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A Framework for Standardization of Distributed Ledger Technologies for Interoperable Data Integration and Alignment in Sustainable Smart Cities

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Abstract

Distributed ledger technologies (DLTs) are considered one of the foremost emerging technologies which can contribute to transform cities to smarter cities. DLT play important role in municipalities to accelerate the digitalization process toward changing the roles and services of enterprises in sustainable smart cities. Standardization of DLTs aids to reduce data and digital assets silos while decreasing vendor lock-in across distributed applications enabling a digital urban ecosystem that supports migration capabilities making it possible for cities to seamlessly achieve interoperability among DLTs and centralized digital platforms, although a few standards such as IEEE 2418, IEEE P2418.5, and ISO/TC 307 have been developed. The alignment and integration mechanisms required to support standardization of DLT for interoperable services in smart cities is lacking. Therefore, this study presents an understanding on current and open issues on standardization of DLTs in sustainable smart cities with a specific focus on data integration and alignment efforts related to interoperable DLTs. A framework is developed to promote standardization of DLTs to support integration and alignment for interoperability in smart cities. Design science research methodology was adopted based on three use case scenarios which illustrates how IOTA tangle is employs as a DLT for secured standardized communication between physical sensors, devices, and digital platforms in smart city environment. Findings from this article provide exploratory evidence demonstrating the potential uses of IOTA tangle through the developed framework applied for decentralized and centralized digital services. Based on this evidence, this study provides interface integration and alignment strategies to better exploit distributed applications full potential by improving DLT standardization in urban environment.

Keywords Standardization · Interface integration and alignment · Interoperability · Distributed ledger technology · IOTA tangle · Sustainable smart cities

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Introduction

The use of emerging technologies has been heavily impacting economies, organizations, and modern societies over the years (Hofmann et al., 2017). As an emerging technological field, distributed ledger technologies (DLTs) such as blockchain, Hashgraph, Directed Acyclic Graph (DAG), Holochain, and Tempo (Radix) have emerged as a potentially disruptive digital innovation which enables new business opportunities (Anthony Jnr, 2021a). Presently, there are more than two dozen variants of DLT platforms implemented in different phases of evolution (Narang, 2020), and one of the main challenges faced by DLTs is the lack of standardization (König et al., 2020; Zeuch et al., 2019), and achieving interoperability by enabling different distributed networks to integrate among each other (Belchior et al., 2022). Such standards for DLT can support coordination between different DLT platforms as well as between external digital platforms (Tang, 2021). Although considerable progress on interoperability of DLT has been made, legacy systems, public blockchains, and private blockchains cannot seamlessly communicate among each other. Likewise, current solutions are not standardized and do not support the possibility to seamlessly transmit data and value (Belchior et al., 2022; Hyland-Wood & Khatchadourian, 2018).

Accordingly, the overall deployment of DLTs in cities is still not widely accepted due to several issues such as the lack of interoperability and standards which influence the further adoption of DLT in urban environment. Also, there are no one size fits all standards that cater for mass integration of DLTs which is needed for the continuity and sustained survival of the entire DLT ecosystem (Anthony Jnr, 2022; König et al., 2020), although interoperability of DLTs has been established with some DLTs such as Interledger, Polkadot Overledger, or Cosmos. Their acceptance in terms of a distributed platform ecosystem is not well achieved. Cristea and Stiller (2020) stated that according to IBM, 83% of establishments believe that the existence of a governance standard will enable different types of DLT networks to connect and collaborate allowing potential cities to widely join the DLT ecosystem (Cristea & Stiller, 2020). To this end, several industrial alliances and standardization organizations are now working collaboratively to develop an international DLT standard (König et al., 2020). But presently, there is limited consensus on the potential for DLT standards linked to technical requirements (e.g., size of data, format in which data is stored, communications protocols to be employed) (Deshpande et al., 2017), although standardization as related the terminologies used by practitioners could be a challenging process, as several corporations develop different DLT systems, protocols, and services with their own definitions and implementations (Deshpande et al., 2017).

Standardization processes typically take years from inception until publishing (Belchior et al., 2022). But since 2016, standardization organizations for example Telecommunication Standardization Sector of the International Telecommunications Union (ITU-T) and International Organization for Standardization (ISO) have accelerated the advancement of DLT standardization. Over the years, a series of standardization projects have been authorized and some standards have been published. However, the standardization of DLT is not mature enough as there is still a long way to go for achieving an efficient standard system to reach consensus (Li, 2020; Tang, 2021). Therefore, DLT standardization and interoperability are of the most important toward widespread deployment of distributed applications in smart cities. A universal standardized approach based on interoperability by framework is required (Zeuch et al., 2019), to offer a generic approach to foster DLT standardization for interoperability of DLTs. Hence, it is important to investigate the existing DLT standard projects and roadmap for actualizing an aligned DLT standard platform (Tang, 2021). Thus, this study aims to address the following research questions:

- What are the current DLT standards in progress or already developed to supporting DLT interoperability in sustainable smart cities?
- How to promote standardization of DLTs toward promoting DLT interoperability in sustainable smart cities?
- What are the open issues of DLT standardization and possible recommendations to facilitate DLT standardization in sustainable smart cities?

Accordingly, the objective of this article is to draw on the academic literature to identify the current state of the art on DLT standardization toward interoperability, and then present the developed framework to support standardization for interoperable DLTs deployment in urban context. As pointed out by Romano and Schmid (2021) a reference model for DLT is needed in order to offer a comprehensive and integrated view of the role and function of the various tools and concepts offered by DLT. Findings from this study attempt to address this gap by providing roadmap on DLT standardization for researchers and practitioners. The remainder of the paper is written as the "Literature Review" section presents the literature review and the "Method" section introduces the developed DLT standardization framework. The "Design Artefact (DLT Standardization Framework)" section presents the method. In the "Findings" section, findings are presented, and the "Discussion and Implications" section is the discussion and implications. Finally, the "Conclusion" section is dedicated to presenting the conclusions.

Literature Review

Overview of DLTs in Sustainable Smart Cities

DLT is one of the emerging technologies that has stimulated novel business models (Li, 2020). DLT is essentially a digital system that aids in recording data or transactions of assets and stores these data in multiple places simultaneously (Geroni, 2020). It enables the recording of data in multiple nodes (systems) in an asynchronous manner while aiding multiple parties to access the data (Gourisetti et al., 2021). DLT comprises of immutable distributed digital records or ledgers which allows digital transaction of service, product, data, or payment to be carried out, transferred, shared, and stored on a dedicated public or private network without having a dominant authority to maintain integrity, security, and trust. The authentication and validation of all transactions are deployed between nodes within the DLT network achieved based on a consensus mechanism such as proof of work (PoW) and proof of stake (PoS) (Cali et al., 2019). The main type of DLT adopted in smart cities comprises of Blockchain, Hashgraph, DAG, Holochain, and Tempo (Radix) (Geroni, 2020) as seen in Fig. 1.

Blockchain

Blockchain is presently the most popular DLT adopted in sustainable smart cities. In blockchain data transaction of records are stored within the ledger in the structure of a chain of blocks, like a long list of data records. The data stored within the blocks typically comprises of the date, time, and specifications of a transaction (Anthony Jnr & Abbas Petersen, 2021). Additionally, the blocks in blockchain also comprise of the sender's information with a unique digital signature to maintain anonymity. The blocks within a blockchain include a special ID characterized as the "hash" that synchronizes and differentiates transactions. The hash function offers reliable support to differentiate all the transaction blocks within the distributed ledger (Geroni, 2020). In blockchain once a new transaction takes place the existing node within the network authenticates it. After authentication, the transaction is assigned a unique hash ID along with the new transaction hash ID which is stored in the distributed ledger. Also, once new data transaction is added to the ledger, it cannot be altered or removed (Ezzi et al., 2022).

Hashgraph

Hashgraph is another prominent type of DLT which allows the storage of multiple data transactions within the ledger with the same timestamp (Geroni, 2020). A record or transaction within the ledger in a Hashgraph is referred to as an "Event"

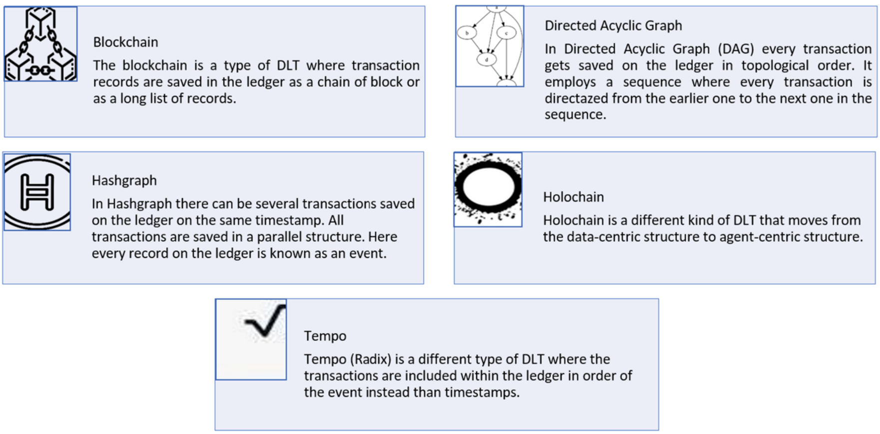

Fig. 1 Types of DLTs applicable in sustainable smart cities. Each of the types of DLTs applicable in sustainable smart cities are discussed below

and entails the storage of data transactions in a parallel configuration. A Hashgraph-based DLT platform guarantees that no nodes within the network can change the information or transactions. In a Hashgraph, all node users within the network would reach an agreement on the procedure of the data transaction and list the process appropriately. Hashgraphs employ the Gossip consensus protocol to relay information about a transaction regarding a transaction. It occurs through a virtual voting method in which when two-thirds of the network nodes authenticate a transaction, it becomes legitimate after being validated by every node. Thus, in Hashgraphs, once a transaction occurs, the neighboring node user share that information with other nodes, and later, all the nodes would know about the data transaction. Therefore, Hashgraphs are suitable for institutions that have high-speed data transaction use cases (Geroni, 2020).

Holochain

Holochain is one of the most innovative DLTs that provides developers with new methods for the development of decentralized apps. Holochain limits global consensus mechanisms by offering all agents their own forking system. Thus, in Holochain structure, every node within the network has their own ledger that they maintain. Holochain offer a promising alternative for institutional use cases that demand higher integrity and system scalability. Holochain do not employ global consensus protocol but uses a network of individual modules for development of the complete distributed ledger system (Geroni, 2020). The entire Holochain network manages a group of rules termed the DNA to confirm each individual ledger.

Tempo (Radix)

Tempo (Radix) is one of the new DLT variants that gives the benefit of timestamp alongside other DLT functionalities. One of the main focuses of Tempo is that there is no need for any alteration to adopt Tempo for private and public modules. Additionally, when Tempo is used, there is no need for prominent additions in terms of hardware modules for the development of decentralized applications, tokens, or coins (Geroni, 2020). Tempo constitutes modules known as shards which have their own distinctive identification code distributed within the nodes. Thus, Tempo does not inconvenience nodes with the whole global distributed ledger but synchronizes using the gossip protocol thus providing a prospect for scalability. To validate a data transaction, nodes employ the sequence of a transaction instead of the timestamp (Geroni, 2020; Narang, 2020).

Directed Acyclic Graph

The Directed Acyclic Graph (DAG) is a DLT with a different structure that can support nano or micro transactions and offer better improvement in scalability with the expansion of the distributed network. Furthermore, DAG differs from other DLT based on its employed consensus mechanism. In DAG every node within the network provides a proof of transactions on the ledger and could initiate transactions.

