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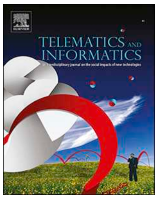

A systematic literature review of blockchain-based applications: Current status, classification and open issues

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ABSTRACT

This work provides a systematic literature review of blockchain-based applications across multiple domains. The aim is to investigate the current state of blockchain technology and its applications and to highlight how specific characteristics of this disruptive technology can revolutionise “business-as-usual” practices. To this end, the theoretical underpinnings of numerous research papers published in high ranked scientific journals during the last decade, along with several reports from grey literature as a means of streamlining our assessment and capturing the continuously expanding blockchain domain, are included in this review. Based on a structured, systematic review and thematic content analysis of the discovered literature, we present a comprehensive classification of blockchain-enabled applications across diverse sectors such as supply chain, business, healthcare, IoT, privacy, and data management, and we establish key themes, trends and emerging areas for research. We also point to the shortcomings identified in the relevant literature, particularly limitations the blockchain technology presents and how these limitations spawn across different sectors and industries. Building on these findings, we identify various research gaps and future exploratory directions that are anticipated to be of significant value both for academics and practitioners.

1. Introduction

Almost a decade ago Satoshi Nakamoto, the unknown person/group behind Bitcoin, described how the blockchain technology, a distributed peer-to-peer linked-structure, could be used to solve the problem of maintaining the order of transactions and to avoid the double-spending problem (Nakamoto, 2008). Bitcoin orders transactions and groups them in a constrained-size structure named *blocks* sharing the same timestamp. The nodes of the network (*miners*) are responsible for linking the blocks to each other in chronological order, with every block containing the hash of the previous block to create a blockchain (Crosby et al., 2016). Thus, the blockchain structure manages to contain a robust and auditable registry of all transactions.

Blockchains introduced serious disruptions to the traditional business processes since the applications and transactions, which needed centralised architectures or trusted third parties to verify them, can now operate in a decentralised way with the same level of certainty. The inherent characteristics of blockchain architecture and design provide properties like transparency, robustness, auditability, and security (Greenspan, 2015a; Christidis and Devetsikiotis, 2016). A blockchain can be considered a distributed database that is organised as a list of ordered blocks, where the committed blocks are immutable. One can see that this is ideal in the banking sector as banks can cooperate under the same blockchain and push their customers’ transactions. This way, beyond transparency,

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blockchain facilitates transactions' auditing. Companies invest in this technology as they see the potential of making their architectures decentralised and minimising their transaction costs as they become inherently safer, transparent and in some cases faster. Therefore, blockchains are not just a hype.

The number of cryptocurrencies illustrates Blockchain's importance, currently exceeding 1900 and growing (CoinMarketCap, 2017). Such a growth pace could soon create interoperability problems due to the heterogeneity of cryptocurrency applications (Tschorsch and Scheuermann, 2016; Haferkorn and Quintana Diaz, 2015). Furthermore, the landscape is rapidly evolving as blockchain is being used in other fields beyond cryptocurrencies, with *Smart Contracts (SCs)* playing a central role. SCs defined in 1994 by Szabo as: *"a computerised transaction protocol that executes the terms of a contract"* (Szabo, 1994), allow us to translate contractual clauses into embeddable code (Szabo, 1997) thus minimizing external participation and risks. So, a SC is an agreement between parties which, although they do not trust each other, the agreed terms are automatically enforced. Therefore, within the blockchain context, SCs are scripts running in a decentralised manner and stored in the blockchain (Christidis and Devetsikiotis, 2016) without relying on any trusted authority. In particular, blockchain-based systems supporting SCs enable more complex processes and interactions so they establish a new paradigm with practically limitless applications.

As a result, Blockchain technology is becoming increasingly relevant (Zhao et al., 2016). Almost 1000 (33%) of C-suite executives declare that they are considering or have already been actively engaged with blockchains (IBM, 2017). Researchers and developers are already aware of the capabilities of the new technology and explore various applications across a vast array of sectors (Christidis and Devetsikiotis, 2016). Based on the intended audience, three generations of blockchains can be distinguished (Zhao et al., 2016): Blockchain 1.0 which includes applications enabling digital cryptocurrency transactions; Blockchain 2.0 which includes SCs and a set of applications extending beyond cryptocurrency transactions; and Blockchain 3.0 which includes applications in areas beyond the previous two versions, such as government, health, science and IoT.

While there are several reviews regarding blockchain technology (Tama et al., 2017; Brandão et al., 2018), we argue that the state-of-the-art of blockchain-enabled applications has received limited attention. Even in Zheng et al. (2016) the applications of blockchains are not covered to their full extent nor applicability. There are indeed some reviews focused on the particular role of blockchain including the development of decentralised and data-intensive applications for the IoT (Conoscenti et al., 2016; Christidis and Devetsikiotis, 2016), and managing big data in a decentralised fashion (Karafiloski and Mishev, 2017a). Other reviews focus on security issues of the blockchain (Khan and Salah, 2017; Li et al., 2017a; Meng et al., 2018) and on its potential to enable trust and decentralisation in service systems (Seebacher et al., 2017) and P2P platforms (Hawlitschek et al., 2018). Some technical aspects of the blockchain design such as its consensus protocol (Sankar et al., 2017), the vulnerabilities of SCs (Atzei et al., 2017) and other technical characteristics like its size and bandwidth, usability, data integrity, and scalability have also been studied in Yli-Huumo et al. (2016) and Koteska et al. (2017). Moreover, there are other surveys such as Bonneau et al. (2015), Tsukerman (2015), Mukhopadhyay et al. (2016), Khalilov and Levi (2018) and Conti et al. (2018) which are more focused on the currency aspect of blockchains and the offered security and privacy.

Evidently, the literature lacks a concrete and systematic review of the current blockchain-enabled state-of-the-art applications, a limitation which was the primary driver for conducting this research. In particular, we try to address this by answering the following three questions: (i) How blockchain-based applications develop over time? (ii) How certain technical limitations of the blockchain architecture affect procedures/processes in particular domains? Which are these limitations? (iii) What is the suitability of blockchain technology across different domains and thematic areas?

Our work contributes towards a thorough understanding of the blockchain features and provides a snapshot of current blockchain-enabled applications across sectors. Based on a content analysis approach, we highlight the growing interest from the academic community and identify three key research streams: (i) classification of the range of blockchain-based applications across a vast array of sectors (ii) suitability of the blockchain technology to create value in these sectors taking into account the various limitations this technology presents, and (iii) guiding researchers by providing a roadmap of promising research avenues, challenges and opportunities for which further research is needed. It is worth noting that this review cannot by any means be considered as exhaustive since blockchain technology is continuously growing at a very fast pace.

The remainder of this work is organized as follows. In Section 2 a brief overview of blockchain architecture is presented. The method followed to conduct the systematic literature review is outlined in Section 3. The descriptive analysis of the retrieved literature is presented in Section 4 while in Section 5 a taxonomy of the blockchain-based applications is presented. Relevant open issues, trends, and further research lines are discussed in Section 6.

2. Blockchain overview

In principle, a blockchain should be considered as a *distributed append-only timestamped data structure*. Blockchains allow us to have a distributed peer-to-peer network where non-trusting members can verifiably interact with each without the need for a trusted authority (Christidis and Devetsikiotis, 2016). To achieve this one can consider blockchain as a set of interconnected mechanisms which provide specific features to the infrastructure, as illustrated in Fig. 1. At the lowest level of this infrastructure, we have the signed *transactions* between peers. These transactions denote an agreement between two participants, which may involve the transfer of physical or digital assets, the completion of a task, etc. At least one participant signs this transaction, and it is disseminated to its neighbours. Typically, any entity which connects to the blockchain is called a *node*. However, nodes that verify all the blockchain rules are called *full nodes*. These nodes group the transactions into *blocks* and they are responsible to determine whether the transactions are valid, and should be kept in the blockchain, and which are not.

A valid transaction means, for instance, that Bob received one bitcoin from Alice. However, Alice may have tried to transfer the

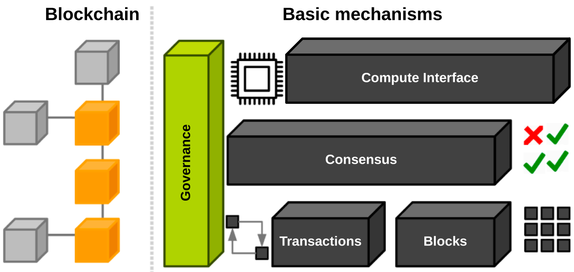

Fig. 1. An overview of blockchain architecture.

same bitcoin, as it is a digital asset, to Carol. Therefore, nodes must reach to an agreement on which transactions must be kept in the blockchain to guarantee that there will be no corrupt branches and divergences (Vukolić, 2015; Christidis and Devetsikiotis, 2016). This is actually the goal of the second *Consensus* layer. Depending on the blockchain type, different Consensus mechanisms exist (Mingxiao et al., 2017). The most well-known is the *Proof-of-work (PoW)*. PoW requires solving a complicated computational process, like finding hashes with specific patterns, e.g. a leading number of zeroes (Antonopoulos, 2014), to ensure authentication and verifiability. Instead of splitting blocks across proportionally to the relative hash rates of miners (i.e., their mining power), *Proof-of-Stake (PoS)* protocols split stake blocks proportionally to the current wealth of miners (Pilkington, 2016). This way, the selection is fairer and prevents the wealthiest participant from dominating the network. Many blockchains, such as Ethereum (Dannen, 2017), are gradually shifting to PoS due to the significant decrease in power consumption and improved scalability. Other consensus approaches include *Byzantine Fault Tolerance (BFT)* (Castro and Liskov, 2002) and its variants (Zheng et al., 2016).

An additional layer, the *Compute Interface*, allows blockchains to offer more functionality. Practically, a blockchain stores a state which consists e.g. of all the transactions that have been made by the users, thereby allowing the calculation of each user's balance. However, for more advanced applications we need to store complex states which are updated dynamically using distributed computing, e.g. states that shift from one to another once specific criteria are met. This requirement has given rise to SCs which use nodes of the blockchain to execute the terms of a contract.

