure is implemented into three categories which includes blockchain, Directed Acyclic Graph (DAG), and hybrid DLT (Farahani et al. 2021).

Blockchain is the most broadly known and employed DLT. Blockchain is simply a cryptographically secure decentralized ledger that generates a digital log of immutable and trusted transactions, which are captured into blocks through a procedure referred to as mining and can be distributed either as a private or public network. Over the years other DLTs have been developed to address the shortfalls of blockchain such as transactions per second and scalability which leads to high energy utilization. One of these DLTs proposed are the directed acyclic graphs, Holochain, and Hashgraph. Directed acyclic graph is currently the second most deployed DLT which stores data transactions in nodes. DAG uses two prior data transactions to authenticate each new data transaction, thus creating more consensus as compared to blockchain (Asante et al. 2021). Other type of DLT is the Hybrid DLT which comprises of different types of DLTs which are seamlessly connected.

3.2.1 Suitability of Direct Acyclic Graph (DAG)

Presently, DLT infrastructures including blockchain and directed acyclic graph are transforming the way data is disseminated across VE (Farahani et al. 2021). However, this current study is more aligned to DAG employed by IOTA Tangle. The DAG is a graph where data transactions act as the nodes within the graph and the edges of the graph have directions (Churyumov 2016). The whole graph starts with an origin transaction that is authorized directly or indirectly by all the data transactions within the graph. When a new data transaction is suggested, it must be authenticated and confirmed by two previous data transactions from the graph that was not yet authorized (for example., tips selection algorithm). The tips selection algorithm is based on the Markov Chain Monte Carlo algorithms, and it uses the aggregate weights of sub-tangles. When a situation of contradictory transactions occurs, the greater the cumulative weight of the data transaction, the more reliable it is (Antal et al. 2021).

In comparison to blockchain, DAGs are not made up of blocks and mining is not needed when data transactions authenticate one another. Similar to blockchain, DAG can store data transactions. These data transactions are described by nodes connected to at least one, but probably many other data transactions. Though, connections are particularly directed from previous data transaction to newer one in accordance with a predefine topological order. DAGs do not allow loops since they are acyclic. Also, new data transactions must validate at least one previous data transaction when joining the DAG. Each new data transaction is required to refer earlier to the parent data transaction. Then the new data transaction signs the parent transaction hashes and then integrates those hashes to the new data transaction (Farahani et al. 2021). Since its inception several DLT platforms have been creating solutions based on DAG adaptations such as Flowchain HashGraph, Dagcoin, Holochain, and IOTA. Among the DAG-based platforms, IOTA is the most employed solution. It utilizes a DAG, so-called Tangle, as a ledger for storing data transactions.

3.2.2 Pertinence of IOTA Tangle in Virtual Enterprise

As previously stated, DAG is an alternative to blockchain since it provides some gains over conventional blockchain, including scalability transaction costs, and performance. In this study, IOTA based on DAG is adopted as the DLT infrastructure as previously stated. IOTA was developed in 2015 with no blocks, mining, or trading fees. IOTA employs Machine to Machine (M2M) principle, as it was intended specifically for the Internet of Things (IoT) and micropayments-based enterprises with an interconnected architecture via the tangled network. IOTA manages and securely shares data transactions via an encrypted channel using Masked Authenticated Messages (MAM) protocol which is one of the most notable characteristics of IOTA. It ensures that the receiver of data transaction receives data transactions with integrity via a trusted source using a security key. To decrypt data transactions stored in the Tangle, the key must be private, so only approved stakeholders can access the data. Overall, the IOTA community provides two public networks (the Devnet and the Mainnet), with each one having its own Tangle which nodes can conduct transactions. Additionally, a private node can be implemented and connected to the network (Lima et al. 2021).

3.2.3 Applicability of RESTful API Gateway in Virtual Enterprise

The notion of gateway in DLT infrastructure helps to support the transfer of data or assets among DLTs and external digital systems. Gateways utilize machine resolvable addresses such as identifier of a specific resource (URI) or Uniform Resource Locator (URL) to connect with other systems to obtain information such as protocol-specific messages and public-key certificates. Gateways provide support for semantic and platform interoperability, unlocking value from data. In this study RESTful APIs are employed as gateway to help manage data assets. RESTful APIs offers a standardized approach for applications to communicate, and it was first explained by Roy in his PhD Dissertation (Fielding 2000). RESTful APIs are referred to as either centralized or decentralized trusted third-party gateway that can help data transfer process among DLTs.

Findings from the literature (Margaria et al. 2021), suggest that RESTful APIs helps to share data between application frontend and the backend. RESTful APIs are commands encoded via the widely adopted HTTP standard to aid data exchange in many formats. The most common data format employed by RESTful APIs is the Java Script Object Notation (JSON) and Extensible Markup Language (XML) which can be used to send and request data transaction to external digital systems within VE. However, including a trusted third-party gateway such as RESTful APIs is opposed to one of the DLT features, decentralization. The API methodology is more feasible (Asante et al. 2021), as it allows DLT-based systems integration with centralized legacy systems. API gateways can also be leveraged for data and asset transfers within the DLT eco-system in a non-repudiable and secure manner similar to oracles allowing integration with external data providers.