But nodes must validate at least two of the earlier transactions on the distributed ledger to verify their transaction. Thus, transactions with longer branches of earlier confirmed transactions are more likely to be deemed valid. Hence, in DAG, a sequence of transaction is known as a "branch," and the longer the branch the more valid all the data transactions become. Overall, DAG is suitable for institutions that need to process massive volumes of transactions. DAG use quantum computing proof via a signature scheme. This distinguishes it from other DLTs (Geroni, 2020). An example of DAG is IOTA tangle.

Each of the five DLTs discussed has unique feature which makes it applicable for smart cities. For example, blockchain is particularly dominantly adopted because of its immutability. Tempo provides the benefit of modularity. Hashgraphs offer credible instruments for promoting transparency of transactions. Holochains employ agent-based distributed ledgers which enables nodes to work as independent units. Lastly, DAG is mostly useful use cases for its ability to ensure near-infinite quantum resistance and scalability (Geroni, 2020). Accordingly, DAG as IOTA tangle is employed in this study to promote a standardized interoperable DLT deployment in smart cities (see the "Findings" section).

Background of DLT Interoperability in Sustainable Smart Cities

Data is everywhere in the society and the management and governance of data is crucial to the success of urban applications and operations. DLT is an effective tool that can help to facilitate, increase effectiveness, and accelerate digital platforms involving data exchange and storage across multiple domains. DLT offers a clear advantage to data exchange and management as compared to legacy database management system (Narang, 2020). The ability of DLT to offer security and access management and a secure data storage mechanism makes it a useful tool in a multitude of smart city scenarios. One of the challenges faced in smart cities depends on facilitating coordination, communication, and cooperation among different processes and units.

Thus, interoperability of DLTs has been as issue faced in smart cities. Interoperability refers to the capability of two or more software components to work together despite differences in interface, language, and execution platform (Wegner, 1996). *The literature defines interoperability among urban platforms as a measure of the ability to perform integration between objects (processes, software, systems, city units*) (Anthony Jnr, 2021b). Interoperability also refers to the reliance between distinct distributed ledgers and digital platforms to aid the transfer or exchange of data or value, with guarantees of validity. A technical report published by the national institute of standards and technology defined interoperability of DLT as a composition of different DLT systems, each with a unique identification that enables atomic transaction execution across multiple heterogeneous DLT systems. In so doing facilitates data recorded in one DLT to be referable, verifiable, and reachable by another digital platform in a compatible manner (Belchior et al., 2022). The interoperability landscape of DLT-to-DLT solutions remains immature for urban use. Most DLT solutions such as Bitcoin, Ethereum, and IOTA employ different protocols and do not seamlessly speak to each other. Some DLT platforms attempts to resolve this issue by deploying sidechains and alternative techniques such as atomic swaps.

Significance of DLT Standardization in Sustainable Smart Cities

According to Gray (2021), one of the early critiques of DLT, besides to not scaling well, is the lack of standards. Standardization in the world of ICT is not new. Without standardized processes and procedures, global communication would not be viable. A standard is defined as an established way of executing something. It could be about managing a process, designing a product, providing a service, or providing materials. Standards can comprise of a huge range of activities deployed by organizations and utilized by their clients (Deshpande et al., 2017). Standards could play a significant role in ensuring interoperability between multiple DLT implementations and thus decreasing the risk of fragmented ecosystem. Standards play a central role for international technology systems and industrial societies (Narang, 2020). Standardization of DLT is an essential step toward a common concept, interoperability, auditing, scaling, and possible further regulation of DLTs. The complete lack of standardization is seen as a barrier to the adoption of DLTs in smart cities (König et al., 2020). IT practitioners believe that DLT standardization will lessen transaction costs, improve the process of technology implementation, decrease regulatory risks, foster interoperability of systems, enhance the quality of interaction between stakeholders, and accelerate the attractiveness of securing assets within DLT platforms (König et al., 2020).

Employing standards to DLT establishes a stronger consensus on consistent vocabulary and terminology that could improve understanding of DLT. Establishing standards helps to create trust toward DLT adoption in smart cities (Deshpande et al., 2017). Particularly organizations such as the *Institute of Electrical and Electronics Engineers (IEEE)* are well known for offering technical standardization (König et al., 2020). *The International Standards Organization (ISO*) is concerned with standards and is dedicated to advancing technological advancement, whereas IEEE focuses more on standards for specific applications and engineering such as digital applications in IoT, autonomous driving, and power engineering. IEEE is also actively pursuing developments that uses blockchain to optimize business process. *The International Telecommunication Union (ITU)* is dedicated to developing interoperable DLT standards. The *World Wide Web Consortium (W3C)* blockchain community group released a standard for distributed ledger protocol and format (Li, 2020). Researchers such as Narang (2020) stated that protocols or parts of protocols may be employed for adoption as formal standards.

For instance, *ERC-20* is an example of a community standard for token deployment in the Ethereum network and utilized in hardware wallets, decentralized applications, and exported to other digital platforms such as the *EOS-21* teleport communications protocol (Narang, 2020). Hence, standardization of DLT can help address interoperability of DLTs and legacy systems. Standard help the industries to evolve in the right direction as the technology becomes much matured (Cali et al., 2019), and it typically takes about 2–3 years for a new standard to be fully established. Standards enable the diffusion of innovations development and follow-up of innovations (Narang, 2020). Standards could help in having a taxonomy about the actual meaning of different terms. This will ensure that different technologies are speaking the same language. Standards can also help manage risks associated with liability, identity, and compliance from a cross-sector perspective (Deshpande et al., 2017). Thus, standardization of DLTs promotes interoperability between DLTs fostering synergies between different digital platforms, scaling up existing applications, and creating novel urban use cases. For instance, an urban developers should be able to transfer digital assets from one DLT to another or build cross-decentralized applications (DApps). In particular, standardization of DLTs promotes DLT scalability, as it offers a way to offload transactions to other DLTs such as blockchains, e.g., via sharding, it can create improve privacy and create new business opportunities (Belchior et al., 2022).

The existence of standards can facilitate cross-platform interoperability between different DLTs to seamlessly exchange their information and assets. Using standards DLTs can reuse components and use common interfaces making it easier for developers. Standards can help to clarify the decentralization scalability, and security features of each DLT platform while facilitating implementers to select the most appropriate DLT platform for their city (Narang, 2020). To date, there are widely no accepted interoperability standards which has resulted to silos of DLT platform. As mentioned in the literature (Blind & Gauch, 2009; Gauch, 2006; Hofmann et al., 2017), there are four categories of standards which comprises of semantic standards, measurement and testing standards, interface standards and compatibility standards and quality standards and variety-reducing standards. Regarding the software product life cycle Sherif (1999) specified three types of standards which comprises of anticipatory standards, participatory standards, and responsive standards. Anticipatory standards are standards which must be made before the widespread acceptance of a particular service or device.

Participatory standards advance within the deployment by testing the specifications before adopting any IT system and lastly responsive standards occur to codify a service or product that has been traded with some success. Irrespective of the benefits of standards, they can also introduce risks such as increasing costs of competitors, monopoly power, and decrease choice on markets regulatory capture (Hofmann et al., 2017). Presently, most DLTs are developed as standalone systems. Standardization toward interoperability between DLT platforms will prevent cities from being locked to one chosen DLT (Hyland-Wood & Khatchadourian, 2018). Furthermore, it supports the extensibility of this technologies. Standardization and interoperability help for integrating different DLTs such as Ethereum, Bitcoin, Ripple, Hyperledger Fabric, and Corda (Zeuch et al., 2019). Standards could play an essential role in ensuring interoperability across multiple DLT reducing the risk of a fragmented data ecosystem (Deshpande et al., 2017).

History and Current Approaches of DLT Standardization

During 2013 to 2016, DLTs such as Hyperledger and Ethereum developed rapidly, and the deployment of smart contract and other digital technologies promoted the applications of DLT such as blockchain in diverse domain. Related standardization associations began to discuss themes related to blockchain standards. Hence, the standardization of blockchain was first initiated by organizations in late 2016 (Tang, 2021). But researchers such as Cali et al. (2019) mentioned that blockchain standards emerged in late 2017. Ever since several standards organizations have stepped up their efforts to develop a set of standards for the adoption of DLT/blockchain across industries (Cali et al., 2019). Organizations such as *ISO* instituted a new technical committee known as *ISO/TC 307* in September 2016 aimed at improving the standardization of blockchain and DLT. *ITU-T* was another organization that started its first blockchain specification project in 2017. Both *ITU-T* and *ISO* gradually promoted the advancement of a series of blockchain standards. Moreover, *IEEE Standards Association (IEEE SA)* also started the blockchain standardization work amidst 2018 (Tang, 2021). *W3C* organized its first seminar on blockchain in June 2016 where issues related to the standardization of blockchain was discussed. In August 2016, an expert group of *ISO/IEC JTC 1* (Joint technical committee for information technology) suggested to set up a new blockchain sub-committee in ISO/IEC JTC 1 (Tang, 2021).

ISO's TC 307 technical committee is another standard that attempts to define a reference architecture toward the formal vocabulary, taxonomy, and ontology for blockchain (Hyland-Wood & Khatchadourian, 2018). Apparently, standardization of DLT should include efforts directed to assist with interoperability between DLTs implementations and between DLTs and established urban information systems (Hyland-Wood & Khatchadourian, 2018). Many DLTs deploy specific Application Programming Interfaces (APIs) that allow external digital applications such as cryptocurrency exchanges and cryptographic wallets to communicate with blockchain nodes. As pointed out by Hyland-Wood and Khatchadourian (2018), one might be persuaded to suppose that standardization of API could be productive areas for DLT standards development. However, such blockchain-specific APIs are unlikely to be generalize across other DLTs which have different technical implementations specification. Additionally, it may be feasible to develop general protocols to characterize high-level functionality such as cryptocurrency exchange or transfer, data migration, cross-chain smart contract operations, and data copying. Also, generalized protocols (such as Hypertext Transfer Protocol (HTTP) or the Transmission Control Protocol/Internet Protocol (TCP/IP)) can be employed as they are more likely to be standardized as compared to APIs (Hyland-Wood & Khatchadourian, 2018).

Exiting Standards for DLT Implementation in Sustainable Smart Cities

To improve interoperability of DLTs, major international groups have established formal activities to address standardization of DLT such as blockchains. Existing Standards Development Organizations (SDO) toward DLT standards comprises of

IEEE and *ISO/TC 307* as seen in Fig. 2. Most of the well-known standards such as *IEEE* and *ISO/TC 307* employs a process for development and deployment of the standards which comprises of preliminary, proposal, preparatory, committee, enquiry, approval, and publication phase.

Figure 2 depicts the main standards employed to improve DLT interoperability in smart cities. Each of which are discussed in detail below.