Finally, the *Governance* layer extends the blockchain architecture to cover the human interactions taking place in the physical world. Indeed, although blockchains protocols are well defined, they are also affected by inputs from diverse groups of people who integrate new methods, improve the blockchain protocols and patch the system. While these parts are necessary for the growth of each blockchain, they constitute off-chain social processes. Therefore, blockchain governance deals with how these diverse actors come together to produce, maintain, or change the inputs that make up a blockchain.[1]

Current literature categorises blockchain networks in several ways (Buterin, 2015; Zheng et al., 2016; Eris Industries, 2016; Christidis and Devetsikiotis, 2016; Kravchenko, 2016; Wood, 2016). These categories are formed according to the network's management and permissions as *public*, *private* and *federated*. In public blockchains (*permissionless*) anyone can join as a new user or node miner. Moreover, all participants can perform operations such as transactions or contracts. In private blockchains; which along with the federated belong to the *permissioned* blockchain category, usually, a whitelist of allowed users is defined with particular characteristics and permissions over the network operations. Since the risk of Sybil attacks is almost negligible there (Swanson, 2015), private blockchain networks can avoid expensive PoW mechanisms. Instead, a wider range of consensus protocols based on disincentives could be adopted. A federated blockchain is a hybrid combination of public and private blockchains (Buterin, 2015; Zheng et al., 2016). Although it shares similar scalability and privacy protection level with private blockchain, their main difference is that a set of nodes, named *leader* nodes, is selected instead of a single entity to verify the transaction processes. This enables a partially decentralised design where leader nodes can grant permissions to other users. In this article, we provide a more fine-grained blockchain network classification than current the state-of-the-art (Buterin, 2015; Zheng et al., 2016; Christidis and Devetsikiotis, 2016; Kravchenko, 2016) because, in addition to classical features such as the ownership and management of the information shared in the blockchain, we consider features such as transaction approval time, or security aspects such as anonymity. Table 1 summarises the main characteristics of each blockchain network regarding efficiency, security and consensus mechanisms.

Well-known implementations of public blockchains include Bitcoin, Ethereum, Litecoin and, in general, most cryptocurrencies (Nakamoto, 2008; Haferkorn and Quintana Diaz, 2015). One of their main advantages is the lack of infrastructure costs: the network is self-sustained and capable of maintaining itself, drastically reducing management overheads. In private blockchains, the main applications are database management, auditing and, in general, performance demanding solutions (Zheng et al., 2016). Multichain (Greenspan, 2015b) is an example of an open platform for building and deploying private blockchains. Finally, federated blockchains are mostly used in the banking and industry sectors (R3, 2015). This is the case of the Hyperledger project (Hyperledger Project, 2015) which develops cross-industry permission-based blockchain frameworks. Recently, Ethereum has also provided tools for building federated blockchains. Other projects such as Cardano (2018) are rather ambitious trying to provide more functionality. For more on blockchain categorisation, the interested reader may refer to Walport (2016) and Swanson (2015).

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[1] https://www.oii.ox.ac.uk/blog/understanding-public-blockchain-governance/.

Table 1
Classification and main characteristics of blockchain networks.

Property	Public	Private	Federated
Consensus Mechanism	• Costly PoW • All miners	• Light PoW • Centralised organisation	• Light PoW • Leader node set
Identity Anonymity	• (Pseudo) Anonymous • Malicious?	• Identified users • Trusted	• Identified users • Trusted
Protocol Efficiency & Consumption	• Low efficiency • High energy	• High efficiency • Low energy	• High efficiency • Low energy
Immutability	• Almost impossible	• Collusion attacks	• Collusion attacks
Ownership & Management	• Public • Permissionless	• Centralised • Permissioned whitelist	• Semi-Centralised • Permissioned nodes
Transaction Approval	• Order of minutes	• Order of milliseconds	• Order of milliseconds

3. Research methodology

To provide a transparent, reproducible and scientific literature review of blockchain-based applications, the process suggested by Briner and Denyer (2012) as well as some features of the PRISMA statement (Moher et al., 2009) have been adopted. The overall methodological approach includes the following steps:

1. Identify the need for the review, prepare a proposal for the review, and develop the review protocol.
2. Identify the research, select the studies, assess the quality, take notes and extract data, synthesise the data.
3. Report the results of the review.

3.1. Locating studies

To address our primary research question, a systematic literature search was carried out during January 2018 without timeframe restrictions and the results were subsequently updated during April 2018. Scopus was used as the main scientific database in which the term "*blockchain*" was searched in all articles' titles. Additional searches using the referenced works of relevant articles were also conducted (snowball effect). Relevant "grey literature", including unpublished research commissioned by governments or private/public institutions was also identified through electronic searches. To identify the published grey literature, we evaluated the first 200 hits from Google. Alternate terms for "blockchain" and "application" were used during the search. The hand-search reference list in several reports resulted in additional grey literature, particularly research and committee reports or policy briefs from both private and public sector institutions/organizations. A flowchart of the strategy implemented is presented in Fig. 2. In addition, several refinement features of Scopus were extensively used (multiple refinements of results following the context of specific articles, related documents search, etc.). When the abstract of a particular study was not available, the full article was retrieved and assessed for relevance. All potentially relevant articles were retrieved in full text.

3.2. Study selection and evaluation

The eligibility of the retrieved literature was evaluated independently by the authors based on a set of predefined exclusion and inclusion criteria (see Table 2). Some exclusion criteria were used before introducing the literature in the bibliographic manager (language, subject area and document type restrictions). Initially, the abstracts of all research papers and introductory sections of grey literature were assessed. Articles meeting one of the exclusion criteria were excluded and sorted by reason of exclusion. Afterwards, a full-text review also took place, and some additional articles were excluded from the study documenting the reasons for exclusion. Any discrepancy with respect to the relevance of reviewed articles was resolved through discussion until consensus was reached. Overall, several studies were excluded because they were focused primarily on the technical aspects of blockchain technology and/or blockchain architecture. Articles not fitting the inclusion criteria were set aside and consequently used in the introduction of this article.

3.3. Analysis and synthesis

All articles and reports meeting the inclusion criteria were entered into a qualitative analysis software (MAXQDA11), and data were analysed in emerging themes. The reviewers independently carried out the thematic content analysis. Afterwards, the three clusters of coded segments were compared (rate of consensus was approximately 75%), agreed upon for all articles and summarised in one set of themes and sub-themes.

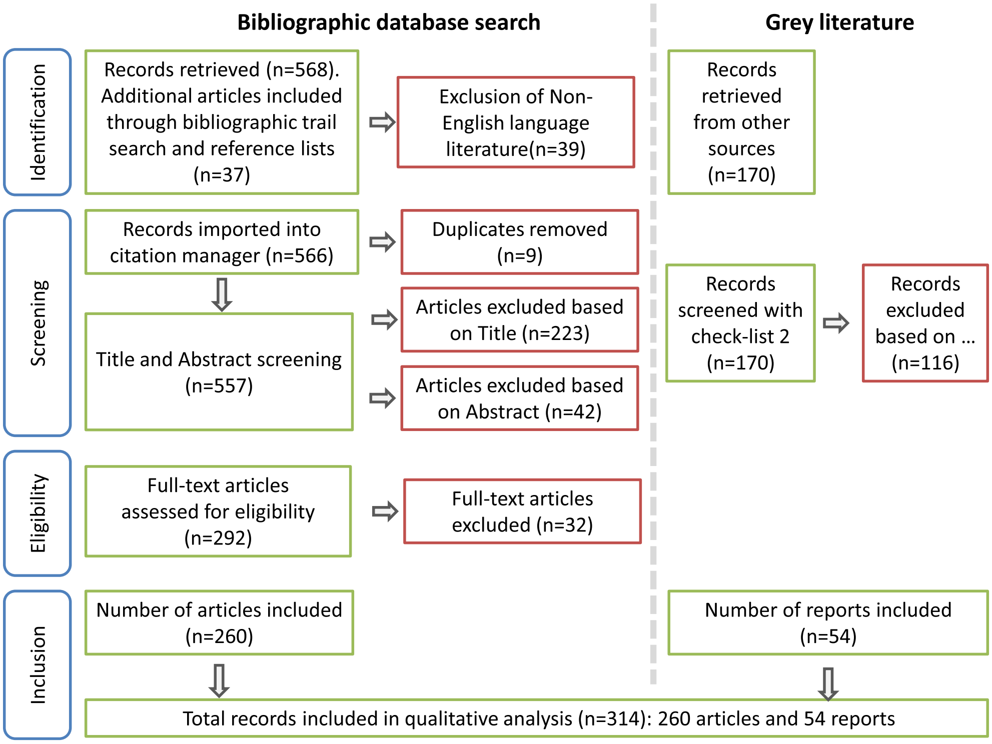

Fig. 2. Flowchart of the search strategy.

Table 2
Inclusion and exclusion criteria.

Selection criteria	Scientific database		Grey literature
Inclusion	Peer-reviewed research articles (including articles in press), conference proceedings papers, book chapters, review papers, short surveys, serials etc. Without time-frame restrictions		English reports Without time-frame restrictions
Exclusion	Prior to importation to bibliographic manager	Non English articles, articles with missing abstracts, notes, editorials	Generic reports related to the blockchain technology without describing specific applications.
	During title screening	Generic articles related to the blockchain technology and/or blockchain architecture	
	During abstract screening	Software-oriented articles related to the blockchain technology	
	During full-text screening	Articles addressing technical aspects of blockchain technology	

4. Descriptive analysis

The study analyzes 260 research papers published between 2014 and April 2018 (for conformity, grey literature has been excluded from the descriptive analysis). The purpose of the descriptive analysis is threefold: (i) it provides interesting insights regarding current research trends in blockchain technology, and its applications (ii) it helps to visualise the multidisciplinary research approaches developed so far in the scientific literature, and (iii) it further supports the classification structure presented in Section 5. For classifying the available literature, the descriptive analysis is based on two key-criteria: (i) distribution of publications over time and thematic area and (ii) distribution of type of publication over time.