RESTful APIs retrieves validated data and deliver it to a DLT platform and pull data from DLT platforms to achieve interoperability. RESTful API was employed by prior DLT studies (blockchain smart contract health care (Biswas et al. 2021), Ethereum and Hyperledger Fabric health care (Madine et al. 2021), IOTA Tangle for healthcare care (Lima et al. 2021), Hyperledger Fabric for product authentication (Prada-Delgado et al. 2021); Ethereum and Hyperledger Fabric for patient's decentralized application (Madine et al. 2021)). Therefore, this study employs APIs in DLT analogous to prior study Karoudis and Magoulas (2018).

4 Findings

4.1 Background of Case scenario

Case scenario is adopted in this study and qualitative data was collected from partners involved in a VE that collaborate to provide digital payment for seamless electric mobility as a service to customers. IOTA Tangle was deployed as a DLT within the VE. To facilitate DLT interoperability, RESTful API is employed in this study to enable communication from IOTA Tangle with other external digital systems deployed within the VE as a connector or bridge to enable platform interoperability as previously mentioned in Sect. 2.2. IOTA Tangle ensures privacy and data governance concerns within VE and enables traceability and immutability of transaction among consortium members. Using IOTA Tangle an innovative virtual asset payment platform was developed by IOTA Foundation in a smart city project (cityxchange.eu), to enable micro payment via IOTA virtual assets and is modelled in the presented layered architecture. The layered architecture comprises of seven layers (context, service, business, application and data processing, data space, technologies, and physical infrastructures) as discussed in Table 4.

Table 4 Findings from use case scenario on relevance of the architecture layers

Layers	Description
Context	The context layer comprises of the modules that specify the concerns and main requirements of stakeholders within the VE. It also comprises of drivers, enablers, quality factors, and main goals of all partners within the consortium.
Service	The service layer specifically describes virtual services provided by all partners within the consortium. Also, the service layer uses data from different platforms deployed by business actors. The services layer is mostly driven by the VE objectives, and which is aimed at achieving DLT interoperability with external digital platforms.
Business (Virtual Enterprises)	The business layer highlights all enterprises involved in consortium that collaborates to provide various virtual services aimed at supporting the actualization of DLT interoperability. This layer is envisioned to include all stakeholders or actors that work together to provide a value-added service to clients. This will enable new constellations of VEs, easy creation of innovative services, innovative collaborative business models, and evolution of virtual services.
Application and Data Processing (DApps)	The application and data processing comprise of all software systems utilized by partners to support the consortium. This layer entails different thematic, or distributed or centralized platforms applications deployed to support the provision of virtual services, such micro payment, e-trading, data analytics, etc.
Data space	This layer gathers different types of data through such as open data (e.g., weather forecast, energy trading, etc.), real time data (e.g., sensor data, data from IoT, etc.), mobility data, data from social networks, historical data, etc. These collected data are stored and treated in the data space layer. Data space layer define the data, meta data, and data that support DLT interoperability and open innovations within VE. Also, in this layer all different data sources utilized by different digital platforms deployed by all stakeholders within VE are captured to support collaboration.
Technologies	The technologies layer mainly encapsulates the hardware and software employed to support applications and data processing layer for achieving DLT interoperability. For example, micropayment technologies used by IOTA Tangle and other cloud-based technologies used by RESTful APIs, etc. Moreover, in the technologies layer some data processes are carried out on real time data generated from the physical infrastructures layer.
Physical Infrastructures	Thus, the physical infrastructures layer involves all physical hardware infrastructures to support DLT interoperability. It mainly captures all metering devices, sensors, equipment, industry 4.0 machinery etc. deployed within the enterprises involved in the consortium.

4.2 Deployment of IOTA Tangle and RESTful API

Grounded on the layered architecture the deployment of the virtual asset payment platform is shown in Fig. 1 to depict how DLT interoperability is attained with external digital systems. The qualitative data collected is coded based on the layered architecture layers to show the relevance of each layer. The data coding and analysis are carried out using descriptive analysis modelled in ArchiMate as seen in Fig. 1. All data for this case is collected from partners in IOTA (IOTA, 2022), and from the +CityxChange project deliverable on "Report on the Architecture for the ICT Ecosystem" (Petersen et al. 2021). The collected data is coded to show how DLTs such as IOTA Tangle can help to achieve interoperability in business environments such as in VE. The data as related to each layer provided by IOTA is represented in Fig. 1.