IEEE 2418

IEEE is a non-profit professional enterprise that develops standards. IEEE covers a several standards that encompasses several facets of electrical and computing domains. Like other standards, the IEEE employs a numbering convention for their standardization. As related to DLTs and blockchain, the IEEE 2418 is proposed (Gray, 2021). The IEEE 2418 standard relates to the establishment of an open blockchain energy framework. Within the IEEE 2418, a reference architecture model has been developed by IEEE (IEEE 2418, 2022), as a layered model comprises of the devices layer which comprises of communications network and peer-to-peer network. Next is the platform layer which comprises of DLT technologies such as Bitcoin, Ethereum, and IOTA tangle. At the higher levels of the architecture is the processes, services, and data models. The top layer comprises of a distributed application (DApp), which uses one of more processes, services, and data models to interact with deployed DLT platform (Gray, 2021). Another IEEE standard is the

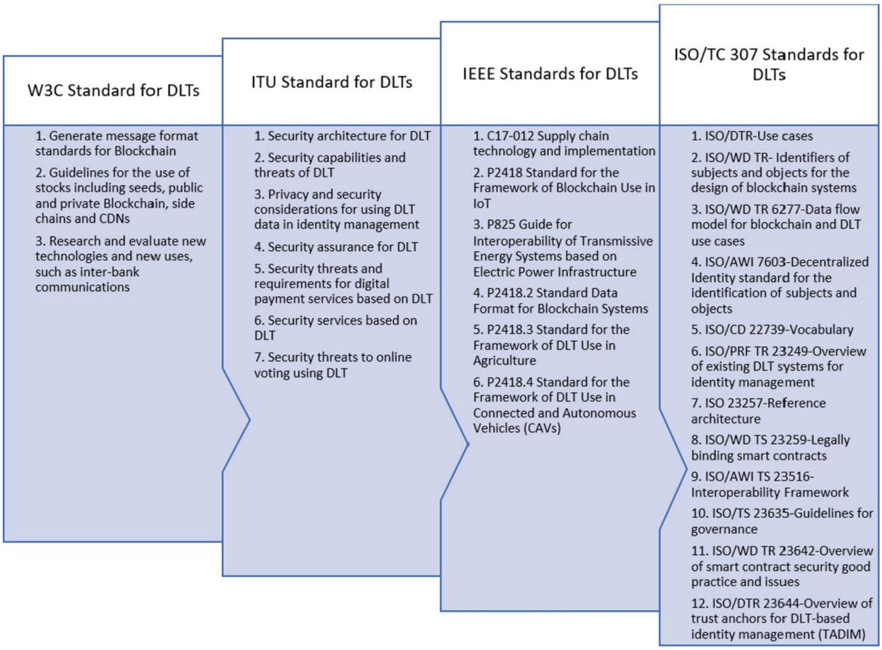

Fig. 2 Main standards employed for improving DLT interoperability in smart cities

IEEE Standards Association (IEEE-SA), which is a globally known standards that has been keenly engage in blockchain standardization by launching different activities in multiple industrial sectors (Li, 2020). IEEE has initiated the several other blockchain projects as seen in Fig. 2. IEEE also have an ongoing project related to blockchains known as the standard for the framework of blockchain use in Internet of Things (IoT) (Gramoli & Staples, 2018). Furthermore, the IEEE future directions committee has endorsed the creation of the IEEE Blockchain initiative (BCI) effective from January 1, 2018, to be the focal point for all IEEE blockchain activities and projects (Bhowmik et al., 2019).

IEEE P2418.5

In 2018, the IEEE introduced the first global blockchain in energy standard working group termed as the "IEEE P2418.5." The IEEE P2418.5 blockchain in energy standards offers a common, open, and interoperable reference model for blockchain within the energy sector. It also included three areas that serve as a reference for blockchain use cases in and renewable energy, oil and gas, and electrical power industries and their related services. Overall, it aimed to create standards based on the reference architecture for interoperability, provide terminology, and offer system interfaces for blockchain applications within energy sector by developing a technology agnostic and open protocol layered framework. Lastly, IEEE P2418.5 help evaluate and provide guidelines on interoperability, performance, security, and scalability through assessment of smart contracts, consensus algorithm, and different types of blockchain deployment for energy sector (Cali et al., 2019).

ISO/TC 307

ISO is the most known independent, non-governmental global organization for developing international standards (Cristea & Stiller, 2020). One of the standards proposed by ISO is the *ISO/TC 307* blockchain and DLT standard (ISO/TC 307, 2022). The ISO technical committee 307 (TC307) whose secretariat is led by Standards Australia (SA) developed standards for DLT which comprises of 3 published standards with an additional 11 ISO-related DLT standards which are under development as reported in the technical report (Gramoli & Staples, 2018; Bhowmik et al., 2019; Li, 2020; ISO/TC 307, 2022) (see Fig. 2). The technical committee on ISO/TC 307 comprises of 46 active members and 14 observing members as of April 2021, and has further formed various advisory groups, study groups, and working groups to promote blockchain standardization in interoperability, security, use cases, ontology, privacy, smart contract, and other directions (Bhowmik et al., 2019; Tang, 2021).

Another standard related to DLT is the *ISO 22739:2020* for blockchain and DLT Vocabulary. *ISO/TR 23244:2020* for blockchain and DLT Privacy and personally identifiable data protection considerations (Gray, 2021). *ISO/TR 23455:2019* for blockchain and DLT for overview of and interactions among smart contracts in blockchain and DLT platforms (Gray, 2021; König et al., 2020). Besides the ISO/TC 307 there are also other technical committees working on developing blockchain standards, for example the *ISO/TC 68* which comprises of a technical committee for financial services, *ISO/TCv46* which involves a technical committee for information and documentation, and *ISO/IEC JTC 1* which is a technical committee for information technology (Tang, 2021). The technical committee for ISO/TC 307 held their first and second plenary meetings in April and November 2017 individually. In the two plenary meetings, different groups (WG1, SG2, WG2, SG5, SG6, and SG7), as seen in Fig. 3, were formed toward standardization of DLTs.

Figure 3 depicts the working groups committed to promote blockchain and DLT development. Working groups such as the SG6 in future aims to produce a governance guide research report for blockchain and DLT to explicate the relationship between the strategic deployment of blockchain (including market, business goals, benefits) and blockchain users and stakeholders, and propose a reference model for system lifecycle consensus and management. SG7 under TC 307 focus to conduct more research on inter-system and inter-chain interoperability solutions, thereby providing a standardized framework for enabling interaction between different digital technologies while managing and reducing the business and technical complexities faced within and across different sectors which adopts DLTs (Li, 2020). This is prompted as many cities adopt DLTs such as blockchain based solutions to support administrative process. This significantly necessitates the need for integration and interaction between DLT platforms and other external solutions (Anthony Jnr, 2021a).

W3C

The W3C is also a non-profit international community which comprises of 429 members which works collaboratively toward contributing to develop Web technologies and standards (Anjum et al., 2017). In 2016, W3C (https://www.w3.org) began a Blockchain Community Group (BCG) aimed at promoting blockchain development (Cristea & Stiller, 2020; W3C Mission, 2021). W3C have initiated a blockchain community group to generate message format standards for blockchain based grounded on ISO200223 (Gramoli & Staples, 2018). W3C goal as related to blockchain comprises of generating message format standards for blockchain, providing

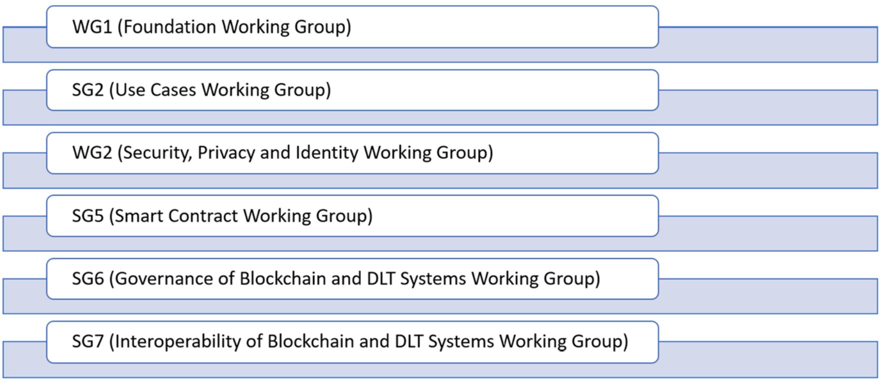

Fig. 3 ISO working groups for blockchain and DLT development

guidelines for the usage of stocks including side chains, public seeds, private blockchain, and research and evaluating innovative technologies and novel uses, such as inter-bank communications (Li, 2020; W3C Mission, 2021). W3C provide support message format standards for blockchain based on ISO20022 and suggestions on how to use storage including torrent, side chain, and content delivery network (CDN) (Cristea & Stiller, 2020).

ITU-T

ITU is an organization of United Nations focused on areas related to telecommunications, Information and Communication Technologies (ICTs). It has a permanent Telecommunication Standardization Sector (ITU-T) that manages operating, technical, and tariff issues and issue related to recommendations clearly on global standardizing telecommunications (Cristea & Stiller, 2020). The ITU-T organization manages standards established a focus group for DLT in terms of architecture, use cases, terminology, security, evaluation, regulation, etc. In compliance with their charter, the group considers the ongoing activities of ITU, as well as other standardization organizations, groups, and forums in order to develop a standardized path for interoperable DLT services (König et al., 2020; Li, 2020; ITU, 2022).

One of the divisions of the telecommunication standardization sector has created a focus group on DLT application and services was founded in May 2017 and it is overseen by Switzerland to provide guidance and best practices to support the implementation of digital applications and services on an international scale and to recommend a way forward for related standardization work in the ITU-T study groups (Gramoli & Staples, 2018). ITU-T also set up specialized research groups in SG16 which is study group on multimedia, SG 17 which is study group on linked to security. SG 13 is linked to study group on future networks and cloud and SG 20 on study group on IoT, smart cities, and communities and have also begun the standardization work linked to blockchain (Tang, 2021). Thus, the focus group on DLT also develops a standardization roadmap for interoperable DLT-based solutions (Bhowmik et al., 2019). The ITU-T standardization focus group on application of DLT comprises of seven documents aimed to improve as seen in Table 1.

The Internet Research Task Force (IRTF)

The Internet Research Task Force (IRTF) is another standard that focuses on long term research related to platform architecture and technology of internet protocols. The work of IRTF is linked to the contribution of 14 research groups (Cristea & Stiller, 2020). One of this groups is invested in the Decentralized Internet Infrastructure (DINRG) and has been introduced in September 2017. Since its inception, this forum had several meetings from 2018 to 2020. During these reunions, there were numerous discussions around DLTs starting with research on blockchain as an auditable communication means effectively deployed with Ethereum, Bitcoin, or Hyperledger Fabric, continuing with exploring how DLT can be deployed to IoT and analyzing various use cases such as Chainspace which is a scalable smart contracts platform, Coconut which is a structure for selective disclosure credentials

Table 1 ITU-T standardization focus group on application of DLT

ITU-T code	Description	Strength	Limitation
FG DLT D1.1	This is the first publication which provided a technical specification about definitions and terminology for DLT. This report included example of diagrams to highlight some key definitions and functionality of DLT	It provided terminology to organizations to understand the components and elements of a blockchain	It is mostly used as a preliminary document that serve as a reference guide for other documents of the working group
FG DLT D1.2	This report is titled distributed ledger overview, concepts, ecosystem, and its aspects. It provides an overview of the DLT components	Provides new users with an extensive overview of DLT	It may be particularly too basic for experienced practitioners
FG DLT D2.1	Provides a technical report about DLT use cases showing possible benefits and competitive advantages for diverse industries and fields of application adopting DLT. Additionally, the report states the concerns and issues on DLT adoption. The essence of this report lies in its broad collection of use cases	Provides an extensive list of sector specific use cases for DLTs	Simply provides an overview and suggests no guidance
FG DLT D3.1	This technical report comprises of a full reference architecture for DLTs. It also serves as a guidance tool for new users and service providers of DLT. Each DLT component is described in detail including a generalized outline of architectural information	Provided a reference architecture and outlook on how a DLT-system can be deployed	Compliance and legal requirements are not considered in the report
FG DLT D3.3	Provided an assessment catalog of criterion for DLT platforms. The technical specification comprises of description on how to use the described criteria serving as a guiding document for DLT assessment	Presented several assessment criteria which can be valuable when deciding potential use of DLT	The assessment of different platforms is only limited to some purposes

Table 1 (continued)

ITU-T code	Description	Strength	Limitation
FG DLT D4.1	This report summarizes existing regulatory issues that can negatively impact the adoption of DLT. A collection of specific DLT attributes was analyzed and combined based on challenges. Moreover, possible mitigation strategies are provided to help overcome identified regulatory issues	Provided a framework that really focuses on regulatory DLT issues	Compliance related to information security standards such as ISO 27001 is still missing
FG DLT D5.1	This document is the final report of the work of the ITU-T focus group on application of DLT. It provides an outline of future standardization projections for DLT on the areas of risk and audit, governance and legal regulation, identity and privacy computation networks, and security and resilience. The complete information described in this report delivers insight on the development and evolution of DLTs and undeniably useful for further development of DLTs	The report attempts to make significant predictions for the development of DLT. Such projections could be valuable to stir up research and innovation toward certain fields	As the subject is about predicting the future of DLTs, these projections may change

or Interplanetary File System (IPFS) as Platform for Decentralized Applications. Besides, in April 2020, a new strategy has been established such as blockchain governance initiative network which was initiated on March 10, 2020, as a global network of academia, regulators, engineers, and industry representatives as well as expert groups and internet pioneers whose main scope was to explore issues and collaborate to facilitate sustainable extension within the blockchain community and contribute to blockchain and DLT standardization (Cristea & Stiller, 2020).