A year-wise analysis of the selected papers is illustrated in Fig. 3. It is worth noting that during 2017 the number of publications has sky-rocketed. Until 2016 just a little more of 40 publications existed related to blockchain-enabled applications whereas during 2017 their number reached almost 180. Therefore, research has slowly, yet significantly, picked up in the area of blockchain-enabled applications during the last couple of years. This upward trend highlights the emerging and growing nature of the blockchain technology and the growing academic interest. Even though blockchain technology was first introduced with Bitcoin as its core underlying technology, it took several years to the research community to become fully aware of blockchain's potential and to take advantage of its possible applications. Unsurprisingly, during its first years, blockchain was considered a synonymous to Bitcoin, and

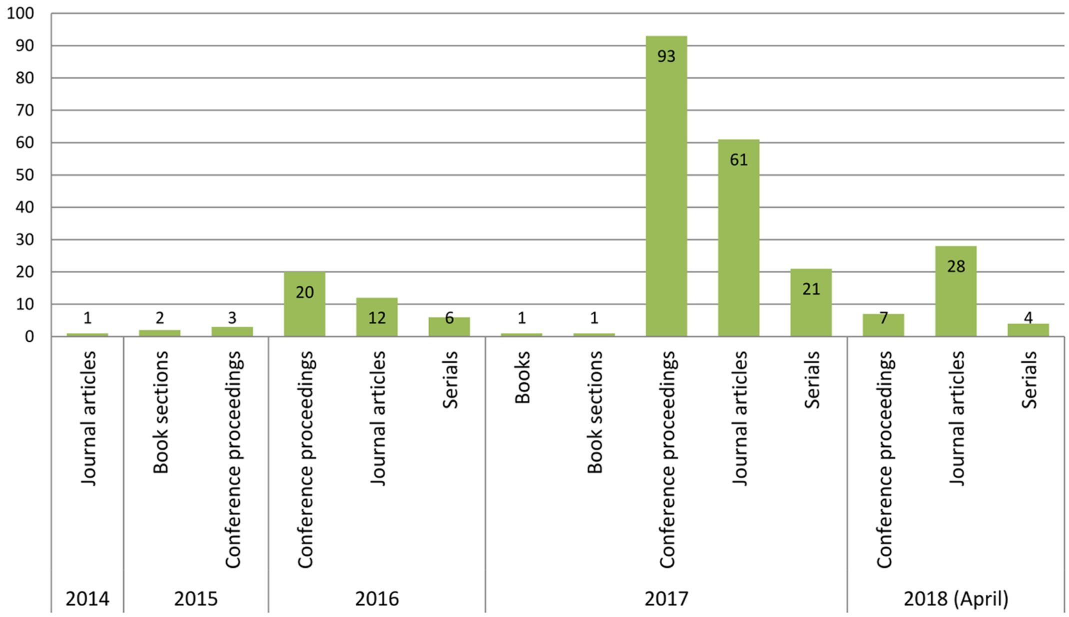

Fig. 3. Year-wise analysis of the selected literature per type of publication.

in principle, researchers were trying to create the infrastructure rather than use this new technology for application purposes. Therefore, journal-oriented content related to blockchain-enabled applications has been notably published from 2016 onwards. From Fig. 3 it is also evident that a large volume of scientific literature has been published in conference proceedings, with a steady upward trend.

The domain-specific distribution of the 260 research items over time may be seen in Fig. 4. Eleven domains of blockchain-based applications have been identified from the analysis. Business-oriented applications represent a large portion of all available applications (58 out of the 260 research items) followed by Governance, IoT, and Data management applications. Health-oriented applications also receive much attention from the scientific community during the last couple of years. Fig. 4 shows that although blockchain seemed to have, at least at its very early stages, a pivotal role to play in finance, the research community is yet to produce a substantial amount of financial-oriented applications. Moreover, the relatively large number of miscellaneous applications (applications that fall outside the categories described above) also highlights the interdisciplinary potential of the blockchain technology.

5. Taxonomy of blockchain-based applications

Most authors classify blockchain applications into financial and non-financial ones (Crosby et al., 2016) since cryptocurrencies represent a considerable percentage of the existing blockchain networks. Others classify them according to blockchain versions (i.e., 1.0, 2.0 and 3.0) (Swan, 2015; Zhao et al., 2016). In this work, we propose an application-oriented classification, similar to the one proposed in Zheng et al. (2016). Our approach, however, differs from other similar works in that it uses a rigorous statistical methodology based on the literature (see Sections 3 and 4), and thus it fits better to current blockchain developments and illustrates with high fidelity the future blockchain trends. Therefore, taking into account the actual and forthcoming heterogeneity of blockchain solutions, we present a more comprehensive and in-depth classification of blockchain-based applications, which is graphically represented in Fig. 5. In the following subsections we provide a sound classification of the available blockchain-enabled applications based on the analysis of the available literature.

5.1. Financial applications

Currently, blockchain technology is applied to a wide variety of financial fields, including business services, settlement of financial assets, prediction markets and economic transactions (Haferkorn and Quintana Diaz, 2015). Blockchain is expected to play an essential role in the sustainable development of the global economy, bringing benefits to consumers, to the current banking system and the whole society in general (Nguyen, 2016).

The global financial system is exploring ways of using blockchain-enabled applications for financial assets, such as securities, fiat money, and derivative contracts (Peters and Panayi, 2016; Fanning and Centers, 2016; Nijeholt et al., 2017; Paech, 2017). For example, blockchain technology offers a massive change to capital markets and a more efficient way for performing operations like securities and derivatives transaction (Van de Velde et al., 2016; Wu and Liang, 2017), digital payments (Papadopoulos et al., 2015; Beck et al., 2016; Min et al., 2016; Yamada et al., 2017; English and Nezhadian, 2017; Lundqvist et al., 2017; Gao et al., 2018), loan

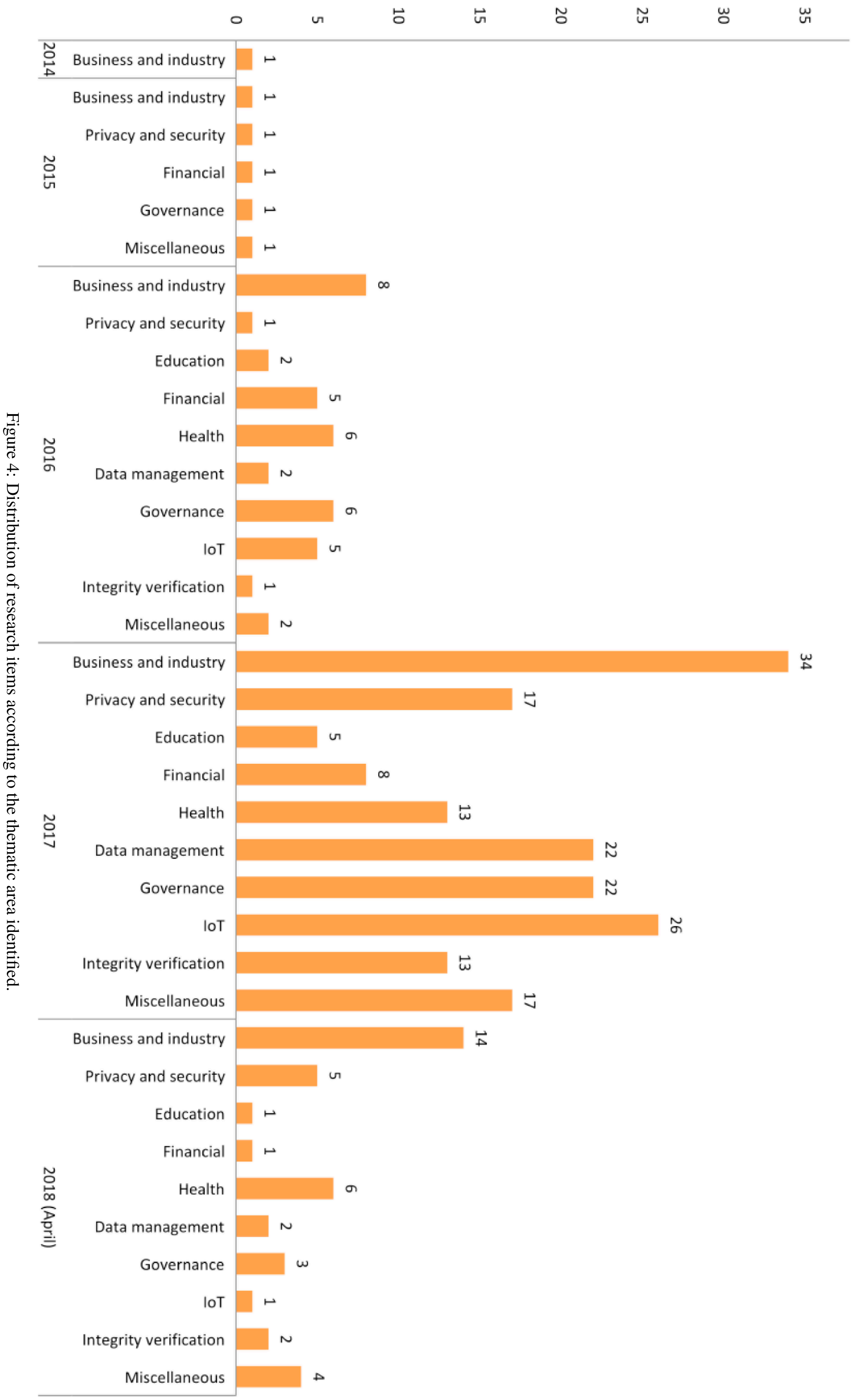

Fig. 4. Distribution of research items according to the thematic area identified.

management schemes (Gazali et al., 2017), general banking services (Cocco et al., 2017), financial auditing (Dai and Vasarhelyi, 2017) or cryptocurrency payment and exchange (i.e., e-wallets) (Cawrey, 2014; Rizzo, 2014). Notably, a set of the world's biggest banks, including Barclays and Goldman Sachs have joined forces with R3 (R3, 2015) to establish an operating blockchain-based framework for the financial market (Crosby et al., 2016). Another example of bank cooperation is the Global Payments Steering

Fig. 5. Mindmap abstraction of the different types of blockchain applications.

Group (GPSG) (Ripple, 2016), whose members include Santander, Bank of America and UniCredit, among others. The cryptocurrency behind GPSG is XRP, created by Ripple (Britto et al., 2012) which implements an interoperable and scalable open-source infrastructure enabling global payments and currency exchanges.

