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# Distributed Ledger Technology: State-of-the-Art and Current Challenges

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**Abstract.** Distributed Ledger Technology (DLT) is making the first steps toward becoming a solution for the growing number of various decentralized systems worldwide. Unlike pure Blockchain, DLT finds many uses across different industries, including eHealth, finance, supply chain monitoring, and the Internet of Things (IoT). One of the vital DLT features is the ability to provide an immutable and commonly verifiable ledger for larger-scale and highly complex systems. Today's centralized systems can no longer guarantee the required level of availability and reliability due to the growing number of the involved nodes, complicated heterogeneous architectures, and task load, while the publicly available distributed systems are still in their infancy. This paper aims to provide an exhaustive topical review of the state-of-the-art of Distributed Ledger Technology applicability in various sectors. It outlines the importance of the practical integration of technology-related challenges, as well as potential solutions.

**Keywords:** Distributed management, Distributed information systems, Data storage systems, Information exchange, Information security

## 1. Introduction and Motivation

The number of new services and devices on the market is growing at a tremendous pace on a yearly basis [59]. More and more functions previously performed by humans are transferred to various smart devices to make life easier. Simultaneously, the devices evolve, intending to become more computationally powerful in addition to more efficient and independent data processing. On the other hand, the centralized coordination of an ever-growing number of devices is already becoming a significant problem for conventional systems designed for a smaller number of active nodes [47]. The Distributed Ledger Technology (DLT) has caused quite a stir over the last years as many experts now consider that it has the potential for facilitating multiple bursts of creativity and catalyzing an exceptional level of digital innovation not seen since the advent of the Internet [80]. DLT has been proposed to ensure the effective interaction of various complex-scalable systems [7].

The original concept of DLT existed before Bitcoin and blockchain concepts. The Byzantine Generals Problem theorized by Lamport et al. as early as in the 1980th described how § 'computer systems must handle [...] conflicting information' in an adversarial environment [40]. Subsequent research led to the emergence of the first algorithm for 'highly available systems that tolerate Byzantine faults' with little increase in latency [16].

The earliest identified occurrences of the concept of a 'Blockchain' can be traced back to the $1990^{th}$ with Haber et al. that introduced the notion of a chain of cryptographically-linked data blocks to efficiently and securely timestamp digital data in distributed systems using cryptographic hashing functions and Merkle trees [62], a mathematical construct known for more than a third of a century [51].

Today, DLT aims at enabling the operation of a highly available, append-only database, which is maintained by physically distributed storage and computing devices (referred to as nodes), in an untrustworthy environment [67]. DLT promises to increase efficiency and transparency of collaborations between individuals and/or organizations based on inherent qualities such as tamper- and censorship resistance, and democratization of data [36]. Using a variety of methods, DLT provides an opportunity to solve several challenges in various industries providing an additional level of secure abstraction for direct interaction between heterogeneous systems [39].

DLT has received growing attention as an innovative method of storing and updating data within and between organizations in recent years. A distributed ledger is a digital ledger that is different from centralized networks and ledger systems in two significant aspects. First, information is stored in a network of machines, with changes to the ledger reflected simultaneously for all ledger holders. Second, the data is authenticated by a cryptographic signature. Together, it provides a transparent and verifiable record of transactions. Blockchain technology is one of the most well-known underlays of DLT, in which the ledger comprises 'blocks' of transactions, and it is the technology that underlies the cryptocurrency Bitcoin [20].

However, the possible uses of DLT go far beyond the financial sector, e.g., its use has also been explored in education [18,61,70], e-Governance [33], agriculture [29], supply chain [57] and many other industries. This paper is a critical review aiming to provide a comparative analysis of existing DLT applications and to answer the following research question:

> What are the main challenges of the distributed ledger technology integration and its further operation?

The rest of the paper is organized as follows. The next section provides an overview of the method applied to the topical literature review. Section 3 describes the use of technology in various industries and the corresponding motivation to move toward DLT. The review covers sectors such as eHealth, education, supply chain, intellectual property, Internet of Things (IoT), finance, energetics, as well as a vision from the horizontal domain perspective. Next, Section 4 outlines the main challenges that can be solved by applying the DLT to the identified industries, thus, outlining the future perspectives of the DLT. The last section concludes the paper.

## 2. Methodology

This section outlines the research methodology adopted to carry out this systematic literature review based on the PRISMA guidelines proposed in [44].

In order to identify key publications on the analysis of distributed ledgers through modeling or simulation, we performed a literature search in scientific databases that cover leading computer science journals and conferences: *IEEE Xplore*, *ACM Digital Library*, *ScienceDirect*, *SAGE Journals Online*, and *Springer Link*.

To find relevant articles and papers for our research, we applied the following search string: *(DLT OR "Distributed Ledger") AND (Applications OR Challenges OR "Future Perspective" OR State-of-the-Art)*

In total, we gathered a set of 963 potentially relevant publications, excluding grey literature and pre-prints.