ANSI Accredited Standards Committee X9

In 2018, ASC X9 study group published a final version of a report on distributed ledger and blockchain. In their study, they collaborated with experts from different fields and evaluated what types of standardization effort would be both required and useful especially for the financial domain and other industries, toward promoting DLT adoption, although the study mainly focuses on permissioned blockchains, as it is considered necessary for conformity with current regulations for the market. Likewise, majority of the report focuses on security issues and needs of blockchains, particularly for finance. The report further provided recommendations for developers and industry to assess if there are existing non-blockchain standards that relates to the same area using incremental developments for blockchain specific implementations and standardization. A high-level reference architecture was included in the study to offer better understanding of the main components of blockchain systems to describe how a DLT system works. The ANSI report provides a considerable overview of potential and required standardization directions that can be of value for bodies of standardization and organizations. However, the report technically comprises of a list of recommendations for possible standardization; there is less value for end users and companies (König et al., 2020).

Associated Standards Developed

In this sub-section, several standards proposed in different geographical locations are discussed.

European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC) For over 60 years, CEN and CENELEC have contributed to the European standardization (Cristea & Stiller, 2020). Thus, over the years, CEN and CENELEC have been facilitating Europe's digital transformation, creating European Standards and ICT standardization solutions in different sectors such as health, machinery, manufacturing, energy, and transport (Bhowmik et al., 2019). The CENELEC and CEN aim to promote the European economy and sees themselves as business catalysts by establishing common standards that guarantees safety and quality (Gramoli & Staples, 2018). CEN and CENELEC began a new focus group on DLT and blockchain aimed to identify possible specific European standardization requirements, particularly in support of the current standardization process being developed in ISO/TC 307 (as discussed in the "IEEE P2418.5" section).

In their report "Recommendations for Successful Adoption in Europe for Emerging Technical Standards on Distributed Ledger/Blockchain Technologies," they identify specific European needs in the field of DLT and blockchain standardization. Some domains of DLT which are uncertain (such as signature management and digital identity) are well described with a set of recommendations toward standardization aim to strengthen their efforts in building a standard fit for the European Union. Moreover, a broad overview of well-defined use cases based on different fields was provided which could prove to be valuable in providing direction for standardization bodies, although the document is seen to be more aligned to Europe and could hence be of lesser importance for other regions of the world (König et al., 2020).

The National Institute of Standards and Technology (NIST) NIST provides a measurement standards laboratory and a non-regulatory organization of the United State (US) Department of Commerce with a goal to promote industrial competitiveness and innovation. At the beginning of 2018, NIST stated that it will collaborate with ISO in order to develop blockchain standards. This declaration took place during a dialog with the Congressional Blockchain Caucus, which is exploring medium on how blockchain technology can enhance U.S. government services (Gramoli & Staples, 2018). During 2018 NIST published the report "NISTIR 8202-Blockchain Technology Overview" which presents a compilation of discussion about blockchain technology. It comprises of basic functionalities and elements of a blockchain system.

It also provided a high-level technology overview of blockchain and included common misunderstandings and limitations of the technology, as well as concerns linked to cybersecurity and the common applicability of blockchains for corporations. Thus, the report served as an entry point for blockchains and DLT as it describes the models and structure, consensus mechanisms and well-known examples of several blockchain specific problems as well as a few technical guidelines. In addition, the glossary part of the document offers a concise overview of the blockchain terminology. But individual use cases are not incorporated within the report. But the document is great for providing a significant overview of what blockchains are (König et al., 2020).

The European Union Agency for Cybersecurity (ENISA) In the report on DLT and Cybersecurity aimed at enhancing information security in the financial industry, ENISA advocated for the benefits of adopting DLTs in financial institutions. Besides, they outlined DLT components and explained the individual elements, forms, and function within a blockchain. These components discussed included smart contracts, cryptography, the consensus protocols, and sidechains. The report also discussed on cybersecurity issues faced in both traditional and technology specific systems. Also, they provided guidance and best practices mapped to specific issues to help businesses to implement DLT/blockchains in a secure way, which is one of the main strengths of the report. As the presented best practices can be utilized to bridge the time until a standardized framework is achieved. However, the presented recommendations are mainly generic and thus relevant for compliance requirements in financial sector. Within the annex of the report, ENISA provided blockchain use cases on the famous Ethereum DAO hack and an overview of various distributed ledgers (König et al., 2020).

The North American Energy Standards Board (NAESB) The NAESB is a non-profit enterprise that serves as an industry forum for the promotion and development of standards which results to a seamless marketplace for retail and wholesale electricity and natural gas. NAESB announced their intent to carry out a workshop to deliberate on the development for blockchain-related standard for the implementation of a smart contract for the purchase and sale of natural gas. NAESB is also involved in the development of supportive standardized modeling language that can be utilized in DLTs (Gray, 2021).

German Institute for Standardization (DIN) The German Institute for Standardization published a few specifications linking to blockchain and DLT (König et al., 2020). Each of these specifications is shown in Table 2.

German Federal Office for Information Security (BSI) In 2019, the German federal office for information security published the report "Towards Secure Blockchains". This report is separated into four different sections and provides significant overview on blockchains. The first part is more focused on the underlying principles of blockchain technology and list of definitions and explains specific matters in blockchain such as smart contracts, trust, and consensus. The second and lengthiest part emphasizes on security characteristics and properties of blockchains including potential cyber-attacks and long-term solutions. The third section presents an outline of legal aspects with a strong focus on data protection and privacy. The last section describes the current use and state of blockchains and further presented a future trend evaluation. Overall, the report provides an overview of blockchain and DLT with particular in comparisons to regular methods of data storage, building block model and legal compliance as well as related information security measures, although the BSI report did not include newer types of blockchains and DLT. Additionally, the BSI second report discussed more on most prominent cyber-attack types and cryptocurrency crime which is far from standardization endeavors (König et al., 2020).

Standards Australia Standards Australia is a non-profit and non-government standard organization involved in the development and deployment of standards in Australia by creating a technical committee which brings together appropriate stakeholders and partners to reach consensus (Gramoli & Staples, 2018). Standards Australia also leads the secretariat for ISO TC/307 standard for blockchain and DLT (as discussed in the "IEEE P2418.5" section). In February 2017, Standards Australia presented the first ISO workshop in Sydney where they published a report named "Roadmap for Blockchain Standards," in which some key issues of blockchain standardization were discussed (Cristea & Stiller, 2020).

Table 2 DIN specifications for blockchain and DLT

DIN code	Description	Strength	Limitation
DIN SPEC 16597	This specification provides a terminology for blockchains and aimed at being pertinent for a broader audience and not limited to a single industrial area. It encompasses terminology from conventional IT, cryptography, and blockchain	The provided terminologies provide understanding of individual blockchains components	It is utilized as a preliminary document and thus missing out on out-of-scope components
DIN SPEC 3103	Discusses specification on blockchain and DLT for Industry 4.0 application scenarios for modern industry development. Moreover, provides information to decision makers to evaluate possible benefit of adopting DLT. The document also presents several use cases and describes respective issues that can occur. These issues are then resolved by establishing a solution by deploying blockchains/DLT including sequence diagrams and user stories to strengthen the understanding. Reoccurring components of these scenarios are then developed to be building blocks, which get developed accordingly so it can be applied for other use cases	The report provides guideline and a good outlook for industry 4.0	Mainly for industry 4.0 and less applicable in other domains
DIN SPEC 3104	The specification of this report is more aligned with blockchain-based validation of data aimed at focusing on data correctness of blockchains. To attain a "proof of correctness" a technical framework and process descriptions was proposed for blockchain validation and verification. The technical framework proposed is employed as a form of a step-by-step outline where each process or block requirements is described	It offers a guiding framework for blockchain-based validation of data	It is not mainly useful for a more generalized methods required by blockchain

Table 2 (continued)

DIN code	Description	Strength	Limitation
DIN SPEC 4996	Provides a blockchain-based method for the transfer of software licenses, aimed at supporting the establishment of a standardized procedure for digital transfer, trade, and management of software licenses utilizing DLT by a set of determined requirements. Moreover, the document defined the necessary elements information needed to carryout software and licensing operations. This specification informs organizations on how the tamper-proof and transparency characteristics of blockchain can be applied to prevent or multiple usage or loss of one license. An outline of different roles involved in licensing processes is explained, as well as a design outline of how a proposed platform could look like	They offer a guiding framework to facilitate blockchain-based transfer of licenses	It is not specifically effective for a more generalized application of DLT apart from licensing operations

Table 2 (continued)

DIN code	Description	Strength	Limitation
DIN SPEC 4997	This specification relates to privacy by blockchain design which is achieved based on a standardized model for processing personal data utilizing blockchain considering the EU General Data Protection Regulation (GDPR) and Privacy by design regulations. This specification aims to support privacy compliance and data protection in blockchain/DLT systems. It clarified what personal data entails and how such information may be identified. This is supported by listing a few scenarios where personal data can be obtained and where it is handled. This specification lists the issues associated with combining blockchains with legal issues and the GDPR in relation to data ownership and data erasure. Also, a considerable summary of risks and mitigations strategies for data protection standards are summarized with a clear emphasis on privacy by design, including a scheme for a privacy by design blockchain architecture design	The document offers a method on how to adhere to the restrictions of the GDPR with blockchain creating awareness on the GDPR and data subject rights	It is more of a theoretical method as no definitive framework was provided in detail with possible case scenarios

Standardization Administration of China (SAC) In China, the Standardization Administration of China (SAC) was established as a national standardization technical committee linked to consortium standards, blockchain standards, industry standards, and national standards which are currently under development or in already published (Tang, 2021).

The Research and Development (RAND) RAND corporation is a non-profit international firm that offers policy-based research and analysis to the U.S. Armed Forces, and is funded by the U.S. government, universities, corporations, private individuals, and private endowment. RAND through its European division, wrote a report for the British Standard Institution, which is the official standards body for the United Kingdom, and argued for standardizing technologies not too early to avoid restricting application nor too late to avoid missing potential opportunities (Gramoli & Staples, 2018).

The International Securities Association for Institutional Trade Communication (ISITC) Europe ISITC Europe is a non-profit organization that promotes operational efficiency, harmonization, and education in the capital markets environment. ISITC has developed Blockchain and DLT working group to develop a platform to discuss, educate, and validate blockchain or DLT and its role in security processing. With collaboration with organization for the advancement of structured information standards, they are describing technical standards for blockchain/DLT (Gramoli & Staples, 2018).