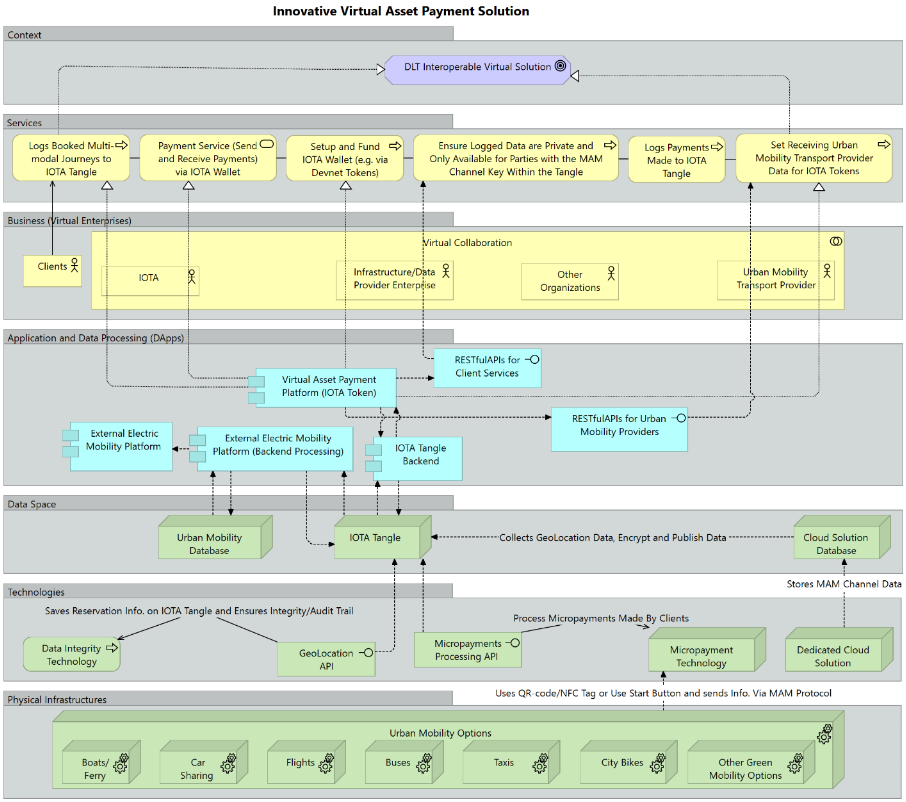

Fig. 1 Modelling of the innovative virtual asset payment platform

Figure 1 depicts the deployment of IOTA Tangle and RESTful APIs to show the application of DLT interoperability for enable micro payment via IOTA virtual assets. Thus, the findings from the case use case scenario for the innovative virtual asset payment platform is modelled in the layered architecture is illustrated in Fig. 1 and discussed in Table 5. Each of the modules within the layers of the architecture shown in Fig. 1 are further discussed in Table 5 to show connection with the findings from the demonstration.

Table 5 describes the findings from the case modelled in Fig. 1. Hence, findings from Fig. 1; Table 5 show that the virtual asset payment platform integrates with existing implemented infrastructure of the IOTA token facilitated by RESTful APIs to achieve DLT interoperability. This enables clients using an external electric mobility platform to be able to promptly book and make micro payment with external payment channels or with IOTA's native virtual asset (the IOTA token) as seen in Fig. 1. The innovative virtual asset payment platform is implemented by IOTA as a proof-of-concept to support clients in reserving and paying for a multi-modal trip, provided by different urban mobility providers seamlessly (Skoglund et al. 2020).

IOTA Tangle connects with existing implemented infrastructure of the IOTA token facilitated by RESTful APIs to achieve DLT interoperability. This enables clients using an external electric mobility platform to be able to promptly book and make

Table 5 Findings from the use case on micro payment via IOTA Tangle and RESTful APIs in the layered architecture

Layers	Interoperability Modules	Applicability
Context	● DLT interoperable virtual solution	● The main requirement is to achieve DLT interoperability with external digital systems. This is achieved by employing the direct acyclic graph IOTA Tangle driven by RESTful APIs.
Service	● Logs booked multi-modal journeys to IOTA Tangle ● Payment service (send and receive payments) via IOTA wallet ● Setup and fund IOTA wallet (e.g., via Devnet Tokens) ● Ensure logged data are private and only available for parties with the MAM channel key within the Tangle ● Logs payments made to IOTA Tangle ● Set receiving urban mobility transport provider data for IOTA Tokens	● All virtual services provided by the virtual asset payment platform to support digital payment for seamless electric mobility as a service are captured in this layer as seen in Fig. 1. ● These virtual services are provided to the different stakeholders such as the clients and urban mobility transport provider.
Business (Virtual Enterprises)	● IOTA ● Client ● Infrastructure/data provider enterprise ● Urban mobility transport provider ● Other organizations	● This layer encompasses the stakeholders that collaborates with to achieve the virtual asset payment platform. ● IOTA is the main partner in the VE, and it works with other organizations which provide data and external digital systems.
Application and Data Processings (DApps)	● Virtual asset payment platform (IOTA Token) ● IOTA Tangle backend ● External electric mobility platform (backend processing) ● External electric mobility platform ● RESTfulAPIs for client services ● RESTfulAPIs for urban mobility providers	● The external electric mobility platform is utilized by the clients to book for virtual electric mobility services and is connected to the external electric mobility platform (backend processing). ● To achieve interoperability the external electric mobility platform (backend processing) sends processed data to the external electric mobility platform which is integrated with IOTA Tangle. ● Moreover, the virtual asset payment platform processes micro payment and provides the IOTA wallet status to the client. ● The virtual asset payment platform is also connected to the IOTA tangle backend which provides data for eMobility services via several RESTful APIs to ensure interoperability.