We then analyzed the titles, keywords, and abstracts of the publications to identify papers and articles that described at least one modeling or simulation approach for distributed ledgers. In doing so, we selected a total of 45 publications. To further extend our literature sample, we analyzed the selected publications' references for additional papers or articles relevant to our research. Following this process resulted in a total of 61 publications.

Once the literature selection process was completed, we carefully read the selected publications and used an open coding approach to identify the described DLT applications and challenges. Next, we classified the extracted applications into six general groups. The results of our analysis form the core of the topical literature review and are presented in the next section.

## 3. DLT Applications State-of-the-Art

Today, the potential for using DLT technology can be already seen in almost all areas of society, from healthcare to complex information systems, see Fig. 1. This section discusses the most promising DLT application areas, according to the literature review.

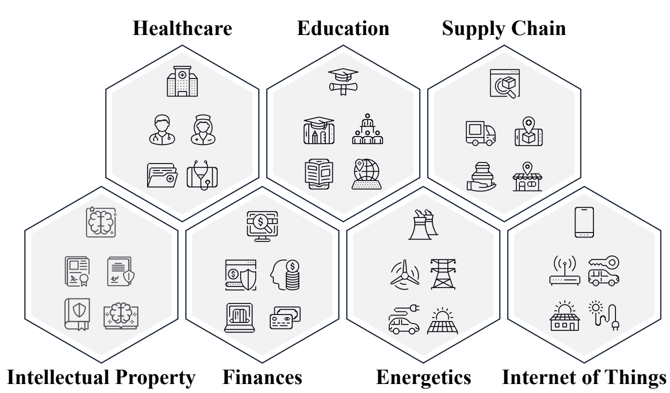



**Fig. 1.** Main DLT Applications Classification

### 3.1. Healthcare sector

The use of Information and Communication Technologies (ICT) for health is commonly defined as eHealth or "an emerging field of medical informatics, referring to the organization and delivery of health services and information using the Internet and related technologies. In a broader sense, the term characterizes not only a technical development but also a new way of working, an attitude, and a commitment for networked, global thinking, to improve health care locally, regionally, and worldwide by using information and communication technology" according to to [56]. eHealth has recently been added to the list of sectors affected by DLT in several ways. DLT's technological advances in eHealth have been documented, among other things, by using data to record and analyze human behavior. The adoption of wearables and IoT devices is expected only to accelerate this expansion [46,55]. It has been partially addressed by General Data Protection Regulation (European Union) 2016/679 (GDPR), which requires transparency in data use as well as covers other aspects related to health-related data [35,63].

One of the main challenges of the modern medical sector is the lack of unified patient data storage [5]. To date, proprietary cloud centralized storages are utilized to solve this problem being individual for different clinics, even city-wise. As a result, the complete medical history or a list of diagnoses per patient can hardly be accessed. Moreover, it is not possible to track the patient's indices and produce appropriate analysis.

In 2015, 78.8 million patients, nearly a quarter of the US population, had their information stolen after a hack occurred on the insurance corporation Anthem [23]. At the end of 2019, the health insurance company started rolling out blockchain-powered features that allow patients to securely access and share their medical data. In the next two to three years, all 40 million members will gain access to it.

In this context, DLT has emerged as a path to application development that enables interoperability between systems by providing secure and immutable information storage and exchange [13,53]. Examples of extant use cases are defined for the following areas of healthcare: pharma, biotechnology, medicine, insurance, genomics [2,68].

The authors of [77] propose a distributed system for patient health data sharing. The content is generated by two types of IoT nodes: wearable devices and static sensors. The data-sharing mechanism is operated through a distributed registry based on a system called Tangle and based on Directed Acyclic Graph (DAG). The Masked Authenticated Messaging (MAM) protocol is used to securely transmit encrypted data streams, thus, ensuring reliable authentication. Merkle tree is applied to ensure data integrity [12].

The next tremendous challenge of the healthcare sector is the need to ensure data confidentiality [27]. In most cases, the patient cannot have a complete view of the patient's medical data processing and access, which should be improved in the next-generation data exchange systems.

Medical data storage is essential in eHealth being extremely sensitive and, therefore, a primary target for various attacks [10]. Since the patients themselves could govern access to their health records, there would no longer be a central point of attack that could be compromised to release large numbers of patient records. Therefore, DLT has the potential to provide a flexible framework for the management of health data. DLTs provide the infrastructure which may enable users in the future to have more control over their health histories and medical records, allowing for better decision making and preventative measures to be applied [76].

Next, the work [25] provides a deep discussion on the main components of blockchain required for developing e-Health targeted distributed architectures. The studied roadmap outlines how DLT can fit into existing Electronic Health Records (EHR) systems or Insurance Content Management (ICM) systems. It also covers important topics of data exchange and privacy in such a heterogeneous environment.

The authors of [22] also presents a system allowing for flexible third-party access to electronic medical records of patients, which makes it possible to confirm the fact of such interaction unequivocally. The authors developed a DLT prototype, which records the validity of information processing using Smart contracts based on Solidity [72].