The United Nations Economic Commission for Europe (UNECE) UNECE is a regional European commission of the United Nations (UN). One of UNECE division is the UN Centre for Trade Facilitation and Electronic Business (UN/CEFACT), which develops standards linking to electronic business and trade facilitation. UNECE is also researching the adoption of blockchain for trade-related use cases and published a white paper on the subject devoted to blockchain and DLT standardization. This effort demonstrates a fundamental need to improve communication with blockchains (Gramoli & Staples, 2018).

The Internet Engineering Task Force (IETF) The IETF is an informal open group that develop Internet standards. It plays a key role in defining the Internet Protocol suite that is utilized for interoperability standards and network communications by publishing request for documents that can influence blockchain technologies (Gramoli & Staples, 2018).

Related Works on DLT Standardization

A few studies have investigated standardization of DLTs from different perspectives and domains. Among these studies Gourisetti et al. (2021) researched on the standardization of DLT cybersecurity stack for energy and power applications. The authors postulated the potential of employing DLTs in supporting applications which has not been fully achieved due to the lack of standardization between and across different DLTs, as well as other required building blocks (such as., communication protocols). Accordingly, a DLT cybersecurity stack was proposed particularly for DLT technology developers, end users/utilities, and researchers. Gray (2021) reviewed how managers adopt blockchain technology and specified how the standards process is managed. The study presented a few standards development organizations that have contributed to the development of blockchain technology such as IEEE, ISO, or the Internet Engineering Task Force (IETF), the North American Energy Standards Board (NAESB). The author stated that if standards do not lead technological developments, this results to the technological invention being lag. Thus, standards help for the technological evolution from one level to the next.

Another study by Tang (2021) identified existing challenges and trends related to blockchain standard system. Findings from the study highlighted the current state of blockchain standardization in respect to standards such as ISO, ITU-T, IEEE-SA, and other national level corporations. Ultimately, a blockchain standard system which comprised of 10 categories of blockchain standards was presented aligned to the trends and challenges of blockchain standardization. König et al. (2020) compared different blockchain standards and offer recommendations for industrial adoption of the technology. The study aimed at providing discussion of standardization organization's which contributed to blockchains/DLT. The reports also comprise of a set of comparison criteria for existing standards. Li (2020) pursued a legal approach from the data protection law viewpoint to improve standardization of blockchain and DLT. The author employed the General Data Protection Regulation (GDPR) in the European Union to ascertain how blockchain can be compatible with the standards of modern data protection law and if blockchain can create a pathway to attain legal objectives. The study also advocated for standardization to mitigate blockchain's limitations and to leverage its benefits.

Additionally, Cali et al. (2019) examined DLT/blockchain in transactive energy use cases standardization and segmentation framework activities which are implemented by IEEE standards association. Findings from the study contribute to improve the advanced economic control and operational functionalities to dynamically stabilize the electrical supply and demand within the electrical grid using advanced ICT. Cristea and Stiller (2020) prepared a report on blockchain standardization and provided an overview of current activities landscape. The authors advocated for having a regulatory framework appropriate to aid with blockchain related business models which is important for a proper interpretation and successful adoption of DLT in large scale. Accordingly, the report presented an overview on the current blockchain standardization strategies to help promote the usage of this technology. Li et al. (2019) provided an overview and ideas on standardization of China's blockchain technology. The authors examined the domestic and international status quo of blockchain standardization and identified problems that need to be resolved under the current condition. Additionally, a system engineering methodology was proposed for standardizing blockchain technology.

Researchers such as Gramoli and Staples (2018) explored blockchain and DLT standard toward achieving consensus. The study listed standards organizations and efforts dedicate to standardize blockchain and DLT. Findings also identify the lack of terminology that hinders communication and propose clarifications to address these ambiguities. In the end, a high-level description of blockchain and DLT was proposed based on three elements of functional architecture. Hyland-Wood and Khatchadourian (2018) contributed by providing discussion on the history of global blockchain standards. This study summarized some existing international standards related to blockchains and proposed guidelines for further standards development that could be meaningfully explored in the future without negatively affecting additional invention. Deshpande et al. (2017) presented a report for DLT/blockchain as related to the opportunities, challenges, and the prospects for standards. The report aimed at prompting further dialog across the DLT/blockchain community regarding the prospective role of standards in encouraging the adoption and development of the DLT/blockchain. Findings from the study provided a set of areas for further importance by DLT/blockchain stakeholders concerning the potential role of standardization.

Hofmann et al. (2017) investigated the immutability notion of blockchains and advantages of early standardization. A framework was developed aimed at understanding the boundaries and dimensions of blockchain immutability. The framework comprises of data layer, system layer, function layer, and execution layer and further provides good practice standard toward the implementation of blockchain applications. Findings from the study provide strategies to better utilize the blockchain technology's full capability via standardization. *But irrespective of the reviewed studies, there is lack of research that explored a decentralized based approach for standardized interoperable DLT deployment in smart cities. Hence, this study aims to address this limitation and provide a framework for standardization of interoperable DLT interface integration and alignment in smart cities.*

Method

The study employs design science research methodology (DSRM) as proposed by Peffers et al. (2007), which concerns the design of artifacts aimed at addressing identified problems (Bokolo, 2023). DSRM approach employing case scenario in information systems was used for exploring the condition where boundaries of evidence are not evidently defined. Thus, case scenario approach has been considered as suitable for finding out the real situation of an occurrence. Besides, DSRM is a suitable method as this research addresses the lack of standardization of DLTs by designing a meaningful artifact in the form of a framework (Bokolo, 2022). The DSRM process employed in this study is shown in Fig. 4.

The first phase involves identifying the framework layers based on secondary data. This phase also involves reviewing existing studies related to DLT and blockchain standardization as well as existing standards development organizations toward DLT standards comprises of IEEE, ISO/TC 307, W3C, and ITU. The second phase involves identifying use case scenarios based on KPIs of the municipality such as achieving an interoperable digital system for the city by deploying DLT such as IOTA tangle to improve integrity, trust, and security within the city. The third phase involves collecting qualitative data to validate the standardization framework

Fig. 4 DSRM process employed in this research

stacks developed as seen in Fig. 5. The next phase entails modeling and mapping the framework stacks with preliminary findings from experts based on use case scenarios. The findings are modeled using ArchiMate modeling language (as shown in Fig. 6). In the final phase, the findings modeled in ArchiMate are communicated to some experts involved in the data collection to refine, revise, and iterate the modeling based on expert's feedbacks.

Data Collection and Analysis

As previously stated, case scenario is chosen as the method to present the findings from experts involved in the + CityxChange smart city project (https://cityxchange.eu/). Use case is a term that originated in software engineering domain, where it describes a list of activities or sequence of steps which usually explain the interaction between the (software) system and the actors. Use case also refers to a scenario, set of scenarios, or illustrations of scenarios in which different stakeholders interact, mainly in relation to a technological ecosystem for specific outcomes (Deshpande et al., 2017). The case scenario analysis methodology is used for exploring standardization framework layers for interoperable DLTs in smart cities. Qualitative data was collected during several workshops and expert interviews with partners in the + CityxChange smart city project. Open-ended questions were used as it allows the generation insight into the concerns, motivations, and challenges faced by the partners involved in the smart city project to gain insight on how DLT (IOTA tangle) can be integrated in fostering interoperable services in smart cities.

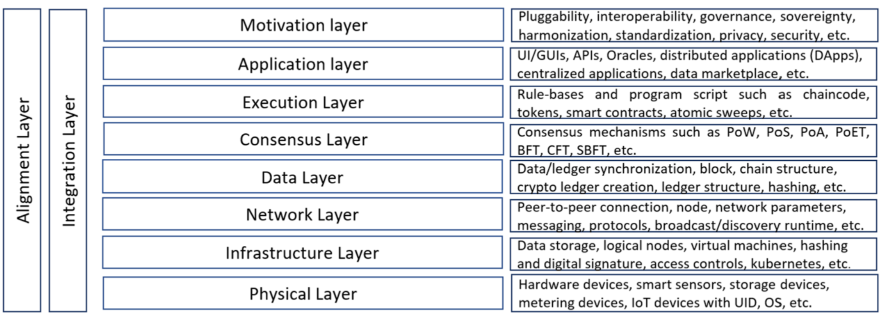

Fig. 5 Developed framework for standardization

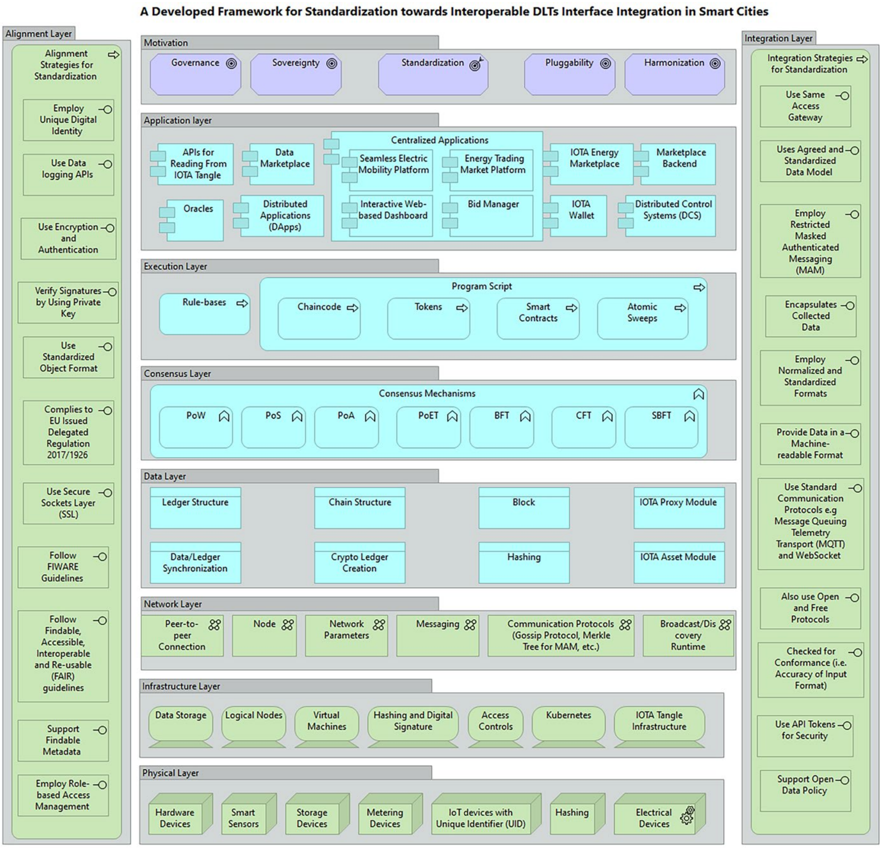

Fig. 6 ArchiMate modeling of use case scenarios for DLT standardization

The interview sessions were held with multiple representatives involved in the project between June 2019 occasionally until May 2020 in a physical location and later digital due to the COVID19 pandemic. Data was also collected from more than 8 participants within 2021 to revise, refine, and iterate the findings in use case scenarios 3. The profiles that participated in the interviews range from urban architects, data architect, ICT practitioners, sustainability experts, and smart urban developers. The workshop and interviews lasted between one to two hours in English language and were transcribed for analysis. No software was employed for data analysis as coding of all data (documents, workshop/interview transcripts) was done manually using descriptive and narrative analysis. The data was coded based on the standardization framework stack (see Fig. 5). To minimize research bias, all findings were illustrated in ArchiMate (see Fig. 6 and Table 3) and referred to some key participants as follow-up and confirmation of the findings represented in ArchiMate tool.