Table 5 (continued)

Layers	Interoperability Modules	Applicability
Data space	• Urban mobility database • IOTA Tangle • Cloud solution database	• The urban mobility database stores all the data related to electric mobility services and is owned and governed by the infrastructure/data provider enterprise within the VE consortium. • Also, IOTA Tangle captures geolocation data of all devices, sensors, and clients, encrypts, and publishes these data to be utilized by IOTA backend. • The cloud solution database mainly stores Masked Authenticated Messaging (MAM) channel information. It also sends stored information to the IOTA Tangle.
Technologies	• Data integrity technology • Micropayment technology • Dedicated cloud solution • GeoLocation API • Micropayments processing API	• In this layer real time data generated from IoT devices, sensors and metering devices deployed in the enterprises are transmitted to IOTA micropayment infrastructure. The data are transmitted MAM protocol which encrypts data stream. The data integrity technology adds privacy and integrity to data also via MAM within the IOTA's Tangle. • The micropayment technology facilitates micropayments processing for all seamless electric mobility services provided to the clients via RESTful API. • Then, the dedicated cloud solution transmits the gathered data via MAM channel to be stored in IOTA Tangle. • The GeoLocation API and Micropayments processing API, integrates with IOTA Tangle to ensure data integrity audit trail to guarantee integrity of micro payments.
Physical Infrastructures	Urban mobility options	• This layer captures all the available electric mobility services. Moreover, in this layer other green mobility options offered by the VE are provided.

micro payment with external payment channels or with IOTA's native virtual asset (the IOTA token). Additionally, findings from Fig. 1 suggest that different enterprises as VE joins and pool their resources to achieve a comment goal which is to achieve a seamless and interoperable virtual solution. As seen in Fig. 1 the virtual asset payment platform node automatically exposes different RESTful APIs to enable interoperability with external digital platform (external electric mobility platform). The deployed RESTful APIs allows the reading and writing operations, such as sending and retrieving encrypted data transactions via MAM protocol which is managed by the IOTA community in a decentralized and distributed manner as highlighted by Madine et al. (2021).

The presented case based on IOTA Tangle is related to a very focused area, i.e., microtransactions in the field of Mobility in cities. However, this approach can be applied to other systems deployed in enterprise operations such as in energy trading, community engagement, human-centered services, data security and trust, IoT devices and sensors. IOTA's Tangle can connect different platforms in energy, infrastructure, mobility sectors, and also supports a common, standardized interoperable platform for securing and sharing data openly (IOTA, 2022).

5 Challenges and Recommendations of DLT interoperability

DLT interoperability refers to the ability of different DLT platforms to share data/information, control, and execute across different, either heterogeneous or homogeneous digital platform. One goal to achieve DLT interoperability involves a digital platform to relay data/information or entities securely and appropriately between two DLT platforms in a fully decentralized manner. Thus, in an ideal DLT interoperable environment, a participant from one DLT platform should have the capability to access and interact with another DLT platform or an external digital platform with little effort. DLT interoperability offers a way to support faster, more effective, and highly safe business-to-business or business-to-client data transactions across multiple DLT platforms. Early adoption of DLT platforms have been seen in both banking and financial industries.

Evidently, research and development of DLT interoperability in VE is still new. Thus, there are open issues that impact the actualization of DLT interoperability in VE that have yet to be fully addressed. Some of these challenges are due to lack of standardization, conventions, and integration which requires enterprise collaboration to address these issues (Lipton and Hardjono 2021). This section is devoted to identifying challenges and possible recommendations that may guide the future work regarding DLT interoperability in VE. The open issues and recommendation on impact DLT interoperability in virtual enterprise are discussed in Table 6.

Despite the prevailing challenges, the adoption of decentralized technologies such as blockchains, Ethereum, Hyperledger fabric, IOTA, corda, etc. can create disruptive innovations and improvements for VE if DLT interoperability can be achieved (Tenorio-Fornes et al. 2021).