Pharmaceutical companies often receive government funding to produce specific drugs, such as vaccines and autoimmune diseases. DLT is useful and presumably suitable in areas such as transferring funds from the state treasury to the company and the transfer of medical supplies along the supply chain. In 2020, counterfeit medicines will cost the world economy more than 75 million USD. Tracking the provenance of drugs using DLT is one approach to reduce this trade in counterfeit medicines [43].

### 3.2. Education sector

From the education perspective, one of the DLT applications is related to professional competencies [54]. The authors propose a procedure for developing a register of the population of professional competencies. The proposed algorithm for the Education Index's critical components evaluation is based on the Ethereum blockchain platform. Moreover, a scoring model for calculating these parameters is developed, and a Solidity smart contract scheme is presented being based on the proposed algorithm.

DLT, based on Blockchain technology, also allows creating a decentralized environment where any third party does not control transactions and data. Based on this technology and the European Credit Transfer and Accumulation System (ECTS) is discussed in [70]. The work proposes to create a global credit platform for higher education based on Ark Blockchain called EduCTX, which ensures the aspects of user anonymity, data privacy & confidentiality due to potential legal reasons, depending on a country's policy. It is achieved by employing sophisticated, flexible multi-signature blockchain address generation based on the home university and dynamically generated student identifiers. The system itself is expected to further process, manage, and control ECTX tokens in a Peer-to-Peer (P2P) manner. The tokens could be ECTS received by students for courses taken. In this case, universities will act as network partners. Interestingly, the designed schema may face a (multi-)single-point-of-failure attack since taking over one university's key generator may create a flood of newly-produced wallets since students are not involved in their private/public keys production (the university delivers those).

Nonetheless, DLT could be utilized in conjunction with other environments [61]. Here, the TEduChain platform is considered for fundraising in higher education and its' control by students. The users of the platform would be students, fundraisers, and sponsors. The system comprises two different operating environments: a traditional unit managed by a relational database and a blockchain-based DLT.

### 3.3. Supply chain monitoring

Another popular niche for the application of DLT is the food industry with respect to supply chain monitoring [57]. The proposed DLT-based systems allow analyzing the record of transactions and related metadata. It is designed to consider data confidentiality and integrity, i.e., origin, contracts, process steps, environmental changes, microbiological records, and many others. Today, the ability to track the food movement route is legally required for all participants in this chain. International standards for food traceability are established through a joint program of Food and Agriculture Organization (FAO) and World Health Organization (WHO), and the principles of food traceability are outlined in CAC/GL 60-2006 [34].

From an agricultural perspective, challenges in the supply chain include disconnected stakeholders, limited financing resources, lack of transparency, costly intermediaries, and more. DLT can be employed to trace and track the farming, food processing, and production, distribution, and retail process and provide an unaltered record of food provenance. The IBM Food Trust initiative started with its collaboration with Walmart and has grown into a global consortium that includes big-name companies such as Dole, Driscoll's, Kroger, Nestle, Tyson, and Unilever. The improved data traceability provided by the IBM platform reduced the time it took to trace a mango from the store back to its source from 7 days to 2.2 seconds [29]. That reduction in time enables companies to identify contaminated supply chains and recall affected products before consuming and cause illness.

As an extension of Amazon's web services, the e-commerce giant offers blockchain tools for companies that do not want to create their own. In Australia, Nestle used the Amazon blockchain product to help launch its new coffee brand, Chain of Origin. The consumers can peer into the coffee supply chain by scanning the QR code and checking where those were planted. Other Amazon blockchain customers include Sony Music Japan, BMW, Accenture, and South Korean brewery Jinju Beer [32].

Biometric Blockchain (BBC) includes individuals' biometric characteristics to uniquely identify users of the system, which can satisfy the growing needs for the logistics of food products [73]. Generally, it is essential after the recent incident with mislabeled food products, which led to the death of a passenger in an airplane [6]. The advantages of using the BBC in food logistics are inevitable: the system aims not only to determine whether the data or labels are genuine but also to indicate the responsible party in case of an accident clearly.

### 3.4. Intellectual property

The next DLT application sector is related to licensing [64]. The authors consider modern blockchain-based applications that support the licensing and distribution of intellectual property. The paper compares both non-technical and technical application criteria. Non-technical criteria are used to evaluate the application functionality range, while technical criteria aim to study the technology used to implement the applications. Finally, eight different platforms were analyzed and classified according to selected criteria.

Authors of [8] analyze Technical Protection Measures, Rights Management Information (RMI), and Digital Rights Management (DRM) while developing the blockchain architecture. Besides, the blockchain-related copyright aspects are highlighted, taking into consideration the specifics of private orders in terms of copyright are examined. Finally, an interface for the DRM legal protection is developed.

