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Blockchain Application for Central Banks: A Systematic Mapping Study

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ABSTRACT Blockchain is a novel technology capturing the attention of Central Banks and a technology with significant disruptive potential. However, a gap in research effort between practitioners and academics seems to have emerged. This paper analyses and maps that gap by exploring trends in peer-reviewed research contributions through thematic categorisation of academic literature on Distributed Ledger Technology (DLT) use-cases for services, operations and functions performed by central banks. Furthermore, this paper provides summaries of opportunities and challenges for central banks arising from blockchain adaptation to each of those use-cases. To achieve this goal, we utilise a Systematic Mapping Study approach. The paper presents an in-depth assessment of statistical and thematic analysis of research maturity and the types of researchers, with specific emphasis on types of central bank use-cases considered for blockchain adaptation. Our work contributes to an understanding of where the most or least attention is directed, allowing for identification of gaps and opportunities for both academics, practitioners and combinations of each. Results show that the research topic is a comparatively new domain. It confirms the gap between depth and volume of the research provision from industry and academia, with industry leading the trend. Our study also found that the most research-intensive use-cases are those for: 1) Central Bank issued Digital Currency (CBDC), 2) Regulatory Compliance and 3) Payment Clearing and Settlement Systems (PCS) operated by central banks; a comparatively low engagement was found in the areas of 4) Assets Transfer/Ownership and 5) Audit Trail.

INDEX TERMS Assets transfer, assets ownership, audit trail, blockchain, CBDC, challenges, central bank, central bank digital currency, distributed ledger technology, DLT, financial regulation, literature review, mapping study, opportunities, payment clearing and settlement, PCS, regulatory compliance, research maturity, research trend, use-case.

I. INTRODUCTION

Interest in the application of blockchain technology comes from various and diverse communities. Amongst others are law, real estate, energy sector, insurance, security, diamond identification, the Internet of Things, computer gaming and finance [1], [103], [104], [106]. Academics, policymakers and market participants, ranging from technical enthusiasts, software developers, start-ups, large enterprises to public authorities, banks and financial regulators [1] are all experimenting with this innovation to enhance their functionality and operations. Blockchain is emerging as a truly disruptive technology and its reach continues to impact IT and a multitude of other areas [102], [105].

Over recent years, the banking industry has started exploring various ways of leveraging blockchain. Industry participants see an opportunity to apply it to their products and services [2] and develop coordinated solutions [2] that could help overcome existing industry challenges by providing greater transparency and improving conduct. A recent study by Ben Dhaou and Rohman *et al.* [3] highlights a critical view that interest in this technology is linked to economic crises and to the fact that current monetary tools are running out of solutions, while showing signs of obsolescence [3].

Since blockchain offers a recorded, mutually agreed, immutable and cryptographically secured trail of digital events that can be shared and maintained by multiple

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participants, banking industry actors are looking at ways of taking advantage of those components. The Bank for International Settlement (BIS) [53] states that application of DLT to banking could fundamentally change how assets are stored and maintained, obligations are discharged, contracts are enforced and risks managed [53]. The hype of blockchain technology promises to build secure value transfer systems, streamline business processes and/or create new ones, increase transparency and ease auditability, thus reducing the trust gap [4]. These promises have pushed financial actors to revisit their antiquated infrastructure, business practices and re-evaluate their priorities [2].

Furthermore, a financial system's participants rely heavily on numerous financial intermediaries and third parties such as central banks, Central Securities Depositories (CSDs), Central Counterparty (CCP) clearing structures, centralised collateral management systems [55] and so on. Those organisations, amongst other things, are responsible for the provision of trust functionality for financial market actors such as management of collateral of partner banks, clearing and settlement of payments, transfer of legal assets ownership versus payments, tracking, recording and reconciliation of transactions in centralised and own ledgers [58]. All these create a risk of data duplication, latency in liquidity turnover, numerous fees and further obstacles. Moreover, the importance of integration of data generated on blockchain into existing financial Big Data analytic practices for filtering and signal extraction for the banking industry is growing [89]; such data could be stored and shared via an instantly accessible Blockchain-ed platform [90] to improve intelligent auditing or tracing functionality [90] for regulators, promoting cooperation among regulatory agencies and the overall financial markets. Central banks and the research community are both looking at ways to harvest blockchain's technological promise, to substitute some of the trust functions performed by financial intermediaries and third parties and to improve financial data management. However, the full potential of blockchain technology is still largely unknown [3] and there are various limitations to current blockchain architectures. Understanding the implications of such technology requires a multidisciplinary approach from the scientific perspective of academics together with policy-makers [3].