6 Discussion and implications

6.1 Discussion

A virtual enterprise is a group of stakeholders with similar goals. Managing a VE is a complex process since it includes many non-trusting participants. Virtual enterprises demand optimized and automated business process and are moving towards a digital and smarter organizational process. This entails the integration, interconnection, and interoperability of heterogeneous physical and virtual systems towards the enterprise goal (Margaria et al. 2021). As emphasized by a recent study (Madine et al. 2021), DLT has been employed across various environments including finance, insurance, real estate, healthcare, etc. As DLT is implemented by an increasing number of firms, there is need to develop appropriate approaches and standards for actualization of DLT interoperability. Nonetheless, the ubiquity of DLT platforms has led to silos and fragmentation (Madine et al. 2021). Hence, this article argued that the development of siloed DLT platforms causes isolation and resulting to the limited adoption DLTs.

Thus, the interoperability of these isolated DLT systems and their associated capabilities is crucial for facilitating a fully connected DLT eco-system that supports the collaboration between participating enterprises within the VE consortium. More-

Table 6 Open issues of DLT interoperability in virtual enterprise

Open issues	Description
Increased cost of deployment	Deploying a cost effective cross-DLT platform in VE context may be an issue. That is because most platforms developed in VE are commercial and the successful integration with DLT platforms will incur associated costs (Alkadi et al. 2021). For example, the price of the Ether cryptocurrencies is mostly not stable and may continue to increase (Madine et al. 2021).
Non-existence of a controlling third party	Even though the decentralized nature of DLT platforms offers several advantages and lessens significant security risks, it is mostly vulnerable to 51% security attacks due to no central body as a governing body (Alkadi et al. 2021).
Choice of cross-DLT technology	Regardless of the extensive efforts devoted to design secure and efficient cross-interoperable DLT platforms, the selection of the most suitable DLT for integrating different platforms within VE is still a critical challenge. Presently available cross-DLT platforms are faced with reliability, security, or efficiency problems. Therefore, it is inevitable to select the ideal DLT to external digital platform that reduces the risks while maintaining interoperability (Alkadi et al. 2021).
Challenge associated in updating smart contracts	Some DLT such as blockchain utilizes smart contracts to automate data transaction between participants within the network. Since these smart contracts are saved within the immutable ledger, they cannot be updated, and thus external platform integration to support future interoperability is needed with a complete re-write of the smart contract (Madine et al. 2021).
Reduced Upgradability	DLT platforms mostly do not support a future-proof and adaptable. For example, it is not easy to upgradable existing DLTs such as Ethereum-based smart contracts. Presently, some solutions have been suggested such as using deploying Truffle Migrations and proxies in ZeppelinOS to aid upgradability (Madine et al. 2021).
Universal classification of DLT systems and public keys	There is presently no standard nomenclature to classify DLT systems in a universal unique manner. Additionally, a public key address may not be exclusive to one DLT platform. A business entity (e.g., an investor or client) may utilize the same public key at several different DLT platforms concurrently (Lipton and Hardjono 2021).
Reduced storage and computational resources interoperability	These are major obstacles in the actualization of DLT interoperability in VE. Especially, because most consensus mechanisms employed by DLT platforms consumes energy. Also, maintaining a copy of the distributed ledger for all consortium members requires a large memory. Increasing the memory capacity while minimizing computational energy of DLTs will be effective to achieve lightweight consensus mechanisms that can support DLT (Alkadi et al. 2021).
Security issues	Security weaknesses may develop if the distributed ledgers in the cross-DLT platform utilize the permissionless architecture. This may lead to decreasing the security level that was allowed by the permissioned DLT. Accordingly, certain DLT might be executed either as private or public, permissionless or permissioned. If integrated together to achieve an interoperable DLT eco-systems, the security level of the entire DLT eco-system will not be optimal (Alkadi et al. 2021).
Standardized APIs for cross DLT token transfers	As previously stated, standard protocols are required to operate token-transfers across different DLT platforms in an approach that is equivalent to the economic worth represented by the token (Tönnissen et al. 2020). Works are ongoing to help define payloads, messages, and APIs for data asset transfers across DLT platforms (Lipton and Hardjono 2021).
Actualization of cross-enterprise interoperability	Presently, in achieving interoperability across heterogeneous enterprises, such as finance-mobility interoperability, further understanding of application-driven parameters are needed including consensus algorithms, transaction formats, and DLT configurations (Madine et al. 2021). Hence, there is need for provision of a generalizable solution for cross-DLT interoperability capability within the DLT eco-system in various industries to further support adaptability.