The work [76] examines the use of the blockchain to create limited editions of digital art with a particular focus on the business models of two companies: Monograph and Ascribe. For some, the development of blockchain technologies and smart contracts suggests an opportunity for artists to protect their work from misuse and expropriation. For others, it indicates the possibility of more robust forms of digital rights management going forward, which may negatively impact digital culture. However, this article argues that the aim of limited editions on the blockchain is usually not to institute more substantial restrictions over the use or a new form of digital rights management but rather to create new kinds of tradable digital assets. In turn, this trend implies a different operation of intellectual property rights concerning digital culture, one where alienation rather than exclusion is significant, and a separate operation of scarcity concerning digital cultural goods, where their free circulation is not necessarily antithetical to profit.

### 3.5. Financial sector

In 2018, an unprecedented shift towards the potential assimilation of DLT infrastructure and the quasi-recognition of cryptocurrencies took place as a new asset class by wealth managers and investors. Many reputable financial intermediaries, including Fidelity Investments, Ameritrade, JPMorgan Chase, and the Intercontinental Exchange, have decided not to remain indifferent to the 21st-century DLT revolution and its consequences for the entire economy [50].

For example, partnering with blockchain leader Guardtime and multiple industry participants, Ernst & Young Global Limited created a blockchain program that connects clients, brokers, insurers, and third parties to distributed common ledgers. These capture data about identities, risks, and exposures and integrate this information with insurance contracts. This program is the first to apply blockchain's transparency, security, and standardization to marine insurance [31].

The work [50] outlines that DLT affects the traditional financial industry and identifies several possible ways for transforming financial services with respect to the DLT ecosystem. The adoption of DLT is expected to take place in three main directions, firstly, through servicing the existing and potential client base both at the retail and institutional levels, secondly, through the improvement of internal and intra-industry processes that remain slow, expensive, and error-prone, and, finally, by tokenizing both liquid and illiquid assets, creating new financial products, and expanding the market. In general, the above changes will open up new opportunities for creating wealth in the financial industry.

The authors of [26] consider the use of DLT to maintain the infrastructure of the securities market, which promises to solve serious challenges of fragmentation and violation of property rights, which also impede market transparency.

At the same time, at least 40 central banks worldwide are currently, or soon will be, researching and experimenting with Central Bank Digital Currency (CBDC) [41]. CBDC, as a commonly proposed application of blockchain and DLT, has attracted much interest within the central banking community for its potential to address long-standing challenges such as financial inclusion, payment efficiency, and both payment system operational and cyber resilience.

Recently, DP Morgan launched its blockchain-based product "Interbank Information Network", which speeds up cross-border payments between banks by using a shared ledger to resolve delays that arise when, for example, one bank thinks a transfer might violate an international sanction [74].

The subcategories for the classification of the use cases in the finance sector are listed in Table 1 below. Tapscott [60] initially inspired the categories.

**Table 1.** Financial sector DLT applications.

| **Subcategories** | **Application of DLT** |
|---|---|
| ID verification (KYC/AML) | DLTs can provide a trusted way to do customer verification to satisfy Know Your Customer (KYC) and Anti-Money Laundering (AML) obligations, e.g., through past immutable data in the DLT. |
| Tokenization and stable coins | The digitization of regulated financial products and services such as security/asset tokens and utility tokens and create new ones, e.g., cryptocurrency/payment tokens through tokenization. |
| Financial management (accounting and auditing) | Smart contracts can automate some accounting processes. Auditing costs can be reduced through cheaper verification of transactions in DLT [17]. |
| Reduction in the risk of fraud | Real-time data is decentralized, and this can increase the trust of the shared information, e.g., management of cash or financial controls, data of maritime industry for insurance purposes, etc. |
| Funding | DLT creates new revenue opportunities such as new funding models and new types of markets such as equity crowdfunding, secondary market, or new kinds of exchanges. |
| Investments | Tokenised assets can support the transformation of the regular investments model and promote accessibility to new asset investments. |
| Regulatory compliance and audit | DLTs can provide accurate and tamper-proof financial, audit, and regulatory reports, improving speed and quality. |
| Clearing and settlement | Automation and improvement of the centralized clearing and settlement processes using DLT can increase efficiency and reduce costs, time, and agents involved. |
| Payments and P2P transactions | DLTs can bring new models and arrangements to make payments and transfers faster with lower costs and fewer/no intermediaries. e.g., remodeling correspondent banking, cross-border payments, etc. |
| New product models | New Peer-to-Peer insurance models can be secured with DLT. |

### 3.6. Energy Supply

In 2019, green renewable energy sources, i.e., biomass, geothermal, hydropower, solar, wind, accounted for 18.49 % of net domestic electrical generation in US [9]. Existing systems can automatically adjust energy absorption, intelligently responding to external on-demand signals from the network. In this case, DLT can be used to transmit real-time data between multiple network participants for more efficient use of resources. The proposed system is based on two key concepts: Transitive Energy Management and P2P communication via DLT. The work [66] provides an assessment of the DLT potential for the energy transition in local markets. The authors propose a new management infrastructure based on DLT in addition to a novel consensus protocol avoiding additional energy costs.