Adaptation of the scientific community to this topic has been comparatively slow and resources have been limited to Bitcoin source code, blog and forum posts, mailing lists and other online publications [1]. Following the work of the 'Bitcoin White Paper' [5], the majority of blockchain-based innovation was provided not via peer-reviewed scientific publishing, but directly by interested industries [1]. Although this reduced time-to-market for blockchain, it has also lead to deficits in systematisation and a gap between practice and the theoretical understanding of this novel field [1]. The purpose of our study is to reduce that gap by presenting a thematic overview of peer-reviewed publications on potential application of blockchain technology to the functions performed by central banks. The objective is to find and systematically map all available scientific papers to empirical and non-empirical research approaches. Identification of the scope for blockchain use-cases, applicable to the business of central banks, allows us to determine what problems have already been investigated, yielding a theoretical understanding or practical contribution. Furthermore, we provide narrative summaries of opportunities and challenges to businesses and operational performance of central banks from hypothetical adaptation of blockchain for each of the identified use-cases: 1) *Central Bank Digital Currency (CBDC)*; 2) *Payment Clearing and Settlement (PCS) systems operated by central banks*; 3) *Assets transfer and ownership*; 4) *Audit trail*; 5) *Regulatory compliance (Regulation)*.

In this study, we are not aiming to promote or highlight any particular approach, a benefit or a challenge, but to help academics and practitioners identify where the greatest or least effort has been directed by the research community, understand where the gaps for future exploration could be and provide a starting point for further systematic discussion. To achieve those goals, we adopt a Systematic Mapping Study (SMS) research methodology that follows the guidelines of Petersen *et al.* [6], [7]. Below, we present a short introductory summary of gains and limitations for each of the identified blockchain use-cases for central banks:

CBDC models are often seen as the next milestone in the evolution of money. Academic publications focus on design characteristics and country-specific requirements of CBDC to guide its potential application and adaptation. Overall, CBDC promises to provide central banks with a reliable close to real-time 'window' on economic activity to guide monetary policy. However, the trade-off between the risks and benefits of such systems are still unclear, because, despite the promises of various benefits and reduction of particular risks, other new unknown risks could emerge, some of which could stem from immature blockchain technology and/or lack of empirical research; some could also arise from operational or security risks stemming from technological disruption.

In relation to hypothetical blockchain underpinned *Payment Clearing and Settlement (PCS) system, operated by a central bank*, researchers predict that such a system could generate value by improving efficiency via modernisation of underlying technology of financial markets infrastructure. These present the possibility of reduction of costs for transactions, reconciliation, clearing and processing, together with reduction of legal, settlement, operational and financial risks. On the other hand, researchers are sceptical about the full substitution of well-established, collective infrastructure and processes, built by banks with currently available blockchain protocols. The lack of incentive for alternative systems is driven by inefficiencies arising from high set-up costs and already existing network effects. Additionally, a one-size-fits-all approach of blockchain application to PCS activities raises a broad range of further challenges.

Transfer and ownership of assets through central bank-maintained systems has also been claimed as a hypothetical beneficiary from blockchain adaptation. Researchers insist that the assets-agnostic nature of DLT can provide trusted, time-oriented, immutable, shared databases for recording transfer of assets and change of ownership, without relying on numerous specialised third-party infrastructures and intermediaries, reducing intermediation costs and risks. On the other hand, serious outstanding questions are raised by some researchers. Current laws do not define DLT-based proof of ownership and overall legal validity of financial instruments issued on the blockchain.

Small numbers of research studies have been devoted to the enhancements of the *regulatory audit trail* from blockchain application. Regulators could attain a real-time opportunity to monitor, supervise and audit trades through a blockchain-based 'global audit log' which promises to ensure integrity of records through the integrity of the blockchain ledger itself. Furthermore, such a system could promote the reduction of multiparty multi-intermediated reconciliation costs and risks, by automating and streamlining it. However, some researchers highlight issues of ensuring the validity and reliability of transactional records, because a DLT system does not provide a mechanism for guaranteeing that the added information is correct.

Lastly, blockchain application for *regulatory compliance* has also been extensively covered in peer-reviewed literature. Researchers suggest that financial regulation could be improved by automating mandatory regulatory reporting or through the creation of an algorithmic rule-following monetary authority on blockchain. That would facilitate embedded supervision thus reducing some legal risks and deterring avoidance of the regulatory arbitrage. Traceability characteristics of blockchain can promote the reduction of risk of fraud through automation of Know Your Customer (KYC), Combating the Financing of Terrorism (CFT), Anti-Money Laundry (AML), tax misreporting and so on. On the other hand, researchers also discuss a number of regulatory friction points to blockchain adaptation. The effects of blockchain application for central banking are not currently covered by the existing regulatory framework, thus spanning new legal issues. Current blockchain architectures provide limited access to the regulators, leaving governance, risk allocation and consumer protection in the hands of the coding experts, who might lack legal and/or financial expertise. Furthermore, blockchain promising information transparency could cause confidentiality and privacy loss leading to competition issues.