Table 6 (continued)

Open issues	Description
Limited protocols and forms	The deployed commitment protocols for data asset transfers within DLT platforms should be standardized based on existing used transaction payment systems (for example grounded on 2-phase commit). The deployed forms of commitment evidence need also to be standardized for different DLT platforms that utilize compatible or similar distributed ledger data structures (e.g., Quorum and Ethereum) (Lipton and Hardjono 2021).
Interoperable operations and policies	The basic DLT structure comprises of different operations and policies that are employed to govern the distributed ledger. Digital platforms interacting with a particular DLT should be able to work based to these pre-defined rules which is difficult to achieve (Lohachab et al. 2021).
Speed of data transaction confirmation	Every DLT platform has its own means of confirming data transactions. Therefore, each DLT platform there have different throughput and speed of data transaction which may generally impact the interoperability of DLTs. Moreover, other parameters such as the consensus mechanism and size of the DLT may also impact the speed of data transactions (Lohachab et al. 2021).
Deployed permissionability and compatibility of DLT	This is seen as one of the key bottlenecks in the actualization of interoperable DLTs. The base of the DLT is proposed as public architecture. Nevertheless, there are other DLT architecture which are developed for consortium and private based networks which may impact the interoperability of these DLTs (Lohachab et al. 2021). Also, most DLT may not be compactable. For example, private permissioned and public permissionless DLT. This may hinder the interoperability of these DLT platforms.
Cryptographic structures	Cryptography is the main aspect that supports DLT as a trustless distributed ledger. Though, in achieving interoperability, cryptography is associate with a lot of complexities. Since each DLT use distinct cryptographic hashing mechanism. As such the data transactions exchanging between DLT with two different cryptographically networks possess a challenge for DLT interoperability (Lohachab et al. 2021).
Standardization challenges	DLT interoperability undoubtedly faces standardization challenges. This requires the need for a well-certified and authenticated standard to improve collaborations provided by international standardization association (Wang, 2021). But in practice the design of standards to accelerate interoperability among existing DLTs, as well to future possible ones is a still a great challenge (Madine et al. 2021).
Anonymization	The idea of anonymity in DLTs relates to the anonymity of the participating user. This anonymization feature of DLTs can result to more complexity during formation of interaction between two semantically different DLT platforms (Lohachab et al. 2021).

over, DLT interoperability is envisioned to decrease associated cost and redundant transactions (Alkadi et al. 2021). Findings from the literature (Alkadi et al. 2021) emphasized that DLT interoperability is a critical requirement for maintaining and managing current and future DLTs. Madine et al. (2021) found suggestions for potential benefit in DLT interoperability, 88% have shared adoption of DLTs between diverse systems, and 73% of enterprises intend to improve their partnership with new partnerships and lastly 9% of sectors are cross-industry as such are involved in VE. Although achieving DLT interoperability involves the management of consensus mechanisms, digital signature schemes, data structures, smart contract language, verification mechanisms, token issue mechanisms (Tönnissen et al. 2020), transmission protocols of diverse DLT platforms.

Additionally, there are fewer studies that address the standardization and interoperability of DLT infrastructure`s building blocks, data formats, messages format, and data flows to support the interoperability of DLTs and external digital platforms (Belchior et al. 2021; Madine et al. 2021). Also, it is challenging to manage data transactions from various DLTs to maintain a cross-DLT DApp, as different DLTs have distinct properties (e.g., access control, protocols, architecture, service discovery, etc.). Furthermore, research and development on DLT interoperability is still in the experimental phase, and there is yet no definitely de facto solution as seen in Table 2 to address DLT interoperability, nor is there any reference architecture (Wang, 2021). Likewise, evidence from the literature suggest that a lot of frameworks and solutions have been developed for integrating DLT such as Ethereum and blockchain into various systems across organizations are still in their infancy (Asante et al. 2021). While there are fewer available DLT interoperability solutions in VE as presented in Table 2. These approaches are still suitable for specific application purposes, with fewer standardized interoperable architecture been developed.

Therefore, this current study aims to explore how DLT interoperability can be achieved in VE. Similar to findings from Madine et al. (2021), this article presents a layered architecture to illustrate how DLT interoperability with external digital systems can be achieved based on a use case scenario for the innovative virtual asset payment platform driven by IOTA Tangle and RESTful APIs deployment. IOTA Tangle is employed in this study. IOTA Tangle is a free and open source underpinned by DLT characteristics such as data traceability, immutability, and tamper-proof. As compared to Ethereum and Bitcoin, IOTA`s data structure is based on directed acyclic graph. IOTA includes no throughput limits or transaction fees, which is more desirable for VE use cases (Farahani et al. 2021). Prior studies that employed IOTA Tangle are based on conceptual designs without real practical application. Unlike the literature, in this study a functional innovative virtual asset payment platform implemented was modelled.

Respectively, findings from this study indicates that RESTful APIs authenticate and send/retrieve data transactions to/from the IOTA Tangle backend as mentioned by Lima et al. (2021). The use case scenario for the innovative virtual asset payment platform was modelled in the layered architecture as illustrated in Fig. 1. The innovative virtual asset payment platform implemented by IOTA as a proof-of-concept aids clients to reserve and pay for a multi-modal trip provided by different mobility providers seamlessly. Interestingly, IOTA Tangle and RESTful APIs are deployed to facilitate interoperability within the presented the layered architecture based on a use cases scenario. The use case scenario shows the application of IOTA Tangle to support seamless micro digital payment of electric mobility as a service. The use case scenario is modelled within the layered architecture using ArchiMate Modelling tool as seen in Fig. 1.