Authors of [14] also analyze various concepts and technologies for the DLT-based energy transition. Given that traditional centralized energy systems are no longer viable, DLT-based P2P transactional controllers in local energy markets represent the most likely evolutionary step for Smart Grids, as confirmed by various pilot projects. The authors have developed and implemented the infrastructure of transactional management based on blockchain and smart contracts.

DLT shows increasing promise for securing Supervisory Control and Data Acquisition (SCADA) systems in traditional energy grids while enabling distributed energy generators such as rooftop solar panels and electric-vehicle charging stations to access cheaper P2P energy transfers [3].

### 3.7. Internet of Things

The most broadly developing niche for the DLT application is the IoT. Many projects focus on this combination to solve the Smart City tasks, decentralized applications, cryptocurrency, spectrum sharing, user incentivization, etc. [4] examines the interaction of the IoT and DLT technologies. It focuses on new and broader technical issues related to the security of solutions based on DLT specifically designed for IoT applications. Authors of [24] also analyze how the IoT and DLT interact in terms of connectivity aspects, introducing DLT-based distributed trust network architecture. Finally, they propose a new classification to simplify the DLT synchronization in classic communication networks. The study showed that wireless systems might become a severe challenge for the synchronization protocols' solid functionality.

DLTs based on DAG could also be utilized in several IoT scenarios [21]. This paper analyzes a commonly discussed attack scenario known as a parasite chain attack for the IOTA Foundation's DAG-based ledger. DLT should serve as an invariable and irreversible record of transactions. However, the DAG structure is a more complex mathematical object than its counterparts in the blockchain, namely, it allows branching of the hash tree.

More and more often, IoT comes hand in hand with Artificial Intelligence (AI). The question of the ability to make AI operation safe for humans in the context of distributed systems is discussed in [15]. This study proposes a number of necessary components to enable various AI operation scenarios without harm to people. DLT is an integral part of this proposal, e.g., smart contracts are essential to solve the problem of AI development, which may happen too quickly for prompt human intervention.

The Web of Things (WoT) paradigm is another segment of the IoT concept to overcome the barriers between heterogeneous network environments. WoT aims at solving the compatibility issue by establishing interoperability at the application level. Work [49] expands WoT's vision of decentralized Smart Grids to create a seamless, autonomous, and interoperable environment of technically and economically interconnected systems presented on HEILA's integrated distributed energy resource business platform [48]. Specifically, this work proposes a new network management system and demonstrates its architecture in the context of WoT design patterns.

Finally, the limited spectrum becomes one of the drivers for applying underlying Blockchain technology to incentivize mobile users and operators to share underused licensed spectrum [58] and/or their computational resources to other nodes in need [78]. Those concepts are expected to find their niche on the Edge and Fog paradigms.

To sum up this section, we overview the leading sectors and related existing solutions in Table 2.

## 4. Main integration challenges

Any technological revolution brings the problems of adapting already formed systems to new processes. Based on the critical review, the primary identified issues of using and implementing DLT are system scalability, DLT design aspects, trust management, identity, security, and data management. Let us consider in more detail each of these challenges.

Scalability issues can create bottlenecks in throughput and processing speed, affected by the consensus mechanism, a number of nodes, and network performance. Many applications must be able to process transactions at a certain rate, and the ability to provide such performance remains a massive obstacle to adoption [1]. Over the past decade, many types of distributed services have become increasingly widespread. This trend is primarily due to the number of users accessing such applications, which are not necessarily humans but preferably various autonomous nodes. Accordingly, such distributed systems require a high level of scalability. While scalability of algorithms has always been a focus for research for a long time, even a carefully designed system is often limited in practice when scaling to such large scale applications, often requiring the developing company to optimize the existing software for higher scalability, despite careful previous design [11].

Since the blockchain's advent, we have seen many kaleidoscopic applications based on the DLT, including applications for financial services, healthcare, or the Internet of Things. In addition to scalability, the DLT design also plays an essential role in running viable applications on DLT. For each sector, different approaches to system design can be applied. Each application has specific DLT performance requirements, e.g., high throughput, scalability, etc. However, an important issue is to find a balance between DLT systems and the prevention of high load [38].