Prediction marketplace systems (PMS), which serve as oracles or information providers, are also an interesting field which may impact businesses and cryptocurrencies. Blockchain-based P2P implementations of PMS can be found in Viacoin (2014), an open source cryptocurrency that features Scrypt Merged mining, a type of PoW that permits much faster transactions than Bitcoin. Augur (2014) is a decentralised PMS that allows users to trade shares before the occurrence of an event under the paradigm of the wisdom of the crowds. Users are rewarded for correctly predicting future real-world events. Bitshares (2014) are digital tokens stored in the blockchain that reference specific assets such as currencies or products. The token holders may earn interest on market products, such as gold, oil, gas and also on currencies. BitShares 2.0 offers a stack of financial services including currency exchange or banking operations in a decentralised blockchain-based fashion. The Nasdaq-Citi platform (Rizzo, 2017) is a platform that enables functionalities such as relationship management and investments for private companies. Ventures (2014) is coined in the blockchain 2.0 platform and uses the Counterparty protocol, which implements financial instruments as SCs, to create a novel stock market. Another example is Coinsetter, a NYC-based Forex trading platform for bitcoins (Coinsetter, 2012). Plasma (Poon and Buterin, 2017) is an SC framework which enables the use of SCs to process financial activity, as well as to construct economic incentives for globally persistent data services.

Other financial-oriented areas may include commercial property and casualty claims processing, syndicated loans contingent convertible bonds, automated compliance, proxy voting, asset rehypothecation, and over-the-counter market (Deloitte, 2016a; F.R. Ltd, 2016; Infosys Consulting, 2016; McWaters et al., 2016). Finally, blockchain adoption by the financial sector will eventually lead to cost savings in areas like central finance reporting, compliance, centralised operations, and business operations (Accenture, 2017a).

5.2. Integrity verification

One of the most emerging blockchain-related fields is integrity verification (Bhowmik and Feng, 2017; Dupont, 2017; Xu et al., 2017a; Jamthagen and Hell, 2016; Zikratov et al., 2017). Blockchain integrity verification applications store information and transactions related to the creation and lifetime of products or services. The possible applications are: (i) provenance and counterfeit, (ii) insurance; and (iii) intellectual property (IP) management.

An integrity verification subset of blockchain applications are those oriented to IP protection (Kishigami et al., 2015; Kitahara et al., 2014; Fujimura et al., 2015; De La Rosa et al., 2017). As stated in Swan (2015), the term digital art refers to IP and not just to online artworks, so blockchain technologies can be considered to cover all such scenarios (O'Dair and Beaven, 2017; McConaghy et al., 2017; Zeilinger, 2018). Mature solutions like Ascribe (Ascribe, 2014) and Mediachain (Labs, 2016) use Bitcoin blockchain to link digital content with their creators. Ascribe uses it to transfer ownership and loan digital assets, while Mediachain tries to store metadata on the blockchain to allow media recovery and querying. Monetisation approaches such as Monegraph (Monegraph Inc., 2014) enable sharing of revenue across the value chain of media distribution for online broadcasts, video clips, image reels, and other licensed or brand-sponsored content, previously verified in the blockchain. Factom (Snow et al., 2015) is another blockchain solution for storage and validation of digital assets. SilentNotary (Silent Notary, 2017) is a blockchain-based service for confirmation of event existence, recorded in a digital format such as communication in messenger, image, video file, and e-mail. Kodakcoin (Kodak et al., 2018), is a novel a payment method used to acquire photo licenses and image rights from a the kodakOne platform, which stores the works of registered photographers. Another example of network media's digital rights management can be found in Xu et al. (2017b). Herbaut and Negru (2017) propose a user-centric approach that helps the necessary reshaping of the content delivery ecosystem.

The work presented in Kim and Laskowski (2016) describes an ontology to store and interpret data in an automated way, in the context of data provenance and integrity. Authors claim that SCs are closely related with ontologies and that such systems can be adapted depending on the topic. Counterfeit solutions such as Everledger (Lomas, 2015) and Blockverify (Blockverify, 2015) use blockchain and SCs to avoid fraud for banks and insurances and to introduce transparency to supply chains, respectively. Further examples on data integrity can be found in Xun et al. (2017), where authors implement the relevant protocols and the following prototype system of a blockchain-based framework for data integrity service and in Jaag et al. (2016), where authors show how blockchains may be used for supply chain management, identity services or device management in a business setting.

Blockchain technology is recently receiving an ever-increasing attention from the insurance industry in a variety of areas, including sales, underwriting, customer onboarding, claims processing, payments, asset transfers, and reinsurance (Cognizant, 2017; Lamberti et al., 2017; KPMG International, 2017). For instance, European-based insurers have recently launched the B3i-a blockchain industry initiative for exploring how blockchain can be used to develop processes and standards for industry-wide usage and to accelerate efficiency gains in the insurance sector (Cognizant, 2017). SCs enabled by blockchain lead to the automation of several processes in the insurance sector, resulting thereby to substantially reduced costs, increased efficiency, and processing speed (Cognizant, 2017). Health insurance-specific potential implications of the blockchain technology may include the establishment of more secure data repositories for medical and wellness information, for triggering alerts to take prescriptions or make regular doctor visits or diagnostic tests, for facilitating continuous underwriting and pricing assessments, for establishing less arbitrary, more up-to-date risk pooling, and for allowing for more personalisation and individualised coverage (Deloitte, 2016b). More examples of blockchain-based insurance applications can be found in (McKinsey Company, 2016; Nath, 2016; Vo et al., 2017).

5.3. Governance

Governments throughout years are entrusted with managing and holding official records of both citizens and/or enterprises. Blockchain-enabled applications might change the way governments at local or state level operate by disintermediating transactions and record keeping (Reijers et al., 2016; Hou, 2017). The accountability, automation, and safety that blockchain offers for handling public records could eventually obstruct corruption and make government services more efficient. In particular, blockchain could serve as a secure communication platform for integrating physical, social, and business infrastructures in a smart city context (Ibba et al., 2017; Jaffe et al., 2017; Biswas and Muthukkumarasamy, 2016; Sharma et al., 2017). Blockchain governance aims at providing the same services that are offered by the state and its corresponding public authorities in a decentralised and efficient way while maintaining the same validity. Examples of such services include registration or legal documents, attestation, identification, marriage contracts, taxes and voting (Swan, 2015).

The World Citizen project (McMillan, 2014) is an example of a decentralised passport service to identify citizens all over the world. Blockchains can also be used to other public services such as marriage registration, patent management, and income taxation systems (Akins et al., 2013). Other projects focus on ideas such as delegative democracy, where delegates (instead of parliamentary representatives) take the voting power (Swan, 2015). Similarly, Holacracy (Robertson, 2015) is a customisable self-management practice for organisations where authority and decision-making are distributed throughout self-organising teams instead of relying on a typical hierarchical organisation setting.

5.3.1. Citizenship and user services

The integration of digital technologies in everyday life requires mechanisms able to determine accurately who the users are (Lee, 2018) and certify their basic attributes like name, address, credit record, as well as other personal characteristics (Lemieux, 2016; Leiding and Norta, 2017; Augot et al., 2017; Buchmann et al., 2017). Therefore, digital identity has become a crucial security measure (Rivera et al., 2017). In Paul Dunphy (2018) the authors analyse three decentralised identity management approaches, namely uPort, ShoCard and Sovrin and assess their benefits and shortcomings. Moreover, according to Roberts (2017), one-sixth of the world's population lack documented proof of their existence. This situation affects immigrants and refugees, since their countries may often refuse to hand over the documents if, for instance, they belong to the opposition. Therefore, blockchain becomes an instrument to reinforce equality and opportunities to worldwide citizens. For more on digital identity and blockchain, one may refer to Rivera et al. (2017).

The emergence of The Internet of Agreements (IoA) (Summit, 2017), which establishes the connection between digital contents (the Internet) and real-world deals, contracts or regulations, enables the next generation of digital commerce. Therefore, blockchain applications that implement SCs to verify multiple types of operations, such as individual properties, are used to state the contractual relationships between the Internet actors, being them companies or individuals (Chen and Zhu, 2017; Ishmaev, 2017; Governatori et al., 2018; Herian, 2017). For instance, Pavilion.io (Duhamel, 2014) is a blockchain-based company that provides an API to enable a verification interface that eliminates the need for e-commerce buyers to place trust in sellers or third-party providers. Mattereum (Mattereum: Smart Contracts, Real Property, 2017) is an IoA project to manage legal rights over physical and IP on the blockchain. Stampery (Stampery, 2015) is a certification company that uses blockchain to create a stamp of emails or documents. This system provides proof-of-existence (PoE), proof-of-ownership (PoO), proof-of-integrity (PoI) as well as proof of receipt by storing the transaction's information in the public ledger. In the Proof of Existence (Proof of Existence, 2017) project, authors use blockchain to ensure the existence of a document and its creation date without revealing its contents. Likewise, Virtual Notary, Bitnotar, Blocksing, btcluck, and Chronobit use blockchain to certify the contents of documents securely and verifiably (Swan, 2015). Thus, we may use the systems above to store proofs of transactions and operations made between individuals and/or companies. In this regard, the increase in online transactions, such as in e-commerce, have caused an upsurge of disputes. Due to the ubiquitous nature of online disputes, efficient conflict management must be provided, that overcomes cross-border and institutional overheads. The methods and projects mentioned above permit the creation of efficient dispute resolution methods since the information stored in the blockchain can be verified and audited. Other methods and projects that implement functional dispute resolution mechanisms can be found in Koulu (2016) and Swan, 2015.

5.3.2. Public sector

In the case of public services, we consider that virtual notary, PoE, PoO, PoI, reputation and dispute resolution are types of services that can be devoted to citizens without the participation of official institutions. Note that PoE, PoO and PoI are closely related and easily verifiable in a blockchain. Government agencies around the world are looking for opportunities related to the adoption of blockchain technology in the public sector (Deloitte Development LLC, 2017; Chiang et al., 2018), particularly for utilising the secure, distributed, open, and inexpensive database technology to reduce cost and bureaucracy, increase efficiency and for authenticating many types of persistent documents (Ølnes, 2016; Nordrum, 2017; Ølnes and Jansen, 2017; Ølnes et al., 2017). Other blockchain applications in the public sector may include document verification, e-residency approaches (Sullivan and Burger, 2017) the development of more reliable and transparent taxation mechanisms (Pokrovskaia, 2017; Wijaya et al., 2017), the development of more robust regulatory compliance frameworks (Filippi and Hassan, 2016; Gerstl, 2016; Engelenburg et al., 2017) and land management (Pichel, 2016).