Additionally, findings from this study depicts how VE can leverage DLTs such as IOTA Tangle to supports data sharing and interaction across various DLT platforms with the capability to provide interoperability support for digital platforms in a seamless manner. In particular, the findings from this study depicts how DLT interoperability can be attained, taking advantage of the pluggability and adaptability of RESTful APIs to develop standardized and practical solution for cross-DLT platforms communication among heterogeneous digital platforms. Analogous to findings from Madine et al. (2021) the primary DLT interoperability hub within the layered architecture presented in this study is the application and data processing (DApps) layer, which aids the exchange of data transactions across different platforms via RESTful APIs. The layered architecture layers can allow the extensibility of VE to visualize DLT to improve their business capabilities (Kazemi and Yazdinejad 2021).

6.2 Implication of study

6.2.1 Theoretical implications

Virtual enterprises are highly dynamic and complex and, accordingly, there are many ongoing attempts to improve digital platforms such as DLTs adopted by these enterprises. But the complexity, fragmentation, and siloed nature of DLT platforms reduces the potential of DLT to manage external digital systems used to improve business activities in VE (Henninger and Mashatan 2021). Interoperability is described as the ability of two or more computer components to work collectively regardless of the existence of differences in interface, execution environment, and language. DLT interoperability entails the interaction and integration between multiple disparate DLT platforms (for example, Ethereum, Bitcoin, IOTA Tangle, Hyperledger Fabric, etc.). Interoperable DLTs facilitates the transfer of data and assets from one DLT to another digital platforms implementable and effortlessly without needing to change the protocol of the base DLT platform (Kazemi and Yazdinejad 2021).

Obviously, DLT platforms have different interoperability requirements and capabilities which has led to isolation and incompatibility in today's DLT ecosystem. Due to various protocols and infrastructures data cannot be freely exchanged between two DLT and other external digital systems. Moreover, findings from the literature (Belchior et al. 2021) mentioned that DLT interoperability is still a gap between practice and theory and existing work is mostly conceptual in nature. Thus, there is need for studies that examine how to connect multiple DLTs and digital platforms to access data/information and act on this information by changing the state condition of the connected DLTs without compromising the trustworthiness and decentralization of the DLT platform (Wang, 2021). Accordingly, this study provides a layered architecture that aids DLT interoperability-facilitating connectivity with external digital platforms.

This study provides a generic approach that illustrates how IOTA Tangle and RESTful APIs aid DLT interoperability in VE without compromising the decentralization property of DLT. Additionally, this article presents a virtual asset payment platform (IOTA Token) that supports DLT interoperability and can also operate as the reference data source via IOTA Tangle to supports the distributed nature of VE. With respect to theoretical implications, this study models how citizens, businesses and other stakeholders can virtually communication and collaboration to achieve a common goal such as the actualization of digital payment for seamless electric mobility as a service. Overall, this paper proposes the deployment of IOTA Tangle with RESTful APIs to show how DLT interoperability can be achieved in VE environment.

6.2.2 Practical implications

With applicability of DLT gaining popularity in industry and academia, many DLT platforms are being developed worldwide. These DLT platforms are highly incompatible and isolated from each other, leading to silos of assets and data. But DLT interoperability can transform and enable asset and data transfers between heterogeneous and homogeneous DLTs. Therefore, as suggested by Lohachab et al. (2021) this study argues that for the absolute understanding of the potentials of DLT interoperability, there is a need for an architecture that can consolidate the heterogeneity of DLT-enabled platforms as well as external digital systems so their functionality can be represented and captured within the architecture. To achieve DLT interoperability, this study presents a layered architecture that supports cross-DLT integration to accomplish communication between distinct digital platforms.

The main contribution of this study is the orchestration and integration of a set of prominent digital tools and virtual services, which develops to actualize a state-of-the-art IOTA Tangle infrastructure to address VE requirements concerning DLT interoperability. With respect to practical implications, this study leverages the existing knowledge in the use of RESTful APIs and IOTA Tangle technologies to advances the digital transformation of VE operations. This article has described a layered architecture modelled in ArchiMate that aims to make provide an efficient, open, and inclusive, data-driven enterprise services. The layered architecture is employed to model a use case on an innovative virtual asset payment platform developed by IOTA to enable micro payment via IOTA virtual assets towards providing a digital payment for seamless electric mobility as a service to customers. The layered architecture has seven layers, allowing for end-to-end interoperability communication. The architecture is modular and flexible, as its components are pluggable supported by RESTful APIs. More importantly, the architecture is modularized allows VE to models interoperable digital system that can be adapted to specific industrial needs.