Table 3 Findings from use case scenarios toward standardization of DLT

Use case scenarios 1	Use case scenarios 2	Use case scenarios 3
• The marketplace backend supports registration of IOTA Asset modules and DCS systems after which a *unique digital identity* is receive that will allow them to verify the authenticity of shared data • The *Bid Manager* can implement simple matching policies as well as more complex ones after using data received from the marketplace to tangle Gateway and stored agreements into the tangle *using the same Gateway* • Bid Manager *uses agreed and standardized data model* and *simple matching policy* for demand and offer bids and agreed bids • In the marketplace to tangle Gateway connection, the Bid Manager verify integrity of data, by comparing the copy on the tangle *using Data logging APIs* to store data (raw or hashes) on the tangle • Asset modules register their identity with the marketplace backed and share their public key and communicate securely with the marketplace backend, directly and/or *using restricted Masked Authenticated Messaging (MAM) channels* stored in the marketplace backend • Marketplace backend *encrypts agreed bid and a payment request stored* on the tangle with public key of involved receiving parties • Agreed bids are encrypted with the *public key* of both asset modules, consumer, and producer, and/or DCS gateways involved • Marketplace backend verify the authenticity of demand and offer bids before passing them to the Bid Manager by *verifying their signature using authorized public key* • Exchanged messages are encrypted with *public key* of message recipient to guarantee confidentiality • Asset modules sign demand and offer bids to guarantee their integrity *using their private key* • To ensure integrity data logging *APIs are asynchronous in reading from IOTA tangle* and cached queries are also returned synchronously • IOTA tangle storage could fail thus the marketplace backend maintains a copy of agreed bids in the cloud • The IOTA hardware module *encapsulates collected data into IOTA transactions (e.g., through a cryptocore)*	• The developed seamless electric mobility platform *retrieves, stores, and provides transport data from various data providers* via *APIs*, and *makes it available in a normalized and standardized format* • The platform`s API delivers data as GeoJSON objects (RFC 7946), which allows developers to easily take the data output as a *standardized object format* • The platform *complies to EU issued Delegated Regulation 2017/1926* based on National Access Point (NAP) to *provide data in a machine-readable format* • Data is pushed to or pulled by the platform using *standard communication protocols, and Message Queuing Telemetry Transport (MQTT) and WebSocket are supported*	• The interactive web-based dashboard data is stored in a cloud-based platform that is secured using Secure Sockets Layer (SSL) • Users of the applications are *required to authenticate using* their login details (username and password) • The platform is built with a *role-based access management* to ensure data security allowing users to access and/or modify data based on their role • The platform makes use of the *MongoDB Atlas cloud database* that implements additional *data security standards* at its own level which makes use of *API tokens* while sharing data with partners • If any access token is tampered with, the platform has a *built-in ability to validate the tokens* issued to all users and prevent access from unauthorized attempts to access • To promote the use of the *automated process of data sharing*, APIs employed in the platform were *structured using the FIWARE guidelines for KPIs* in smart city projects, making the future integration and use of this method by partners easier and more efficient • Adheres to making project data as *Findable, Accessible, Interoperable and Re-usable (FAIR)* according to the *European Commission's guidelines* on management and sharing of data • To increase security, *a token with annual validity* will be provided for each partner accessing MERT data through the portal • The platform provides *API access tokens, called 'API Keys'* to the KPI/data owner that supply data to get data from KPI/data owners' repositories using the APIs. The API key authenticates the data source before any data is shared • In the platform, metadata and data is made universally accessible through *an open and free protocol which includes controlled access* to ensure authentication and authorization of data access • To *support findable metadata* and data are assigned unique identifiers and registered in a searchable resource or repository where it can be easily found • Employs duplication of data on multiple servers that are balanced by a *load balancer* to allow multiple partners to access and process data simultaneously • To be *interoperable metadata and data are presented in a format* that can be used in multiple other representations and applications • Through a back-end process, data collected in the platform is checked for *conformance (i.e., accuracy of input format)*, after which it is processed for calculation of the KPI • For the data to be *reusable metadata and data are checked to ensure accuracy* and a high level of detail as well as *adherence to universal standards (such as FIWARE)* and *use of data are clearly licensed and indicate user permissions* • Use of a *token-based API*, which allows a fetch request to securely pull data from the data provider's repository to the platform to authenticate the exchange of data • In *support of the open data policy* the platform disseminates project data through visual representations, aggregated data calculations, and summary or detailed data reports available for extraction and external use

Design Artifact (DLT Standardization Framework)

A framework is developed grounded on prior studies on DLT approaches (Ghandour et al., 2019; Gourisetti et al., 2021; Hofmann et al., 2017; Anthony Jnr et al., 2021a, b; Mandaroux et al., 2021; Qing et al., 2020; Romano & Schmid, 2021), to support for standardization toward an interoperable DLTs interface integration and alignment in smart cities. The framework comprises of stacks or layers (motivation, application, execution, consensus, data, network, infrastructure, physical, alignment, and integration), as seen in Fig. 5.

Figure 5 depicts the developed framework for standardization toward interoperable DLTs interface integration and alignment in smart cities. Each of the framework layers are discussed below.

Motivation Layer

This layer captures the main needs and requirements for citizens and stakeholders in the urban environment such as issues related to interoperability of DLTs with legacy systems deployed to provide data driven services. These services contain in this layer can be utilized by the stakeholders (e.g., nodes and human users) to interact and integrate with the DLT platforms.

Application Layer

Application layer comprises of applications, scripts, software, programs, and user interfaces (Gourisetti et al., 2021; Mandaroux et al., 2021). It captures specific digital applications to be utilized by citizens and stakeholders within the city (Anthony Jnr, 2021a; Romano & Schmid, 2021). Other components captured in this layer consist of User Interface/Graphical User Interface (UI/GUI), performance analysis systems such as Hyperledger CaliperTM. These components within this layer may be seen as off-chain processes that connects DLT with external systems (Gourisetti et al., 2021). These applications may be centralized or decentralized (Anthony Jnr, 2021a). However, these applications may be developed based on the certain conditions and protocols to be interoperable with existing DLTs. To support standardization most deployed applications should have the ability to initiate rule bases and program code (for instance, chain code, smart contracts, atomic swaps, etc.) that are deployed in the execution or trust layer below (Gourisetti et al., 2021). As mentioned by Gourisetti et al. (2021) these applications have the capability to perform two-way communication. These includes downward connections within the DLT which usually begins from the execution layer and upward connections that are outside the DLT. These upward connections can be achieved through the deployment of gateways such as APIs and Oracles.

Execution Layer

The execution or trust layer represents the contract scripts, programmable scripts, software code, and scripting languages running locally on the end users or nodes hardware that runs on the city`s digital infrastructure ensuring security, stability, or performance improvements (Hofmann et al., 2017; Qing et al., 2020). The execution layer comprises of the program logic, DLT rules, such as chain code and smart contracts. The applications deployed within the application layer calls the code and rules within the execution layer and initiate the code in the execution layer that results to the execution of a DLT transaction. Most complex transactions are stored within DLT platforms in the form of source code or bytecode programs and are executed to support various business logic. These source code programs are known as smart contracts. A typical smart contract structure involves execution of the code, language definition, and compilation (Qing et al., 2020). Smart contracts are implemented in DLT platforms using programming languages or simple interpreted scripts such as Solidity in Ethereum, Golang, etc. (Qing et al., 2020). Smart contracts can be seen as computer programs which implement pre-defined commands when certain requirements are met within the DLT system (Ghandour et al., 2019). The smart contracts code in the execution layer uses data from off-chain data sources, the code can also trigger oracles and APIs that resides in the application layer to fetch data from off-chain data sources to the execution layer (Gourisetti et al., 2021).

Consensus Layer

The consensus layer involves the components of the mutual agreement set of rules applied to select a unique ledger between possible different instances, thus ensuring the consistent state of the DLT (Romano & Schmid, 2021). The consensus layer is the core layer of any DLT platform, as it manages and validates transactions, and ensures inter-DLT verification (Mandaroux et al., 2021). Consensus layer aids distributed control, trust, and ownership. It initiates an agreement among the distributed node users and synchronizes them. It further authenticates transactions and ensures fault-tolerant and reliable operations (Gourisetti et al., 2021). The consensus layer primarily encapsulates different consensus algorithms deployed by network nodes to achieve data consistency in a distributed manner (Qing et al., 2020). Consensus refers to a system which guarantees that parties agree on a particular state of the DLT system as true state (Ghandour et al., 2019). These help to ensure that the DLT system node users will reach a consensus and continue to function even when some node(s) are corrupted or fail (Gourisetti et al., 2021).

Proof of work (PoW), a DLT consensus, is characterized by its rigorous effort to prevent potential malicious computing power usage. PoW is mostly used in Bitcoin and it requires solving a computational tricky puzzle to produce a new block. Proof of Stake (PoS) is another consensus which is based on the wealth processed by the codes. PoS reduces the computing effort and improves security, but also leads to monopoly as the voting power is centralized. Byzantine fault tolerance (BFT) is another consensus mechanism which results to less system overhead and improve transaction speed (Mandaroux et al., 2021). Another consensus mechanism is the Proof of Elapsed Time (PoET) which utilizes a lottery method in which the node user with the shortest wait time produces the next block. Other consensus algorithms included simplified Byzantine fault tolerance (SBFT), proof of authority (PoA), proof of burn (PoB), and proof of control (PoC) (Ghandour et al., 2019).

Data Layer

The data layer involves the data stored on the distributed ledger (Hofmann et al., 2017). It comprises of a certain data structure (Qing et al., 2020). This layer data is distributed and saved across different nodes, and any transaction within any of these nodes are added to the ledger shared across all connected nodes. DLT only permit commit only, which means that no deletion or update is accepted within the ledger (Ghandour et al., 2019). This layer also encompasses all the data mechanisms and structures which give rise to the distributed ledger. Such as Merkle trees and linked lists which make up the ledger data structure (Romano & Schmid, 2021). Thus, the process of grouping transactions into the ledger or appending transactions into the ledger, etc., is carried out in this layer. Functions within this layer are mainly related to data orchestration procedures but in the context of distributed ledgers, databases, etc. Examples of such procedures involves arranging or grouping transactions into blocks for example in blockchain, appending the transactions to the distributed ledger, and duplicating the identical and updated data ledger/structure across the distributed network, etc. (Gourisetti et al., 2021).

Network Layer

The network layer encompasses internode communication that enables decentralized peer-to-peer information transaction, and data sharing among the nodes (Mandaroux et al., 2021). Thus, this layer involves how the peer-to-peer network of nodes is constructed and shares data so that the distributed ledger can be managed and queried (Romano & Schmid, 2021). The network layer involves protocols, authentication/authorization, node management, networking access methods among multiple nodes within the DLT (Qing et al., 2020). When nodes transact and engage in validation and verification of transactions, such procedures are specified in this layer. Protocols such as Transport Layer Security (TLS) employed by Hyperledger Fabric and some private blockchain for ensuring secure handshaking, the Recursive Length Prefix (RLPx) mostly utilized in Ethereum, and other secure node-to-node handshaking mechanisms are captured in this layer. In DLTs standard protocols are suggested to be employed to promote standardization instead of custom based or new commercial protocols (Gourisetti et al., 2021).

Infrastructure Layer

This layer consists of the virtualization where the decentralized distribution of the nodes is the main component (Mandaroux et al., 2021). This layer is analogous to the physical and virtual computers that participate as the authorized nodes within the distributed ledger. The nodes should be able of carryout cryptographic processes such as hashing and digital signature, managing the identity of other nodes and offering identity information for authorization and authentication of nodes within the network and. Tools that ensure permissions, specify identity of the nodes, and facilitate access controls are captured in this layer (Gourisetti et al., 2021).