5.3.3. Voting

For several years e-voting has been considered a promising and inevitable development which could speed up voting processes, simplify and reduce the cost of elections, and the development of stronger democracies (Boucher, 2016). However, existing electronic voting systems rely on proprietary and centralised design by a single entity, characteristics that harm the trust and confidence voters have to the voting process (Moura and Gomes, 2017). Decentralised voting systems such as BitCongress (Deitz, 2014) and Liquid Democracy (Schiener, 2014) propose frameworks to enforce distributed decision making. Futarchy (Hanson, 2013) is a voting system where participants propose topics and possible strategies to achieve them in a two-step fashion. More concretely, participants support policies depending on whether the prediction/betting markets optimise the general revenue for them (e.g. benefits in case of a private company or GDP in the case of a country). In general, blockchain technology offers an open-source, peer-to-peer, decentralised and independently verifiable network to gain the confidence required by voters and election organisers (Noizat, 2015; Kubjas, 2017; Meter, 2017; Hsiao et al., 2018) while being consistent with domestic legislation (Schulz and Schafer, 2017).

5.4. Internet of things

Around 90% of the data in the world today has been created in the past two years alone (IBM, 2017). Such growth pace will increase due to a) the advent of the Internet of Things (IoT), b) to the population growth (Stats, 2017). While the expansion possibilities of the blockchain and IoT technologies are already vast on their own, the symbiotic relationship of these two fields arises myriad more. For instance, the distributed wireless sensor networks, which despite their drawbacks (Pietro et al., 2014; Lin et al., 2017) are one of the pillars of technological and human evolution, demonstrate that blockchain architecture may enhance IoT by minimising its deficiencies and maximising its potential (Kshetri, 2017; Liao et al., 2017; Buccafurri et al., 2017a; Fabiano, 2017; Özyilmaz and Yurdakul, 2017).

The increasing attention and investments for implementing decentralised IoT platforms (Samaniego and Deters, 2016a; Novo, 2018; Zhang and Wen, 2017) are mainly driven by the blockchain technology and its inherent capabilities (Christidis and Devetsikiotis, 2016). The main idea is to provide secure and auditable data exchange in heterogeneous context-aware scenarios (Casino et al., 2017) with plenty of interconnected smart devices (Crosby et al., 2016). Moreover, operating in an automated and decentralised fashion enables the network's high scalability and efficient management (Sharma et al., 2018; Li and Zhang, 2017; Sakakibara et al., 2017).

Blockchain interoperability enables independent and secure real-time payment services, enhancing traditional commerce, e-commerce or public and private transportation systems (Christidis and Devetsikiotis, 2016). There are several examples of applications that agglomerate these characteristics such as the Filecoin (Benet, 2014), which is a memory storage provider, or the EtherAPIs (EtherAPIs, 2016), which enables API calls' monetisation. In the future, IoT devices could be directly linked with their cryptocurrency-based bank account (Christidis and Devetsikiotis, 2016) so that microtransactions (Pass et al., 2015) could be performed in exchange for services (Huckle et al., 2016; Hwang et al., 2017), while similar approaches may also be applied to the smart-grid domain for allowing the energy sale (Rutkin, 2016; Li et al., 2017b). In the case of provenance or supply chains, distributed networks of RFID sensors enable the automated processing of products in multiple contexts, such as in food supply chains, transportation services or inventory management (Liu et al., 2017; Shafagh et al., 2017). In these contexts, the information monitored by the devices could be stored in the form of SCs or transactions into the blockchain. An example of a P2P distributed IoT system can be found in (Foundations for the Next Economic Revolution, 2016). The implementation of blockchain-based IoT solutions could solve several issues, such as the high maintenance cost of centralised approaches (Christidis and Devetsikiotis, 2016; Botta et al., 2016). Moreover, a decentralised and secure P2P model could increase the security of IoT and wireless sensor networks (Pietro et al., 2014; Daza et al., 2017; Ouaddah et al., 2016; Ouaddah et al., 2017), enabling a higher control of IoT devices for keeping systems up-to-date (Lee and Lee, 2017; Samaniego and Deters, 2016b; Boudguiga et al., 2017; Samaniego et al., 2017; Samaniego and Deters, 2016).

Undoubtedly, there are some issues, such as low computational power and storage capabilities of IoT devices, that may limit the use of Blockchain. In Buccafurri et al. (2017a) the authors propose an alternative way to implement a public ledger overcoming these drawbacks and thus enhancing IoT applications. Other efficient architectures are presented in Dorri et al. (2017a) and Dorri et al. (2017b) where authors propose a secure lightweight blockchain-based architecture for IoT in different application contexts.

There exist other examples of IoT applications, such as the Autonomous Decentralised P2P Telemetry (ADEPT) (IIBM, 2015) system developed by the IBM which uses blockchain to build a distributed network of devices. Filament (Foundations for the Next Economic Revolution, 2016) ensures secure economic exchange among autonomous devices. Moreover, the authors assign a unique identity to each device through a blockhain-based IoT software. In the same line, Huh et al. (Huh et al., 2017) proposes the use of the Ethereum platform to perform secure key management in IoT contexts. For more on the IoT and blockchain, we refer the reader to (Christidis and Devetsikiotis, 2016; Khan and Salah, 2017; Conoscenti et al., 2016; Kravitz and Cooper, 2017).

5.5. *Healthcare management*

Blockchain technology could play a pivotal role in the healthcare industry with several applications in areas like public healthcare management, longitudinal healthcare records, automated health claims adjudication, online patient access, sharing patients' medical data, user-oriented medical research, drug counterfeiting, clinical trial, and precision medicine (Mettler et al., 2016; Peterson et al., 2016; Chamber of digital commerce, 2016; Ahram et al., 2017; Al Omar et al., 2017; Capgemini, 2017; Emrify Inc., 2017; Freed Associates, 2017; Shae et al., 2017; Zhao et al., 2017; Mamoshina, 2018; Mytis-Gkometh et al., 2017; Borioli and Couturier, 2018; Lee and Yang, 2018; Xia et al., 2017a, 2017c; Yue et al., 2016; Patel, 2018; Juneja et al., 2018). In particular, blockchain technology and the use of SCs could solve problems of scientific credibility of findings (missing data, endpoint switching, data dredging, and selective publication) in clinical trials (Nugent et al., 2016) as well as issues of patients' informed consent (Benchoufi and Ravaud, 2017; Benchoufi et al., 2017).

Managing patients' Electronic Healthcare Records (EHRs) is probably the area with the highest potential growth (Liu, 2016; Angraal et al., 2017; Hoy, 2017; Kuo et al., 2017; Baxendale, 2016). An EHR contains a patient's short medical history, as part of her medical record, as well as data, predictions, and information of any kind relating to the conditions and the clinical progress of a patient throughout the course of a treatment. A blockchain system for EHRs could be seen as a protocol through which users may access and maintain their health data that simultaneously guarantees security and privacy (Azaria et al., 2016; Young, 2016; BurstIQ, 2017; Dubovitskaya et al., 2017; Sullivan, 2017; Medicalchain, 2017; Center, 2017; Xia et al., 2017b). The benefits of a blockchain-based system for EHRs are manifold: records are stored in a distributed way (they are public and easily verifiable across non-affiliated provider organisations), there is no centralised owner or hub for a hacker to corrupt or breach, data is updated and always available whereas data from disparate sources is brought together in a single and unified data repository (Grey Healthcare Group, 2017).

5.6. *Privacy and security*

Centralised organisations – both public and private – amass large quantities of personal and sensitive information. Although the GDPR (Parliament, 2016) aims to regulate the processing of this data, there is still a big gap to cover (Politou et al., 2018). Blockchain is considered as an opportunity for enhancing the security aspects of big data (Puthal et al., 2018; Kshetri, 2017; Cohen et al., 2017) and its scalability when combined with other efficient storage systems that implement data mining methods (Bozic et al., 2016). Therefore, privacy and security oriented applications that rely on blockchain technology can be found in the literature (Di Francesco Maesa et al., 2017; Dorri et al., 2017c; Hari and Lakshman, 2016; Lee et al., 2017; Tang et al., 2018; Chanson et al., 2017; Anjum et al., 2017).

Namecoin (Haferkorn and Quintana Diaz, 2015) is an open-source blockchain technology that implements a decentralised version of DNS. The main benefits of a decentralised DNS approach are security, censorship resistance, efficiency, and privacy. Alexandria (The Decentralized Library of Alexandria, 2015) is an open-source blockchain-based project that provides a secure and decentralised library of any kind of media while allowing the freedom of speech. Both systems may be enhanced utilising digital identity services which can confirm an individual's identities (e.g. using pseudonyms), enabling security and anonymity in a standardised verification model (Swan, 2015; Zhang et al., 2017). In Zyskind et al. (2015a) the authors propose a decentralised P2P blockchain-based platform that comprises three types of entities: (i) users, which interact with the applications; (ii) services, which provide such applications and process users' personal data for operational and business-related reasons; and (iii) nodes, entities that receive rewards in exchange for maintaining the blockchain. Since only hash pointers are stored, users have control over their data.

Blockchain technology may also be used to enhance security and reliability in distributed networks through hardware and software solutions (Fan et al., 2018; Cha et al., 2017; Suzuki and Murai, 2017). For instance, SIRIN LABS (Labs, 2014) developed the first blockchain-based smartphone, capable of providing fast, fee-less and secure transactions. BitAv is an antimalware blockchain-based solution (Noyes, 2018) that enhances virus pattern distribution. In Axon (2015), the authors implement a privacy-aware public key infrastructure, which enhances security against a single point of failure or malicious attacks. Liang et al. (2018) propose the use of a distributed blockchain-based protection framework to enhance the security of modern power systems against cyber-attacks. In Xu et al. (2017c), authors recall the use of Docker containers (Docker, 2013) in IoT and their benefits. Rodrigues et al. (2017) propose a novel architecture, which combines blockchain and SC technologies, introducing thereby new opportunities for flexible and efficient DDoS mitigation solutions across multiple domains, with particular regard on insecure portable and stationary devices. Tosh et al. (2017) discuss vulnerabilities in blockchain cloud and its capability to enable data provenance. Blockchain could also be used as a verification protocol for enabling, securing and authenticating spectrum sharing in cognitive radio networks (Kotobi and Bilen, 2017; Raju et al., 2017; Niu et al., 2017).