Evidently, this study has interesting practical implications. By employing IOTA Tangle and RESTful APIs, DLT interoperability solution can be achieved which facilitates interaction, data sharing, and cross-platform communication, with no end-user interference analogous to a decentralized system which is the main feature of DLT-driven platforms. This solution supported by IOTA Tangle offers clients an efficient and secure digital payment for seamless electric mobility as a service and cocreation mechanisms, enabling mobility related companies to be unrestrained and to preserve trust among different entities involved in the consortium. The virtual services delivered to clients contribute to the digital transformation via IOTA Tangle and RESTful APIs for sustainable mobility services provided by VE that collaborates. Besides, the approach proposed in this study enables virtual enterprises to contribute and operate in an efficient and secure M2M protocol network for data exchange and virtual service delivery.

6.2.3 Managerial implications

DLT is a disruptive technology that offers an environment with no principal authority for entering, sharing, and synchronizing data transactions within the digital assets

(Antal et al. 2021). DLTs are designed to offer better security of distributed record across systems through their tamper-resistant and tamper-evident, designs. DLT has emerged as a useful and impactful technology in VE environment. DLT such as blockchain, Ethereum, and IOTA Tangle offers dynamic services across enterprise services and have great potential for achieving the seamless integration of digital platforms within VE operations if they can be connected to each other (Asante et al. 2021). Furthermore, the DLT eco-system is still advancing, meaning that there is still a prospect to design a distributed network of decentralized VE solutions which are interoperable by design. These interoperable DLT platforms can seamlessly communicate, interact, and talk with one another.

While DLT interoperability could be addressed in enterprise solutions built on conventional digital platforms, as these platforms were not intended to communicate with DLT platforms. Therefore, to achieve DLT interoperability, it is essential to integrate various current and legacy systems with DLT platforms. Facilitating this type of connectivity will facilitate data transfer across the DLT eco-system. To enable DLT interoperability, this study has proposed the use of a RESTful APIs as a gateway to connect external digital systems to IOTA Tangle. The RESTful APIs acts as a decentralized trusted relay between the source (IOTA Tangle) and destination (external digital systems). Using a RESTful APIs enables the interoperating networks IOTA Tangle) to transmit data with marginal effort achieving a seamless, secure, and transparent communication within VE process.

7 Conclusion, Limitations, and future works

The virtual enterprise itself is a distributed complex group of organizations scattered across the globe. To improve organizational operations these virtual enterprises are now adopting DLTs to enable traceability, provenance, transparency, privacy, ensure reliability of data, etc. DLT were originally utilized as tamper-evident logs to save data. They are usually maintained by autonomous parties without a main authority (Wang, 2021). The adoption of DLT has become a crucial enabler for implementing and advancing VE operations. DLT allows a group of contributing parties (or nodes) that do not trust each other to provide immutable and trustworthy services. DLT interoperability across digital system deployed in VE would facilitate end-to-end business visibility, better provenance, additionally prevent fraud and economic discrepancies, increase responsiveness and efficiencies, and improve analytics reporting (Henninger and Mashatan 2021). Nevertheless, without interoperability, the data within theses DLT platforms are fragmented, and the full capabilities cannot be attained.

Therefore, this study presents a case scenario to show how IOTA Tangle enable virtual enterprises to provide virtual asset payment system for seamless electric mobility as a service to clients. Findings from the case study was modelled in a layered architecture which shows the application of IOTA Tangle to deliver a mechanism to enable the deployment of an innovative virtual asset payment platform driven by RESTful APIs improving trust on data in a safe, reliable, and controllable manner. IOTA Tangle was employed in this study as the chosen DLT platform as it offers flexibility and performance to enable a reliable virtual environment for VE. This paper provides a starting point for exploring DLT interoperability within the domain of VE. Findings presents the background of DLTs in virtual enterprise, overview, and types of DLT interoperability in virtual enterprise, and existing interoperable DLTs in virtual enterprise. Based on what is observed and learned, this study discusses consensus mechanism and operability of DLTs, exiting DLT interoperability paradigms and open issues and recommendations for achieving DLT interoperability in VE.

Finally, this study provides infrastructural implementation of DLTs in VE, and prior research conducted to help advance DLT interoperability. This study introduced IOTA Tangle and RESTful APIs as middleware that enables DLT interoperability across DLT and external digital platforms. By presenting the innovative virtual asset payment platform use case, this study show that IOTA Tangle is an appropriate trust anchor for enterprise digitalization enabling interoperable transfers of data and assets. Although the use case presented in this study was motivated by the seamless electric mobility scenario, its application is applicable in other enterprise areas as reported by IOTA (2022). As future work, it is anticipated to design and develop other real use case application of IOTA Tangle for flexible energy trading within VE. Also, future work will involve the development of a data model that specifies the interfaces to be implemented by any application system that is to be connected to a DLT such as IOTA Tangle. Future work will also support other gateways such as oracles to be involved in data or asset transfer paving the way for inexpensive DLT interoperability across diverse industrial environment.

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Authors and Affiliations

Anthony Jnr. Bokolo[1]

✉ Anthony Jnr. Bokolo
anthony.bokolo@ife.no

1 Department of Applied Data Science, Institute for Energy Technology (IFE), 1777 Halden, Norway