At the same time, end-user smart devices have great potential to be available to external entities as a service for various applications or processes. Along with these, the question of security and, in particular, trust between devices arises [65]. Considering the actual use of DLT and a set of use cases, the following subcategories were defined, which are further described in the following subclauses: identity management, security, data management, management, and Decentralized Autonomous Organizations (DAOs) as well as general crypto infrastructure [1]. DAOs, in a broad sense, are digital entities that manage assets and operate autonomously in a decentralized system and rely on individuals tasked to perform certain functions that the automaton itself cannot. While a comprehensive DLT-based digital identity solution can focus on three essential tasks: security, privacy, and portability. DLT technology can offer a way to solve this problem with or without a reliable central authority. In particular, individuals and legal entities can store and authenticate their identity in DLT, giving them greater control over who has their personal information and how they get access to it [28]. Security management identifies an organization's assets (including people, buildings, cars, systems, and information assets), followed by developing, documentation, and implementing policies and procedures to protect these assets. The organization uses security management procedures such as

**Table 2.** Main challenges and potential solutions.

| Challenges | SGM. | REF. | Brief description | Example | Potential solutions |
|---|---|---|---|---|---|
| Lack of an ability to determine data ownership | H, IR, GA | [46], [55] | A challenge is the inability to determine which data belongs to whom in real-time reliably. It emanates from the fact that healthcare facilities have numerous users who own multiple devices, thereby creating an N x M data source heterogeneity and complexities for the streaming process. | Petri Net | An enhanced Petri Nets service model aids with a transparent data trace route generation, tracking, and the possible detection of medical data compromises. |
| Lack of a unified system for patients' data storage | H, DA | [5], [23], [77] | Currently used cloud storage facilities for clinic networks but does not provide access to the healthcare system as a whole. In addition, the patient cannot track his/her personal data access rights. | DAG, IOTA, Tangle, MAM, Merkle tree, Solidity, Ethereum, smart contracts | A blockchain-powered feature that allows patients to securely access and shares their medical data. |
| The need for high confidentiality | H, GA, IR | [53], [27] | | | System with entries about treatment offers, participants who submitted their data or rejected the offer |
| Lack of the unified and international competency system | E | [54] | Employers and educational institutions cannot receive complete information about the competencies, place of study, and educational opportunities of applicants. | Solidity, Ethereum, blockchain | Decentralized Higher Education Lending System, Certification System, Register of professional competencies of the population |
| Lack of a unified certification system | E, DA, GA | [70] | | | |
| Lack of manageable sponsorship for students | E | [61] | | | |
| Lack of active supply tracking ability | SC, DA | [57] | Lack of a unified system for tracking products, their origin, and movement | Blockchain, BBC | Tracking and Identification Systems |
| Lack of supply chain information immutability | SC, DA | [73] | At the moment, there is no way to determine who is responsible for incorrect labeling | | |
| Inability to license digital assets | SC | [64], [8] | Licensing and ongoing tracking of digital assets that can be easily copied | Blockchain, RMI, DRM | Licensing application and digital protection interface |
| Interaction between IoT and DLT | IoT, DA, GA | [4], [24] | The need for distributed information security enablers | DAG, IOTA, Tangle, MCMC IOTA, blockchain, smart contracts | Special algorithms and protocols |
| Artificial Intelligence Security | IoT, DA | [15] | Artificial Intelligence Development Process Management | | Negative impact analysis and sce- nario correction |
| Trust aspects | IoT, DA | [65], [33] | The need for trust in the systems interaction | GAIA, UML, blockchain with PBFT | DLT-based technical concept |
| User incentivization | IoT, DA | [58], [78] | Attracting new users to share limited resources | Consensus protocols, tokenization | Deep adoption by the operators and big market players |
| Violation of property rights | IR | [26] | Market transparency | All DLT methods, tokenization | Transformation of financial services infrastructure |
| Regulation of loads on electric networks | DA, ES | [66] | Previously, to prevent overload, they used to dump underused electricity | P2P, consensus protocols | Distributed power systems, Development of a transactional management infrastructure, Development of an integrated business platform for distributed energy resources |
| Energy efficiency | DA, ES | [14] | | Smart contracts, HEILA, WoT | |
| Compatibility issue between heterogeneous services | IoT, ES | [48] | Overcoming barriers between network environments | | |
| Scalability | IoT, DA, GA | [11], [38], [79] | An increase in the load on the centralized node occurs with an increase in traffic or the number of users | All DLT methods, DAG, vDLT, Sharding, Sidechain, and cross-chain | Creation of applications, where data exchange is based on the distributed registry principles |
| Identity, security, and data management | IoT, IR, GA | [28], [45] | The identification of an organization's assets (including people, buildings, cars, systems, and information assets) | | |
| DLT design in system functionality | GA | [52], [30] | Depending on the chosen design, the system may have certain functions. | All DLT methods, R3 Corda | Comparison of DLT characteristics by isolating them and compiling groups |

H – Healthcare E – Education SC – Supply chains IR – Intellectual rights
F – Finance ES – Energy Supply GA – General industries DA – Distributed architectures

asset and information classification, threat assessment, risk assessment, and risk analysis to identify threats, asset categories, and assess system vulnerabilities so that they can be effectively controlled [45].

The number of challenges related to DLT utilization is indeed vast. The remaining of this section attempts to highlight the most significant ones in more detail.

### 4.1. System scalability

The study [11] examines the practical consequences of discovering services in systems with a large number of them. Example application areas for this type of system are as follows: Increased automation in homes ("smart home") and urban scenarios ("smart cities") result in large sets of smart components dealing with automation aspects. The study revealed that services could appear and disappear dynamically, negatively affecting the system's general condition.