Transactional privacy is one of the most challenging problems of blockchain technologies. Therefore, several methods have been proposed to improve anonymity of blockchains (Zheng et al., 2016) such as mixing services (Möser et al., 2013) or zero-knowledge proofs. In the case of mixing services, the aim is to provide transactional privacy by transferring funds from N input addresses to M output addresses, so that users avoid always using the same address. Examples implementing such technique are Mixcoin (Bonneau et al., 2014), which is also able to detect dishonest transaction behaviours, and Coinjoin (Maxwell et al., 2013) or CoinShuffle (Ruffing et al., 2014), that uses a third party to shuffle output addresses. In the case of Zerocoin (Miers et al., 2013), transactions and the origin of coins are unlined, while miners use zero-knowledge proofs to validate operations. An improved version with stronger privacy guarantees hides both transaction amounts and the origin of coins (Miers et al., 2013).

5.7. *Business and industrial applications*

Blockchain has the potential to become a significant source of disruptive innovations in business and management through improving, optimising, and automating business processes (Tapscott and Tapscott, 2017; Bogner et al., 2016; Ying et al., 2018). Many e-business models based on IoT and blockchain are emerging. One example can be found in Zhang and Wen (2015) where authors propose a business model in which transactions between devices are performed using SCs on a blockchain-based distributed database. In Hardjono and Smith (2016) the authors propose a privacy-preserving system that uses an IoT network and blockchain to prove provenance manufacturing without the third party authentication.

Blockchain applications appear to offer considerable performance enhancement and commercialisation opportunities (White, 2017; Klems et al., 2017; Kogure et al., 2017), improving credibility in e-commerce and enabling IoT companies to optimise their operations (Xu et al., 2017b; Yoo and Won, 2018) while saving time and cost (IBM Corporation, 2016). Blockchain-based applications could serve as decentralised business process management systems for several enterprises. In such cases, each business process instance may be maintained on the blockchain, and the workflow routing could be performed by SCs, thereby streamlining and automating intra-organisational processes and reducing cost (Weber et al., 2016; López-Pintado et al., 2017; Prybila, 2017; Rimba et al., 2017; Mendling et al., 2018).

5.7.1. *Supply chain management*

Blockchain technology is expected to increase transparency and accountability in supply chain networks, thus enabling more flexible value chains (Ahram et al., 2017; Kshetri, 2017; Kshetri, 2018; O'Leary, 2017). In particular, blockchain-based applications have the potential to generate breakthroughs in three areas in supply chains: visibility, optimisation, and demand (IBM Corporation, 2016). Blockchain can be used in logistics, identifying counterfeit products, decreasing paper load processing, facilitating origin tracking (Hackius and Petersen, 2017; Kennedy et al., 2017; Lee and Pilkington, 2017; Toyoda et al., 2017; Tan et al., 2018) and enabling buyers and sellers to transact directly without manipulation by intermediaries (Subramanian, 2017). Moreover, it has been demonstrated that the usage of blockchain-based applications in supply chain networks can safeguard security (Dorri et al., 2017a), lead to more robust contract management mechanisms between third and fourth party logistics (3PL, 4PL) for combating information asymmetry (Polim et al., 2017), enhance tracking mechanisms and traceability assurance (Apte and Petrovsky, 2016; Tian et al., 2016; Düdder and Ross, 2017; Heber and Groll, 2017; Lu and Xu, 2017; Tian, 2017), provide better information management across the entire supply chain (Infosys Limited, 2017; O'Leary et al., 2017; Turk and Klinc, 2017), food safety (Ahmed and Broek, 2017), enhance IP protection (Herbert and Litchfield, 2015; Holland et al., 2017; Tsai et al., 2017), offer better customer service through advanced data analytics (i.e. encrypted customer data) and novel recommender systems (Frey et al., 2016a; Frey et al., 2016b), improve inventory and performance management across complex supply chains (Madhwal and Panfilov, 2017), and finally, it can improve smart transportation systems (Yuan and Wang, 2016; Lei et al., 2017; Leiding et al., 2016) and offer new decentralised manufacturing architectures (SyncFab, 2018).

5.7.2. Energy sector

The potential applications of blockchain in the energy sector are far-reaching and may have an enormous impact both in terms of processes as well as platforms (Bilal et al., 2014). For example, blockchain may reduce costs and enable new business models and marketplaces, can better manage complexity, data security, and ownership along grids, can engage prosumers in the energy market acting as enabler for the creation of energy communities (Mengelkamp et al., 2018; Wu et al., 2017; Danzi et al., 2017), can enhance the transparency and trust of the energy market system, can guarantee accountability while preserving privacy requirements, can enhance direct peer-to-peer trading to support the smooth operation of the power grid, and can better handle demand response and provide a framework for more efficient utility billing processes and transactive energy operations (Deutsche Energie-Agentur GmbH, 2016; Ioannis et al., 2017; PricewaterhouseCoopers and Wirtschaftsprungsgesellschaft, 2017; Energy Web Foundation, 2018; Kyriakarakos and Papadakis, 2018). Blockchain technology may also be used for issuing certificates of origin, particularly for green energy production and renewable energy sources (Castellanos et al., 2017; Tanaka et al., 2017; Hou et al., 2018; Park et al., 2018; Patil et al., 2018), for developing peer-to-peer energy transactions schemes (Cheng et al., 2017; Imbault et al., 2017; Mylrea and Gourisetti, 2017a; Mylrea and Gourisetti, 2017b; Sikorski et al., 2017; Pop et al., 2018) and for establishing energy management schemes for electric vehicles (Kim et al., 2017; Knirsch et al., 2018; Knirsch et al., 2017; Huang et al., 2018). It is also worth mentioning that blockchain is considered an enabler for the decarbonisation of the energy sector facilitating its move towards more decentralised energy sources (World Energy Council and PricewaterhouseCoopers, 2018).

5.8. Education

Blockchain can solve issues of vulnerability, security, and privacy in the case of ubiquitous learning environments (Bdiwi et al., 2017) and can be used for storing educational records related to reputational rewards (Sharples and Domingue, 2016a; Turkanović et al., 2018). Sharples and Domingue (2016b) propose the use of a blockchain-based distributed system for educational record and reputation. Similar reputation systems are shown in Carboni (2015) and Dennis and Owen, 2015. In Devine (2015), teachers add blocks into the blockchain storing the learning achievements of students. Educational certificate management can also be enhanced by blockchain improving data security and trust in digital infrastructures (Xu et al., 2017d), and for credit management (for instance, relevant to the European Credit Transfer and Accumulation System-ECTS) (Turkanović et al., 2018). Moreover, blockchain-based applications could enhance the digital accreditation of personal and academic learning (Grech et al., 2017). Blockchain-enabled school information hubs could also be established for collecting, reporting, and analysing data about school systems for supporting decision-making (Bore et al., 2017). Finally, in the case of scholarly publishing, blockchain can be used either for better handling manuscript submissions and for conducting suitable reviews in a timely fashion (Spearpoint, 2017) or for manuscript verification (Gipp et al., 2017).

5.9. Data management

Data management is one of the most indisputable properties of the blockchain. Implementations and applications based on this technology have not only enhanced data management (Asharaf and Adarsh, 2017) but have also facilitated by default auditability (Sutton and Samavi, 2017; Neisse et al., 2017) since all of their operations are verifiable. In this last blockchain-based applications section we cite relevant literature that aims at efficient, secure and verifiable data management (Zhang, 2016; Jin et al., 2017).

Although cross-organisational management has not yet reached a level that enables full interoperability between parties, several examples of cross-organisational data management can be found in the literature. In Fridgen (2018) the authors, in a joint effort with a German Bank, follow the Design Science Research approach (Hevner and Chatterjee, 2010) to design, implement, and evaluate a blockchain prototype for cross-organisational workflow management. The results are encouraging and demonstrate that Blockchain has the potential to serve as an infrastructure for cross-organisational workflow management. Hawk (Kosba et al., 2016) is a framework for building privacy-preserving SCs that enables privacy-aware intermediate computations to avoid or minimise several types of disclosures, such as transactional privacy. Authors also provide an algorithmic framework to enable coding functions that will be parsed intro private and blockchain compliant protocols.

Blockchain also disrupts the human resource area (Ahmed, 2018; O'Leary et al., 2017; Wang et al., 2017), by enhancing data storage (Wang et al., 2018) and selection processes, e.g. auditable candidate selection and verifiable participants' data.

In the case of secure data distribution and management solutions, García-Barriocanal et al. (2017) propose the use of a decentralised blockchain-based solution for metadata supporting key functions and discuss its implications towards management and sustainability of digital archives. Yang et al. (2018) stress the importance of trust in the big data area and present a credible big data sharing model based on blockchain technology and SC to ensure the safe circulation of data resources. Do and Ng (2017) propose a system that enables secure and distributed client data management using cryptographic primitives as well as a keyword search service. Besides, the data owner can grant search and read permission of their data to third parties. Similarly, Searchain (Jiang et al., 2017) is a blockchain-based keyword search system that enables efficient oblivious search (the user knows the chosen keyword and the corresponding ciphertext, but they are unknown to the data supplier) over an authorised keyword set in the decentralised storage. More examples can be found in Zyskind et al. (2015a) and Azaria et al. (2016) in which systems that enable blockchain-based decentralised sensitive data distribution with PoO are described. Other secure data sharing approaches can be found in Hull (2017), Fukumitsu et al. (2017), Kiyomoto et al. (2017), Hasnain et al. (2017) and Karafiloski and Mishev (2017b). Note that access control and authentication mechanisms may also be used to ensure privacy and security in data distribution (Kalra et al., 2017; Li et al., 2017c).

Cloud-based decentralised and efficient solutions that use blockchain technology can also be found in the literature (Shetty et al., 2017; Gaetani et al., 2017; Liang et al., 2017). Such systems aim at overcoming big data challenges (Karafiloski and Mishev, 2017b; Yue et al., 2017) to enable the analysis of large volumes of transactions (Abdullah et al., 2017; Xu et al., 2018; Chen and Xue, 2017).