Physical Layer

Physical layer contains all physical infrastructure and hardware devices utilized by application within the city. These physical devices may consist of processing hardware such as RAMs and processors, which are employed for data processing, data analytics, or even for consensus algorithms for verification such as miners in Bitcoin (Ghandour et al., 2019). Physical layer: This layer is very important in domains such as smart cities where IoT devices, smart metering devices, storage devices, sensors, and communication hardware play significant role to improve the sustainability of the city. These physical infrastructures such as sensors and IoT devices are captured in this layer. Most of this hardware may not be able to integrate directly to the distributed ledger. In such cases, these physical devices would need to interact with the middleware to connect seamlessly in the DLT network (Gourisetti et al., 2021).

Integration and Alignment Layer

These layers are included to support standardization of DLTs deployed within the city. These layers are aligned to all the framework stacks (motivation, application, execution, consensus, data, network, infrastructure, and physical). Thus, system alignment is the capability of two systems to identify one another and to utilize resources from one another. System alignment entails that one platform performs an action while being linked to another system (Jnr et al., 2021a). Alignment aims to achieve a compatible or harmonious relationships between two different domains by achieving fitting and linking among different components working together to accomplish a common goal. Likewise, integration refers to software that allows components of different systems to interoperate, particularly to be able to distribute data, communications, and function across services in various environments (Jnr et al., 2021a). Data integration can be handled in various levels such as interconnection of data from hardware, through computer networks, via integration of data from data sources and digital applications, and enterprise integration for coordination of data required for manage, control, and monitor urban processes (Anthony Jnr et al., 2021a, b).

Findings

DLT Use Case Scenarios in Smart Cities

This section validates the framework by practically demonstrates the usability and applicability of the previously discussed developed standardization framework for interoperable DLTs. The framework layers are validated based on evidence from the use cases. Thus, the different smart cities use case scenarios are discussed and mapped to the standardization framework stack. The use case scenarios discussed in this section are as follows:

- Use case scenarios 1—Distributed energy trading market platform
- Use case scenarios 2—Seamless electric mobility system including user interface
- Use case scenarios 3—Monitoring and evaluation platform dashboard

Each of the use case scenarios is part of the +CityxChange smart city project. An overview of each of the above use case scenarios sequence of operations and components in the context of DLT (using the developed standardization framework) is discussed below to described how the framework was validated.

Background of Use Case Scenarios

IOTA tangle is employed as the DLT in the use cases. IOTA tangle is a Blockless DAG which directly appended data or transaction to a chain without being wrapped into a block. This is because all new data can be run concurrently on different chains which are connected to create a network termed as "tangle" (Fan et al., 2019). IOTA tangle possesses a high scalability and has no transaction scale limit which guarantees that all data are securely encrypted and stored in the local Home Nodes (Fan et al., 2019). IOTA has no hidden transaction fees as the infrastructure carries out a very light-weighted proof of work consensus (Bokolo, 2022).

Use Case Scenarios 1

The distributed energy trading market platform is developed based on a model for design and operation of a local power system that maintains management and operation of renewable energy in smart cities. The platform models use DLT for micro trading of green energy resources needed to facilitate renewable energy city when climate data, historical consumption, and resource attributes including flexibility that are available. The distributed energy model computes how available energy resources will be utilized the best way for next day hour based on an hour forecast linked to availability and predictions of load forecasts, weather forecasts, etc. (Petersen et al., 2021; Rood, 2020). Respectively, this use case illustrates how the distributed energy trading market platform facilitated by IOTA tangle as a DLT supports operation and management renewable energy in smart cities. The platform is also developed to manage export, import, general estimates, design, and operation related elements. The system and DLT standardizations are executed through the integration of export and import modules either in file formats or via Application Programming Interfaces (APIs) as seen in Fig. 6.

Use Case Scenarios 2

This use case scenario examines how DLT-enabled platform can facilitate the seamless electric mobility platform including user interface for sustainable transportation in smart cities. It includes a mobility backend system which provides, retrieves, and stores, urban mobility data. The *mobility backend system* gathers data from several data providers via APIs. To ensure standardizations the mobility backend system uses an inhouse API which makes data available in a standardized and normalized format. Additionally, to ensure seamless electric mobility system an *Android application* was developed for citizens to use in managing their mobility needs within the city. The Android application connects to the mobility backend system and shows the transport options that are accessible for the user based on a selected position on the map. A digital asset payment system is facilitated by *DLT (IOTA tangle*), which enable users to reserve and pay for a multi-modal transport choice provided by different mobility providers within the city. Finally, for *standardization an API* is provided by the distributed energy trading market platform in (use case scenario 1) for accessing temporarily available electric vehicles batteries state as flexibilities for use within the city. Also *standardized data* is simulated to provide insights to stakeholder into which data is produce in order to exploit electric vehicles batteries as temporary energy sources.

This simulated data is utilized the distributed energy trading market platform in (use case scenario 1) for orchestration of renewable energy consumption and production within the city (Petersen et al., 2021; Skoglund et al., 2020). Overall, findings from this use case depicts how a seamless multimodal electric mobility as a service and an open/interoperable service platform for public transportation is achieved. The Android application identifies the possible urban transport options for citizens' transport demands and assists users to select a combination of transport modes for their journey. This use case also integrates Vehicle-to-Building (V2B)/Vehicle-to-Grid (V2G) charging methods by connecting electric vehicles through electric vehicles chargers to the community grid. This connects to the overall operation of the local energy consumption and generation by making the electric vehicles batteries a part of sustainable energy business model as suggested by (Anthony Jnr, 2021c). Hence, this use case scenario encompasses electric vehicles infrastructures and business involved within the electric mobility as a service ecosystem. It comprises of different transportation methods such as electric-bikes, light electric vehicles, and electric vehicles. The seamless electric mobility platform also integrates with the distributed energy trading market platform (use case scenario 1) connected to IOTA tangle micropayment solution for use in the electric vehicles.

Use Case Scenarios 3

This case provides a platform as an interactive web-based dashboard to analyze, process, represent data for monitoring and evaluation of smart city goals gathered from implemented devices, sensors, etc. Besides, such KPIs can be used for benchmarking of the sustainability of the city. It provides a data repository for monitoring KPI data collected by and data owners. The data is used for modeled and visualizing of data for urban dissemination (Dahlen et al., 2020; Petersen et al., 2021). The monitoring and evaluation dashboard ensures reliable, accurate, and consistent data smart city development. The monitoring and evaluation dashboard aims to store, process, manage, visualization, and dissemination of data. The data collected can be monitored using online data collection systems, sensors, survey response from stakeholders or other mechanisms as seen in Fig. 6. Data related to smart city development can take place via manual process, online interface or through an automated process for sharing data among stakeholders through API connection. The collected data is integrated to the city dashboard to promotes wider information dissemination and to report on urban key performance indicators (KPI) data such as air quality, CO_2 emission reduction, energy, water, and waste wastage.

Qualitative Findings from Use Case Scenarios

Use case scenario 1 involves the distributed energy trading market platform implemented in DLT (as *IOTA energy marketplace implementation and IOTA module*). *The application uses the IOTA ledger to provide standardized APIs* for the *energy marketplace* to access required data, store agreements and to carryout *micro payments* by the IOTA ledger to *ensure auditability* (Livik et al., 2021). IOTA employs an *IOTA proxy module* use *APIs* to interact with the IOTA tangle and to send energy and thermal power data (or hashes of them). The module exposes APIs that allow *Distributed Control Systems (DCS)* to store selected data onto the IOTA tangle, thus guaranteeing their integrity, immutability, and auditability. Additionally, the IOTA module, locally deployed at prosumer level, gathers required marketplace data and shares it using the IOTA ledger to guarantee data integrity and immutability.

The IOTA asset module collects imported and exported (demand and offer) energy and thermal power data from the connected asset(s) within the city. For auditability and integrity all the data and requests shared between marketplace and *IOTA asset module* are stored onto the IOTA tangle. The IOTA module has the computation capacity to locally create IOTA transactions. This capability is used to create transactions containing the collected data and to securely "send" this information as data transactions to the marketplace, using the *IOTA tangle infrastructure*. This way, data shared using the tangle becomes immutable, its integrity guaranteed and fully auditable. *Marketplace backend* and its related interfaces/APIs aids receiving of data directly from *asset modules* and *Distributed Control System (DCS)* and use the IOTA tangle to read/store immutable data, i.e., energy demands and offers bids and agreed bids generated respectively by *IOTA asset modules*, DCS, and the marketplace bid manager.

Furthermore, to ensure integration and interoperability toward standardization, the following are employed in the distributed energy trading market platform as seen in Fig. 6. In use case scenarios 2, the use case involved the seamless electric mobility platform including user interface facilitated by IOTA. Finally, use case scenarios 3 involved an *interactive web-based dashboard* provides a *repository* for monitoring data captured by KPI and data owners, from where the data is modeled, displayed, and made available for further dissemination. The monitoring data for each KPI is collated within the platform, whether the data is captured automatically using *connected APIs*, or *manually*, *using data capturing sheets* built into the KPI interface of each indicator in the platform (Rood, 2020). The main findings from all use case scenarios are modeled within the framework stack (as shown in Fig. 5), in ArchiMate modeling language as seen in Fig. 6 to illustrate how DLT standardization can be achieved mainly by the alignment and integration layers.

Figure 6 shows all the DLT components, both decentralized and centralized applications employed with the 3 use case scenarios investigated in this study as discussed in the sections "DLT Use Case Scenarios in Smart Cities"/ "Background of Use Case Scenarios." Additionally, to ensure integration and interoperability toward standardization, findings as shown in Table 3 depict how each use case scenarios achieve standardization with DLT (IOTA tangle) in proving distributed and centralized digital services in smart cities. At the moment no relationships are establish among the different components and across the layers in the ArchiMate model as the findings at the time of writing of this article are limited in this aspect.

Open Issues and Recommendations for DLT Standardization

Open Issues of DLT Standardization

Presently, DLT standardization is faced with some technical, organizational, and governance issues. A few of these issues identified from the literature are discussed in Table 4.