One of the solutions to the scalability problem is proposed in [38]. Developers highlight the need for a compromise between DLT non-functional properties (e.g., availability and consistency), so following one feature's requirements may hamper the others. Thus, if one DLT architecture can be ideally suited for a specific use case, its application for other scenarios can be detrimental, which stimulates the appearance of various DLT constructs (for example, Ethereum, IOTA, or Tezos). The authors have identified and characterized existing inter-blockchain integration features (from the English Cross-Chain Technology (CCT)). Then, highlighted characteristics systematized, making it more comprehensive for future comparisons. CCT can potentially extend the functionality of DLT design-based applications (such as Hyperledger Fabric), allowing payments to be made, for example, through Ethereum.

Authors of [36] analyzed the problematics of compromise between DLT characteristics from a universal DLT creating perspective. This paper presents a comprehensive set of 49 DLT characteristics synthesized from the DLT literature that were considered relevant for consideration in viable DLT applications. Besides, an in-depth analysis of the dependencies and tradeoffs between DLT characteristics was performed. Finally, the authors identified and combined 26 compromises in 6 archetypes.

In work [79], the authors describe the blockchain performance problem, mainly paying attention to scalability, and then classify the existing mainstream solutions (Sharding, Sidechain, and cross-chain) into several representative layers.

The use of DLT can also be an effective way to solve the problems of highly loaded systems. For example, the government is already facing issues handling the data generated by its' internal subdivisions [71] while moving to dynamic and distributed systems may maintain a register to store information about enterprises, including their identification number and name. However, a centralized registry-supporting service is the one point of failure for the entire system. Work [69] presents an online tool for generating and deploying registries based on smart contracts with access by Representational State Transfer (REST)-ful Application Programming Interface (API).

Another way to address the scalability issue is to virtualize system elements [75]. In particular, the authors propose a virtualization layer for DLT (vDLT), which abstracts the primary resources, such as, for example, hardware, computing, storage, network, etc. By providing a logical layer of resources, vDLT can significantly improve performance, facilitate system changes, and simplify the management and configuration of DLT. This paper also describes several vDLT options, including DAG-based vDLTs and blockchain-based vDLTs, side-channel mechanisms in vDLTs, and separation of control from traffic.

### 4.2. DLT design aspects

Authors of [52] suggest using an architecture based on the proprietary blockchain of the R3 Corda solution. It was designed with a different network architecture compared to existing blockchain systems. Here, the node can operate on the user's personal mobile device. It allows users to store and manage their data directly and exchange data with authorized network participants. According to the authors, the main challenge in the DLT design is the need for structural comparison of designs.

The article [30] outlines DLT characteristics that are selected according to an in-depth comparison of DLT elements. In addition, a benchmarking process is proposed to structure of the DLT projects according to the application requirements.

Despite the lack of practical examples of the comparative characteristics of DLT, work [37] states that the DLT design must be tailored to specific contextual requirements. A successful DLT configuration requires a deep understanding of DLT features and their interdependencies. This study examines 37 DLT characteristics divided into six archetypes (maximum utilization, maximum development flexibility, maximum productivity, maximum anonymity, maximum security, maximum institutionalization), aiming to define the appropriate way of selection.

### 4.3. Trust management

DLT and IoT always come along with the concept of trust management. The authors of [65] propose a fully decentralized architecture of the Machine-to-Machine (M2M) communication system, where the services can be quickly and flexibly adapted to the specific application requirements. Service delivery's decentralized nature eliminates a single point of failure and improves operational efficiency by intellectually allocating the resources among participants.

Work [33] also examines the use of blockchain technology as a tool for trust management. The authors propose applying club governance to the technical design and development of a number of DLT systems, including cryptocurrencies and corporate applications. It is expected to lead to the emergence of cyber-physical systems. Due to the use of stand-alone systems, new problems arise, associated, on the one hand, with the need for consistency, flexibility, and interoperability, as well as to the reliability of the systems interoperation.

Authors of [42] propose a technical concept for new production systems based on DLT. The proposed system is based on the Gaia method. The Gaia is an agent-based development method closely related to object-oriented development methods. Gaia is based on presenting a multi-agent system as a computing system consisting of nodes with different roles. It focuses on the safety and reliability of cyber-physical environments. The authors recommend a blockchain structure with a coordination mechanism based on the Byzantine generals' task as a basis for their DLT system.

### 4.4. Identity, security and data management

The emergence of DLT has given rise to new approaches to identity management aiming to upend dominant approaches to providing and consuming digital identities. These new approaches to Identity Management (IdM) propose to enhance decentralization, transparency, and user control in transactions that involve identity information. This paper introduces the emerging landscape of DLT-based IdM and evaluates three representative proposals – uPort, ShoCard, and Sovrin – using the analytic lens of a seminal framework that characterizes the nature of successful IdM schemes [28].