5.10. Miscellaneous applications

This subsection refers to research describing blockchain-based applications that fall outside the domains mentioned above. For example, crowd-funding platforms are starting to use blockchain (Bracamonte and Okada, 2017; Buccafurri et al., 2017b; Zhu and Zhou, 2016). Swarm, Lighthouse, and bitFyler are examples of cryptocurrency crowdfunding platforms (Swan, 2015; Li et al., 2017). Blockchain applications may also be found in the humanitarian sector and philanthropy (Mazet, 2017), particularly as a means of fighting poverty (Kewell et al., 2017; Kshetri, 2017; Pilkington et al., 2017; Zhou et al., 2017; Larios-Hernández, 2017; Jayasinghe et al., 2017; Accenture, 2017b; Ko and Verity, 2016). Blockchain can also be used to build intelligent, secure, distributed and autonomous transport systems in smart cities contexts (Marsal-Llacuna, 2017; Sharma et al., 2018; Adam et al., 2017) or to manage event tickets securely (Tackmann, 2017). Blockchain is expected to play a pivotal role in environmental management (Saberi et al., 2018; Khaqqi et al., 2018). For instance, blockchain could be used as a novel "emission link" system within Emission Trading Schemes (Fu et al., 2018). Another interesting application may be found in the context of social media (Fu and Liri, 2016; Sarr et al., 2015; de Soto, 2017). In particular, user-centric blockchain applications could enable end-users to control, trace and claim ownership of every piece of content they share (Chakravorty and Rong, 2017). Of particular interest are some IT-oriented blockchain applications like, for example, edge computing and the establishment of computational resource sharing systems (Hong et al., 2017; Stanciu, 2017), grid computing (Gattermayer and Tvrdik, 2017), cloud computing (Xiang et al., 2017), and the use of blockchain as a software connector (Xu et al., 2016; Teslya and Smirnov, 2018). Finally, blockchain technology may also improve social sharing dynamics (Pazaitis et al., 2017).

6. Open issues and future trends

From the analysis of the selected literature, a series of insights can be derived concerning the limitations of the blockchain technology and its usability across a wide area of domains. As described in Section 5, blockchain is nowadays adopted in many research fields and business areas, providing limitless opportunities for exploration. However, like any other emerging technology, issues and challenges arise. In this section, we discuss certain limitations of the blockchain technology, and we develop several avenues of fruitful areas for further research directions.

6.1. Suitability of blockchain

Companies across different sectors are excited about blockchain technology and its potential to drive their digital transformation while solving real-life problems (Umeh, 2016). Nevertheless, while several IT specialists envisage the usage of blockchain in almost every project, they do not quite understand the fundamental reasons for using it, particularly from a data management perspective. For instance, if no data needs to be ever stored, blockchain will not add any value to already established technical solutions. Similarly, if only one writer in a given system is foreseen, a blockchain will not provide additional guarantees compared to a regular database which would most probably be a more appropriate choice, particularly from a performance perspective (transactions speed) (Greenspan, 2015c). On the other hand, blockchain is suitable when one requires a transaction between trustless sources or a permanent historical record. For instance, if there is a need for multiple mutually mistrusting entities to interact and change the state of a system, then blockchain may be a viable solution (Wüst and Gervais, 2017).

Therefore, before adopting blockchain-enabled solutions one should examine the suitability of the blockchain technology against the use cases requirements (Lo et al., 2017). A limited number of frameworks have been developed in the scientific literature for assessing the suitability of blockchain-enabled applications. For example, in Lo et al. (2017) the authors propose an evaluation framework for blockchain-enabled applications in specific industrial domains like supply chain, EHRs, identity management, and the stock market. In Wüst and Gervais (2017) an analysis is provided related to the properties of different blockchain types (i.e., permissioned and permissionless) and a methodological framework is developed for identifying the suitability of blockchain-enabled applications across several domains.

Databases are by their very nature *mutable* where a predefined set of entities have access and may insert or update data. These entities may have specific roles, but their identities are known. However, there are administrative roles which may completely alter the contents and structure of the hosted information regardless of whether they are centralised or not.

Based on the findings of our research, we highlight the requirements of each sector, see Table 3, and we developed a framework (Table 4) to evaluate the suitability of blockchain-based solutions. More concretely, we evaluate the potential of blockchain against traditional databases in four main domain areas: required trust assumptions, context requirements, performance characteristics and required consensus mechanisms. An intuitive three-level scale (i.e., low, medium and high) is used to measure the relevance of each prerequisite. The framework acts as a comprehensive tool for practitioners aspiring to evaluate whether their systems will be enhanced by blockchain or not. In terms of trustness, blockchain avoids the use of trusted third parties, on which databases rely on, and thus, enhances reliability and verifiability of contents. Blockchain is also suitable when transactions and operations need to be traced (sequential chain of events) or when operations require strong security and privacy (centralised data structures are more vulnerable to malicious attacks than decentralised structures (Zyskind et al., 2015b)). Regarding maintenance, blockchain may provide a

Table 3

Characteristics/requirements that enable/require each family of blockchain applications. Check (✓) denotes that this requirement is mandatory while ∘ denotes that it depends on the case.

	Scalability	Privacy	Interoperability	Audit	Latency	Visibility
Finance	✓	∘	✓	✓	✓	✓
Citizenship Services		✓	✓	✓		
Integrity Verification				✓		✓
Governance	∘	✓	✓	✓		
IoT	✓	✓			✓	
Health	✓	✓	✓	✓		
Privacy & Security		✓		✓		
Business	∘	∘	✓	✓	∘	✓
Education		✓	✓	✓		
Data management	✓		✓	✓	∘	✓

Table 4

Analysis of attributes and prerequisites of blockchain versus traditional databases.

Attributes	Prerequisites & determinants	Architecture Blockchain		
		Permissionless	Permissioned	Database
Trust	Lack of Trusted Third Parties	High	High	Low
	Accountability	High	High	High
	Immutability	High	High	Medium
	Multiple non-trusting writers	High	High	Low
	Peer-to-peer transactions	High	High	Low
Context	Traceability of transactions	High	High	Low
	Verifiability of transactions	High	High	Low
	Data/transaction notarization	High	High	Low
	Data transparency	High	High	Low
	Security	High	High	Low
	Privacy	High	Medium	Low
Performance	Latency and transaction speed	Low	Medium	High
	Maintenance costs	High	High	Low
	Redundancy	High	High	Medium
	Scalability	Low	Medium	High
Consensus	Rules of engagement	High	High	Low
	Need for verifiers	High	High	Low
	Autonomous/dynamic interactions between transactions of different writers	High	High	Low

significant cost reduction since it does not require hosting. Finally, consensus mechanisms implemented in blockchain networks (Nguyen and Kim, 2018) enable multiple writers to modify the database and provide an authoritative transaction log in which all nodes provably agree.

6.2. Latency and scalability

Most cryptocurrencies have a low transactions' rate. For instance, Bitcoin transactions[2] cannot by any chance compare to systems like VISA's credit card processing network that constantly handles up thousands of transactions per second. Undoubtedly, the broad adoption of cryptocurrencies needs to address this latency issue as well (Swan, 2015). Note that each Bitcoin block is processed in approximately 10 min which, along with the associated security checks (e.g. to avoid the double-spent attack in the subsequent transactions), results in each transaction confirmation to last up to several minutes[3]. Therefore, blockchain architectures face serious latency issues which may be proved more significant as they evolve. Private blockchains, on the other hand, although they are indeed far more efficient, they have not reached the required standards.

Data storage optimisation examples may also be found in the literature. In Bruce (2013), authors propose a scheme where old transaction records are removed by the network and a tree-structured database balances all non-empty addresses. Hence, the number of transactions stored by the nodes is decreased, thereby improving the transaction validation step. In Eyal et al. (2016), the authors proposed Bitcoin-Next Generation where the core idea is to decouple a block into two parts: the key block for leader election and

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[2] https://blockchain.info/charts/transactions-persecond.

[3] https://blockchain.info/charts/avg-confirmation-time.

microblock to store transactions. So, miners compete to become a leader, which is the responsible role for microblock generation. Moreover, the authors improved the longest chain strategy to enhance the trade-off between block size and network security.

In IoT networks, a properly configured centralised architecture means higher transaction processing throughput than blockchain solutions, in general. Still, in the case of public networks, this inadequacy is further exacerbated (Vukolić, 2015) since consensus mechanisms in public blockchain structures are costly. To overcome this limitation, the Ethereum community is currently considering sharding[4], an act to partition the blockchain into shards where each shard stores its piece of state and transaction history. This way, nodes process the transactions of specific shards, and the blockchain is divided into smaller ones, drastically increasing the overall performance. All these approaches imply some additional changes in the balance between security, scalability, and decentralisation that blockchains offer by default. Therefore, considerable research effort needs to be undertaken for finding the proper equilibrium.

6.2.1. Sustainability of the blockchain protocol

One of the main drawbacks of blockchain technology, especially affecting public blockchains, is the waste of resources of the mining network. Such concern generates two main questions: (i) how to reduce energy consumption and, (ii) whether to apply the computational power to useful data processing.

Bitcoin mining, which is lead by China (Blockchain hash rate distribution, 2017), consumes more electricity than 159 countries of the world (Digiconomist, 2017). Nevertheless, the real power consumption could be even worse, since there may be cases where users are mining without their knowledge due to malware infections (Malwarebytes, 2017).

As already discussed, several consensus mechanisms and procedures could be adapted to decrease energy waste. Besides the energy consumption problem, current consensus algorithms like PoW or PoS may face the “rich get richer phenomenon” (Zheng et al., 2016). Many efficient consensus mechanisms related to cryptocurrencies and bitcoin have been proposed. In Sompolinsky and Zohar (2013) the authors propose the GHOST chain selection rule, which weights branches according to some parameters, easing the selection task for miners. In Chepurnoy et al. (2016), the authors present an alternative consensus protocol for Bitcoin-like P2P systems where a party receives permissions to generate a block providing non-interactive proofs of storing a subset of the past state snapshots. Therefore, a network using such protocol is safe if nodes prune full blocks, which are not needed for mining. The PeerCensus system (Decker et al., 2016) enables strong consistency in Bitcoin and similar systems. Moreover, Discoin, which acts on top of PeerCensus, decouples the block creation and transaction confirmation operations so that consensus efficiency can be increased. In Kraft (2016), the authors proposed a new consensus method to avoid multiple hash-rate scenarios. This way, the system guarantees stable average block times.

Well-known examples of projects exploiting the benefits of blockchain’s computational resources are SETI@home and Folding@home, which reward participants with Gridcoin and FoldingCoin respectively (Swan, 2015). Another example is Primecoin (King, 2013) where miners are required to find long chains of prime numbers instead of computing hashes. Moreover, big data processing applications, such as genomic sequencing (Swan, 2015) and personalised genomics (Kido et al., 2013) also benefit from blockchain resources.