Recommendations for DLT Standardization

As an emerging technology, early standardization of DLT may limit the adoption and development of this technology (Gramoli & Staples, 2018). Confronted with this issue, standardization would be needed for taxonomy to clarify the exact meaning of different terms, for example, the meaning of data modification, data erasure, and to explain to what degree data can be gathered in minimization. Standards can help to define what can and cannot be required from these DLT based platforms and what is the responsibility of stakeholders such as end users, developers, regulators, business owners, miner, investors, administrator/operator, supplier, and service provider (Lima, 2018), within this emerging technology (Gramoli & Staples, 2018). As such strict standards can decrease the number of misunderstandings faced and there should be a procedure that aids malleability and flexibility to support future DLT innovation (Li, 2020). Taking into consideration the trend of DLT development

Table 4 Open issues of DLT standardization

Open issues	Description
Adhering to existing international regulations	Technically, new technologies as well as standards need to *consider existing international regulations* and try to adjust to these existing global laws. This is usually a challenge as most regulations are not written to be compliance to DLT. For example, in the case of European General Data Protection Regulation (GDPR), the immutability conflicts with the rights of users to control. Thus, it is an issue to manage personal data, to restrict data usage, to correct, or to be forgotten. GDPR requires organizations to agree and conform to limit data transfer between countries, but on public DLT the data is processed by many parties in different geographical location (Cristea & Stiller, 2020)
Usage of similar definitions	One important determinant for the standardization of DLT is the *use of similar definitions* of related terminologies and terms across different organizations. This factor has been a priority for both ITU and ISO in start of their efforts toward achieving DLT standardization (Cristea & Stiller, 2020)
Ensuring collaboration	Another issue is how to *ensure collaboration* between stakeholders involved in the standardization of DLT at all levels. The collaboration is crucial in creating or extending regulations, laws, agreements, or policies and has developed into a requirement not only between organizations but also among countries at the global scale (Cristea & Stiller, 2020)
Establishing consensus mechanism	The significance of designing effective governance frameworks (Carayannis & Grigoroudis, 2022), through standards will guarantee the confidence of future users of DLT. Developing and establishing standards entails *consensus mechanism*, which encourages the international community of experts to collaborate, share, and agree on direction toward DLT standardization (Cristea & Stiller, 2020)
Repeated standards	There is also the issue of *repeated standards*. As supported by the literature (see the "Exiting Standards for DLT Implementation in Sustainable Smart Cities" section), there are similar standards aimed at improving the standardization of DLTs and this is quite a lot for an emerging technology. However, over-development is very usual for DLT and blockchain standards. Also, most of the existing blockchain standard projects share similar or same titles. For example, one of the two largest standardization companies, ITU and ISO are both developing a reference framework/architecture standard for ensuring security standards within financial applications. Such repeated standards may result to negatively impact standardization resources, and thereby result in separation of standardization among the organizations (Tang, 2021)

Table 4 (continued)

Open issues	Description
Achieving alignments between standards	*Achieving alignments between standards* is quite challenging due to different standardization projects being approved by different institutions, who work simultaneously on their projects. Due to this development, the alignments of different standards, particularly standards from various groups are quite difficult. While variety of liaison and cooperation have been established between DLT/blockchain standardization organizations, the synchronization is limited in ensuring alignments. An example is the inconsistency of either blockchain or DLT. As ISO/TC 307 uses the terms blockchain and DLT, whereas ISO/TC 46 uses only blockchain, and ITU-T uses the term DLT in their standardization projects leading to different understandings of both terms (Tang, 2021)
Unequal development with different directions	The development of standards for technological inventions toward achieving governance standards (Carayannis & Campbell, 2021), interoperability standards, and standards for smart contract is considerably slower. Standards to improve interoperability such as ISO/TC 307 has been established as an interoperability working group (Tang, 2021), yet there are fewer standard projects in ensuring alignment and integration related to DLT standardization (Anthony Jnr et al., 2021a)

existing standardization frameworks should support privacy protection, information security, and data exchange.

Besides, there is need to provide DLT standardization training to developers and organizations to enhance their capabilities and provide knowledge to research and develop the DLT open-source communities. Furthermore, the standardization of DLT should specify mediums that help data providers exercise their rights. For example, how citizens modify or complete their incomplete or incorrect information within the DLT platform. In what scenarios can citizens delete their existed data and how can they do that. Therefore, standardization should make sure that basic needs by data consumers can be achieved within a distributed ledger environment. Likewise, more detail standards on pseudonymisation and anonymisation of data stored in DLT platforms (Li, 2020) would be use for smart city development. There is need to carry out pilot programs for standard verification. Thus, organizations should provide best practices based on the acquired experiences from pilot programs embarked on in their standardization projects. This will accelerate wider application, promoting new formats and new modes such as big data transactions, distributed data storage, and Blockchain as a Service (BaaS) to promote the integration of DLTs within the society.

Researchers such as Tang (2021) advocated for revision of standardization projects. As DLT landscape is quickly developing. There is need to update some standards related to DLT applications models. For example, ISO began a revision project after the publication of the DLT vocabulary standard. Revision provides a medium to enhance the quality of standards and lessen the inconsistency across standards (Tang, 2021). Another important part of standardization is integration and alignment of digital applications with distributed ledgers. It would be of benefit to develop a standard smart-contract template that can be automatically executed in to different DLTs (Narang, 2020). Research areas such as governance of DLT, interoperability and intraoperability of DLT, and other related areas that further foster smart city development (Carayannis & Campbell, 2021), and standardization should be explored.

Governance standards for DLT should also be deployed as it provides support for governance process within DLT platforms. This helps to address concerns associated with governance standards such as goals, mechanism, objects, contents, and principles of governance, as well as responsibilities and roles involved in the adoption of DLT in urban environment. The difference of DLT governance between public, consortium, and private DLTs should addressed in governance standards developed for DLTs (Tang, 2021). Another area with potentials is the smart contract standards. Smart contract standards for DLT such as Ethereum. The identification of smart contracts, normalization of smart contract scripts and formal verification procedures for smart contract are areas which need standardization (Tang, 2021). Standardized smart contracts for different use case scenarios in smart cities is also a beneficial area for the extension of DLT ecosystem.

Discussion and Implications

Discussion

The potential for DLT goes beyond cryptocurrency, allowing tradeable digital tokens which represents digital or physical assets. This has expanded to other range of application to many industries and sectors, including financial applications, supply chain, education, healthcare, smart cities, and so on. Therefore, the adoption of DLTs in domain such as smart cities is rapidly growing due to the potentials of this emerging technology. The apparent need for DLT standards has led to some associations initiating standardization efforts. Major international corporations as discussed in the "Exiting Standards for DLT Implementation in Sustainable Smart Cities" section have created formal working groups and activities to research on the standardization of DLTs and blockchains (Gramoli & Staples, 2018). Generally, standards are seen as being valuable to support innovation and facilitate trust, and thus to the advancement of emerging technologies such as DLTs. Additionally, standards contributed to defragmenting and coordinating a market comprised of disconnected initiatives and to unlock potential network effects. This would support to improve the coordination among various actors within and across areas to foster business convergence. DLT standardization process enables stakeholders to ascertain the use of DLTs to resolve social problems and to promote legibility (Deshpande et al., 2017).

Standards helps to streamline a particular area by creating an overlap among different suppliers, especially in a way that supports creation of markets (Anjum et al., 2017). Findings from the literature indicate that standards could prove to be crucial to the wider development and adoption of DLTs in different domains (Deshpande et al., 2017), although researcher such as Ghandour et al. (2019) suggested that there is no agreements or standards related to business implementation or development process of DLTs. But, as with any emerging technology, there has been calls for standardization of DLT to optimize the alignment, integration, and interoperability of this technology (Ghandour et al., 2019). Likewise, there are different diversity of DLTs which leads to isolation, fragmentation, and vendor lock-in (Anthony Jnr, 2021a; Narang, 2020). Vendor lock-in decreases diversity increases operational risks, and creates dependency (Narang, 2020). Thus, the extent and pace of the adoption of DLT technology are hindered by interoperability challenges (Gramoli & Staples, 2018).

This can make it more challenging for DLTs to interoperate with each other, and to integrate with traditional urban information systems. This may negatively impact for regulatory acceptance of DLT. A technological solution to DLT interoperability issues is the adoption of standards. One of the major prospective benefits of standardization is to improve interoperability by providing a clear and common shared technical foundation for smart cities (Gramoli & Staples, 2018). Also, there are fewer standards that support data exchange between distributed ledgers (via inter-chain interoperability) that may include hash values, public keys, tokens, or other data managed by smart contract (Narang, 2020). According to a report from IBM, 41% of companies consider the lack of standards as one of the major challenges that impedes blockchain proof of concept (Cristea & Stiller, 2020). Therefore, to address these shortcomings, a range of standardization-related strategies have been deployed to examine different facets of DLT/Blockchain (e.g., Interledger, Chain Protocol, Blockcerts, Hyperledger).

Notably, organizations such as ISO setup a technical committee in 2016 to examine standardization concerns in DLT/Blockchain to support interoperability and data exchange among users, digital applications, and systems in developing strategies to maximize the benefits of DLT for stakeholders (Deshpande et al., 2017). A common approach toward standardization such as a reference architecture or framework that defines the fundamental building blocks, their relationship, and information exchange points is suggested. The standard should also define the lifecycle operations of the DLT platforms which constitute the standard operation of such ledgers that developers should develop into (Narang, 2020). Against the backdrop this current study provides an understanding on standardization of DLT and further develop a framework for standardization toward interoperable DLTs interface integration in smart cities as seen in Fig. 5. In addition, findings from this study offer detailed research on IOTA convergence within the framework based on three working proof of concept use case scenarios in smart cities (see Fig. 6).

Research and Practical Implications

Currently, there is need for interoperability of DLTs focused on resolving different transaction formats (Gramoli & Staples, 2018), fragmented ecosystem, data, and value silos (Belchior et al., 2022; Deshpande et al., 2017). The development of standards and good practices can offer fundamental support for addressing interoperability of DLTs. As standardization support common taxonomy, open protocols, common language, and support of interoperability between various DLT platforms that presently exist or that will be developed in the future (Deshpande et al., 2017). Standards are used by governments as a trusted solutions to complement regulation (Cristea & Stiller, 2020). Stakeholders will benefit from adopting such standard to guide and govern DLT platforms. As it will help to provide a shared understanding, coherent structure allowing for additional innovation (Cali et al., 2019), and the development of DLT ecosystem could result to the creation of innovative business and economic models, such as new forms of enterprise collaboration and cryptocurrencies. Clearly, standardization can enable DLTs to be interoperable (Anjum et al., 2017). But the number of international published DLT standards is very limited, and the large-scale deployment of available DLT standards are few at this stage (Tang, 2021).

Moreover, the unbalanced development of and inconsistence between existing DLT standards negatively impact the widespread adoption of DLTs in smart cities. Accordingly, this study develops a framework for standardization of DLTs to support different centralized and decentralized platforms to connect based on different layer or stacks as a mechanism to ensure the integrity of data exchanged across different use case scenarios or via cross-sector applications. The developed standardization framework can help establish and improve the integration and alignment of smart devices, smart sensors, metering devices, etc. with DLT platforms such as IOTA tangle deployed in smart cities ensuring securely data communicate and real-time synchronization. The standardization framework provides an open, common, and interoperable reference architecture for DLTs, such as IOTA tangle. It also offers guideline for cities in developing data driven use cases in in making cities smarter. Findings from this study present the standardization framework as a reference architecture to clarify DLT layer terminologies, support interoperability, and provide system interfaces for DLT applications in smart cities to achieve an open protocol and layered framework.

Conclusion

Sustainable smart cities have a lot of open opportunities and challenges to be resolved. DLT as an emerging technology is one of the most valuable technologies adopted in cities due to its limitless benefits. Therefore, cities are deploying DLTs, including cryptocurrencies, following the prospect of this technology opportunity to improve urban operations. However, municipalities need to connect their existing digital applications to DLT systems to eliminate data and value silos securely and reliably. Hence, the interoperability of DLTs is emerging as one of the crucial challenges of this emerging technology. To address these shortcomings, standardization efforts and initiatives are being carried out to provide globally approved specifications for DLT interoperability. However, none of these standards focuses on improving alignment and integration of DLTs. This study explores the current DLT standards in progress or already developed to supporting DLT interoperability in smart cities. In particular, this study develops a framework to promote standardization of DLTs toward promoting DLT interoperability in smart cities.

Also, findings from this study identify open issues of DLT standardization and possible recommendations to facilitate DLT standardization in smart cities. Qualitative data from three use case scenarios is modeled in ArchiMate modeling language to depict how and standardization alignment/integration strategies are provided to support DLT interoperability. Findings from this study illustrate how DLTs such as IOTA tangle can operate with other digital systems. The limitation of the current study is that only IOTA tangle was integrated in the developed framework to promote standardization of DLTs in this study. Other DLTs such as Ethereum, Bitcoin, Ripple, Hyperledger Fabric, and Corda were not included for modeling possible use case scenarios in solving smart cities issues. Therefore, future research will explore how to achieve interoperability among DLTs (public, private, or permissionless/permissioned).

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Declarations

Conflict of Interest The authors declare no competing interests.

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