In [45], a cryptographic membership authentication scheme, i.e., authenticating graph data. was proposed to support Blockchain-based Identity Management Systems (BIMS). The system is designed to bind a digital identity object to its real-world entity. Specifically introduced a new Transitively Closed Undirected Graph Authentication (TCUGA) scheme, which only needs to use node signatures, e.g., certificates for identifying nodes. The trapdoor hash function used in the scheme allows the signer to update the certificates without re-signing the nodes efficiently. This scheme is efficient even though the graph dynamically adds or deletes vertices and edges.

DLT can be used to create new tools to realize governance for a decentralized global public utility for self-sovereign identity on the Internet, for which a new term has been put forward as DAOs. A DAO is similar to a regular corporation in that it is a separate entity and has its bank account (here it is cryptocurrency wallet) and ID number (the contact address). The main difference is that a DAO is autonomous. In contrast to regular corporations, a DAO is managed by itself (its code) rather than by humans (in the form of executive management, i.e., the CEO). The benefit here is that it is a public offering and open for everyone so that it gives equal rights to all token holders, brings in more liquidity, and makes it easier to buy and sell stocks. DAOs provide the organization a high level of transparency, which means less opportunity for corruption and less administrative costs [19].

Thus, the use of the DLT allows not only to improve the processes in the sectors of health care, education, finance, and others presented above, but also allows to solve problems that arise as in modern systems when they are scaled and developed, but also when DLT itself is applied.

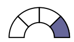
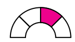
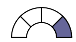
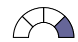
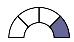
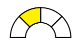
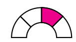
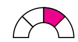
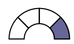
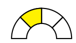
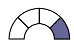
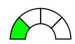
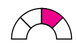
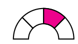
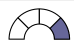
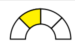
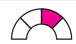
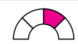
Based on the critical review, we quantitatively analyzed the complexity to overcome the main DLT integration challenge and presented the results in Table 3.

## 5. Discussion

The evolution of centralized systems towards the distributed ones is a complicated step with numerous challenges to be solved. The primary outcomes of this topical review are as follows. First, it surveys the main representative applications of the DLT operation. Next, it outlines the main related challenges and, finally, highlights recommended solutions provided by other researchers in a critical review manner.

The results identify that the major problem for most DLT-based systems at the moment is still scalability. It is mainly due to an increase in autonomous users in contrast to conventional human-oriented system design, which significantly affects the network and overall system load negatively. Still, many researchers foresee the future of DLT systems

**Table 3.** Main DLT integration challenges.

| **Parameter** | **System scalability** | **DLT design aspects** | **Trust management** | **Identity, security and data management** |
|---|---|---|---|---|
| **Migration from centralized system** |  |  |  |  |
| **Development-related costs** |  |  |  |  |
| **Integration-related costs** |  |  |  |  |
| **Maintenance-related costs** |  |  |  |  |
| **Complexity of implementation** |  |  |  |  |
| **Main challenge** | Dynamically appearing services [11] | A lot of characteristics and services [37] | Requests from untrusted sources [42] | Handling various data sources [28] |

Characteristic: – low, – moderate, – high, – very high

as avoidance of the centralized systems' overload and additional protection of the private data. Finally, this review provides a comparative analysis of the challenges that could become a baseline for potential future research activities in the DLT field.

While there have been many diverse efforts in different research directions, we outlined that there are still many open questions, no universal solutions, and significant space for future research and experimentation. We conclude that DLT has great potential to support the economies, while many problems are still to be solved and carefully considered.

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## List of Acronyms

| | |
|---|---|
| DLT | Distributed Ledger Technology |
| AI | Artificial Intelligence |
| AML | Anti-Money Laundering |
| API | Application Programming Interface |
| BBC | Biometric Blockchain |
| BIMS | Blockchain-based Identity Management Systems |
| CBDC | Central Bank Digital Currency |
| CCT | Cross-Chain Technology |
| DAG | Directed Acyclic Graph |
| DAO | Decentralized Autonomous Organization |
| DRM | Digital Rights Management |
| ECTS | European Credit Transfer and Accumulation System |
| EHR | Electronic Health Records |
| FAO | Food and Agriculture Organization |
| GDPR | General Data Protection Regulation |
| ICM | Insurance Content Management |
| ICT | Information and Communication Technologies |
| IdM | Identity Management |
| IoT | Internet of Things |
| KYC | Know Your Customer |
| M2M | Machine-to-Machine |
| MAM | Masked Authenticated Messaging |
| P2P | Peer-to-Peer |
| REST | Representational State Transfer |
| RMI | Rights Management Information |
| SCADA | Supervisory Control and Data Acquisition |
| TCUGA | Transitively Closed Undirected Graph Authentication |
| TPM | Technical Protection Measures |
| vDLT | Virtual Distributed Ledger Technology |
| WHO | World Health Organization |
| WoT | Web of Things |

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