The use of renewable energy might be proved critical (Potenza, 2017). Projects such as solarcoin (Gogerty and Zitoli, 2011) encourage the use of renewable energy. Another example can be found in Zyskind et al. (2015c) where authors proposed a lightweight blockchain architecture to protect personal data.

6.3. Quantum resilience

At the core of blockchain, we have two cryptographic primitives: hashes and public key encryption which are used for signing transactions. When blockchain was initially designed, quantum computing did not sound very close. However, recent breakthroughs[5] made us radically revise the situation.

In most blockchains, the hash algorithm is SHA-256 which a quantum computer would need 2^{128} operations to crack using Grover’s algorithm. While this makes SHA-256 resistant to quantum attacks, the same does not apply for the public key encryption algorithms that most of them use. The ECDSA algorithm will be broken once a big enough quantum computer is built, rendering almost all blockchains insecure. Currently, there is a significant effort towards evaluating and standardising post-quantum cryptographic primitives[6]. For the case of public key cryptography, the most promising candidates originate from lattice (Micciancio and Regev, 2009) and code-based cryptography (Overbeck and Sendrier, 2009). Apparently, as we are currently designing platforms on blockchains which we aim to keep for years to come, quantum resilience becomes a major issue. Nevertheless, blockchain-based quantum-resilient approaches can be found in the literature. For instance, in Kiktenko et al. (2017) the authors develop a quantum-safe blockchain platform that uses quantum key distribution across an urban fiber network for information-theoretically secure authentication. More recently, Rajan and Visser (2018) presented a method which involves encoding the blockchain into a temporal Greenberger-Horne-Zeilinger state of photons that do not simultaneously coexist. The authors state that their approach can be viewed as a quantum networked time machine.

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[4] https://github.com/ethereum/wiki/wiki/Sharding-FAQ.

[5] https://research.googleblog.com/2018/03/a-preview-of-bristlecone-googles-new.html.

[6] https://csrc.nist.gov/Projects/Post-Quantum-Cryptography.

6.4. Blockchain adoption and interoperability

The number of blockchain-based applications is growing at a fast pace, creating a humongous number of heterogeneous solutions. The wide diversity of implementations and features implies hard interoperability issues, hindering standardisation.

Many companies, especially from the U.S., are colluding to bring a bitcoin exchange-traded fund to the market (Bitcoin ETf Channel, 2018). If the bitcoin market ware to be regulated, users, as well as numerous international funds, would have easy access to invest in bitcoins. However, the uncontrolled growth of cryptocurrencies enables the creation of scenarios where speculative attacks (Rochard, 2014) or malicious currency exchanges may cause a crisis.

Most APIs provided by cryptocurrencies are far from being considered easy to use. Therefore, several authors have proposed their solutions towards more interoperable architectures (Kosba et al., 2016). Efforts like Blockstream try to coordinate transactions between different blockchains (Blockstream, The blockstream company, 2014) by providing software and hardware solutions to companies aiming at new blockchain-based networks. Moreover, the services for purchasing and exchanging cryptocurrencies are realising an emerging practice that is gaining more adepts (Coinbase, 2012). Such services offer essential security guarantees to the management of all types of cryptocurrencies and enable purchases between currencies of legal course and cryptocurrencies.

Although the adoption of blockchain technology is continually growing, not all businesses are embracing blockchain because it does not enhance their systems (see Section 6.1) or due to the lack of regulations (Summit, 2017). Nevertheless, requirements such as big data storage, digitalisation, and efficiency, as well as security and privacy, are important for governments, which need to enhance management and administrative tasks. One of the prevalent research topics in finance is cryptocurrency exchange, which will enable multi-currency transactions (Nath, 2016; Peters and Panayi, 2016). Additionally, as far as interoperability is concerned, businesses, companies, and governments are already working towards automated and configurable SC creation procedures which will be compliant with many standards and will also facilitate auditing tasks (Governatori et al., 2018; Cheng et al., 2018). Therefore, SCs and transactions between users and/or businesses or public entities will become practical and efficient. For instance, the adoption of blockchain in the healthcare sector will create opportunities in secure and structured health data storage and ubiquitous personalised healthcare. In the case of citizenship and education services, as well as data management, blockchain will enable interoperable services (e.g. query, verification, integration, and adoption).

6.5. Data management and privacy & security solutions

Despite the great benefits of blockchain in the context of secure and private data management and storage (see Section 5.6), blockchain has several limitations and weaknesses (Eyal and Sirer, 2014; Blockchain Weaknesses, 2017; Yli-Huumo et al., 2016; Lin and Liao, 2017). In general, privacy and confidentiality is still a problem for blockchains, because information is stored as a public ledger. Several anonymisation or encryption-based mechanisms can be adopted to protect the confidentiality of the information (Greenspan, 2015b). However, these mechanisms are not a panacea and depend on the implementation and the context of the system (e.g. such solutions can be too demanding for IoT networks (Christidis and Devetsikiotis, 2016)). Further mechanisms to prevent disclosure are suggested in Christidis and Devetsikiotis (2016) where authors express that networks' file sharing should be performed using secure protocols like telehash (TeleHash – Encrypted Mesh Protocol, 2014), Whisper (Dannen, 2017) or directly using a content-addressed P2P file system such as IPFS (IPFS, 2016).

A well-known problem in blockchain data privacy is transactional privacy (Suhaliana et al., 2018). Most businesses and individuals are concerned about the traceability of transactions and SC operations, which are propagated across the network. Moreover, measures such as the use of pseudonyms are not enough to guarantee transactional privacy (Kosba et al., 2016). For instance, there are de-anonymisation approaches which analyse transactional graph structures of cryptocurrencies (Meiklejohn et al., 2013; Ron and Shamir, 2013). Also, it has been already shown that bitcoin's transactions can disclose a lot of sensitive information (Barcelo, 2014; Biryukov et al., 2014; Goldfeder et al., 2017).

As SCs are similar to programs, they frequently contain errors, which can cause hefty losses. Recent examples of vulnerabilities include the DAO attack (Siegel, 2016); leading to a loss of around 47 M$, and the Parity wallet bug which allowed the theft of around 280 M$ (Parity Wallet Security Alert, 2017), or the recent discovery of thousands of vulnerable SCs (Pearson, 2018). The very nature of SCs makes their operation sometimes difficult to understand as they drastically differ from traditional programming environments, easing the task of hiding illegal behaviours. These could range from the relatively blunt implementation of a Ponzi scam (Bartoletti et al., 2017) disguised as some sort of investment opportunity yielding incredibly high returns, to more subtle schemes that compromise private keys or do not guarantee the return of funds to investors when funding goals are not met. Out of the many written proposals to date for avoiding some of the most important SC vulnerabilities or abuses (Suiche, 2017), we believe that the most promising is the one which approaches the problem by limiting the expressiveness of the underlying programming language (Dannen, 2017). Other solutions rely on SCs checkers (Mavridou and Laszka, 2018; Nikolic et al., 2018; Kalra et al., 2018), which implement a framework to verify the correctness and the fairness of SCs and to trace their vulnerabilities. In the case of IoT, big companies and flagships are open-minded towards blockchain technology, as shown in Section 5.4.

Based on the above, a lot of research needs to be carried out to secure not only the blockchain per se but the SCs as well.

6.6. Big data and artificial intelligence

The broad adoption of artificial intelligence solutions could be tuned, utilising SCs, to manage particular characteristics or behaviours, autonomous drones or cars. Moreover, intelligent transactions between entities and/or devices may also enable real-time implementations and a wide range of possibilities.

The race of data acquisition, increases the effectiveness and accuracy of data across many AI domains (Halevy et al., 2009). In the case of public blockchain systems standardisations and interoperability will improve AI algorithms and market prediction solutions since data will be available via a public ledger. The above pave the way for scalable and more accurate solutions and better AI models (McConaghy, 2016) within multiple contexts, enhancing the possibilities of data analytics.

The secure and verifiable blockchain structure may be used to ease big data management (Karafiloski and Mishev, 2017b). However, data analytics using blockchain structure imply too much overhead. Despite this, in most cases processing all transactions will not be necessary and, hence, intermediate or efficient auxiliary structures may be implemented, increasing thereby the overall efficiency. Therefore, solutions must be adopted ad hoc. Nevertheless, there already exist blockchain-based architectures for big data storage (Kumar and Abdul Rahman, 2017).

The adoption of deep learning in conjunction with faster machines and larger storage spaces have paved the way for modern auditing, which is already being enhanced by blockchain (Appelbaum et al., 2017; Issa et al., 2016). Such procedures often involve examination of clients that are using big data analytics to remain competitive and relevant in today's business environment. However, at the heart of AI lie machine learning algorithms which are characterised by their opaque features. Their opacity most commonly stems from the large number of possible features included in a classifier which, as it is rapidly growing way beyond what can be easily grasped by a reasoning human, prevent us from understanding and explaining decisions made by AI (Burrell, 2016). The latter creates many headaches when people are trying to justify why a specific choice was made, mainly due to the enforcement of the GDPR and its derived "*right to explanation*". Additionally, with regard to automated decision-making, a data subject has the right to be provided with meaningful information about the logic involved. In this regard, blockchains can provide auditable trails to prove why a particular decision was made by an AI system and resolve the discrepancies raised by the non-linear use of numerous factors and use of randomisation.

Evidently, the use of big data and AI enable numerous interesting and innovative blockchain-based applications which could augment the transparency of such technologies.

6.7. Concluding remarks

While blockchain applications are being widely deployed, many issues have yet to be addressed. By doing so, blockchains will become not only more scalable and efficient but more durable as well. The features they offer are not unique if judged individually, and the bulk of the mechanisms they are based on are well-known for years. However, the combination of all these features makes them ideal for many applications justifying the intense interest by several industries.

As blockchains become more mature, their applications are expected to penetrate more industries/domains than the ones covered in our survey. However, while many try to propose blockchains as a panacea and an alternative to databases, this is far from true. As already discussed, there are many scenarios where traditional databases should be used instead. Moreover, we identified the individual characteristics that are mostly required per each application domain. This facilitates the choice of the proper blockchain and the corresponding mechanisms to tailor the blockchain to the actual needs of the application.

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