The notion of a ''Technical Argument'' [107] is also relevant to the work presented in this paper and allows a dissection of the different elements of why we undertake studies and the motivation for doing such studies. Such an argument has several components. The first is ''a vision'' for the work. From the point that we started this mapping study, we envisaged the work as potentially seminal and that it would be a source of reference for central banks to use for understanding the state-of-knowledge in blockchain utilisation. The second component of a technical argument asks ''why progress is needed'' in the area. So, we see central banking as a fundamental part of society's fabric. Understanding of how the disruptive technology of blockchain could influence practices of central banks has the potential in the future to shape those banking practice and the implications of these factors is essential for highlighting problems and areas for progress in this domain. The third component of a technical argument is ''prognosis''. Although it is difficult (as for most things in life) to predict the likely outcomes of blockchain use in central banking, not least because the field is advancing so quickly, we highlight throughout this mapping study the areas that could be exploited, the areas that come to the fore and those that present new challenges and that can be extended. The final component is an explanation of ''why the status quo is not good enough''. Blockchain provides a wealth of opportunities for the banking sector and the impact of exploiting those opportunities is extensive. As such, the inadequacies of current systems should not be seen as problems necessarily reflecting a poor situation, but as exciting ideas for the future. The work in this mapping study brings these ideas to the fore through a complete study of industrial and academic work thus far.

The remainder of this paper is organised as follows. The next section describes background information and related work. It covers banking broadly and central banking specifically, what blockchain is and summarises the most closely related surveys. Section III provides a detailed research methodology for the current study and includes research motivation, research questions, the protocol for study selection and data extraction. Section IV contains the results of this study. Section V provides an evaluation of threats to validity of the study and we discuss some key findings. Finally, in Section VI, we summarise the results and draw conclusions from the research.

II. BACKGROUND AND RELATED WORK

A. BANKING AND CENTRAL BANKING

In this study, we focus on central banks, but it is important to understand the role of wider banking, as this should help to determine where and how innovative the blockchain technology can potentially fit. According to Casu *et al.* [83] banks, as other financial intermediaries, play a pivotal role in the economy by channelling funds from units in surplus to units in deficit. They reconcile the different needs of borrowers and lenders who do not know and do not trust each other. They transform small-size, low-risk and highly liquid deposits into loans which are of larger size, higher risk and illiquid. The banking industry is broad and combines sectors related to central banking, investment, corporate, commercial, retail banking and so on, differing by their business models and performance goals. More specifically, a central bank, a reserve bank or a monetary authority is a financial institution that manages domestic money supply, interest rates and oversees a country's broader banking system. According to Hayes [75] some functional dimensions that set a central bank apart from other banks are that a central bank is a monopoly note issuer, the government's banker, the lender of last resort, and, in some cases, serves as a clearing house for settlement of payments - it is the banker's bank [75]. For example, as a clearing house, a central bank on a larger wholesale money market scale reconciles the funding needs of the commercial bank's participants, each of whom might have different business goals and do not trust one another. The other dimension is that a central bank must maintain a non-competitive stance and not seek profit maximisation. Most central banks also have supervisory and regulatory powers to ensure solvency of member institutions [52] and are seen in many jurisdictions as the keeper of economic health, usually independent of the government and trusted to deliver public interest and overall economic welfare [66].

B. CENTRAL BANKS: OVERVIEW OF PROBLEMS

These days, global central banks vary substantially in their structure and purpose [98]. They face complex issues in designing effective governance policies for each of their major functions and to accommodate their many differences [98]. As a monetary authority, they sometimes fail to contain macro-economic crises [75] that could stem from incentivised excessive risk-taking e.g., via unconventional monetary policy tools such as negative rates or Quantitative Easing (QE). These, in times of financial distress and high volatility, exacerbate negative outcomes [75]. Further problems result from large numbers of financial intermediaries [55]. In addition to high fees, service charges paid for financial intermediation and cost of regulatory compliance, there are delays, onerous paperwork and opportunities for fraud and crime [79]. Multifaceted linkage between banks and a variety of central intermediaries adds to current incomplete understanding of the post-crisis financial system; in particular, this relates to the concentration of the risk management of credit and liquidity risks in those intermediaries and the impact on systemic risks [99], [100].

Ben Dhaou and Rohman [3] suggest that there are issues with the banknote creation functionality of central banks, when used as a main instrument of tax evasion, money laundering and the financing of illegal activities. Cash also limits the scope for monetary policies based on negative interest rates, since it provides a zero-rate alternative that can be stored [3] and it deteriorates rapidly, especially in high inflation countries [3].

The current set-up of the European post-trade market is still a legacy of earlier domestic market infrastructures [64]. The problems stem from the lack of interoperability between centralised proprietary databases and that often restricts straight-through processing for a range of non-vertically integrated financial institutions [64]. This prolongs ongoing use of siloed digital records of ownership and requires manual updating to be reconciled with any change that occurred in the records of counterparties at different levels of the post-trade value chain [64]. These escalate the cost of back-office procedures and inflate certain risks such as: operational risk, chains of settlement failures (as delayed settlement of one transaction may affect the settlement of trades with third parties), human errors (the system being reconciled manually) and limited collateral fluidity [64]. Overall, all payment systems suffer from settlement or payment risks for technical or financial reasons, such as settlement, credit and market risks [101].

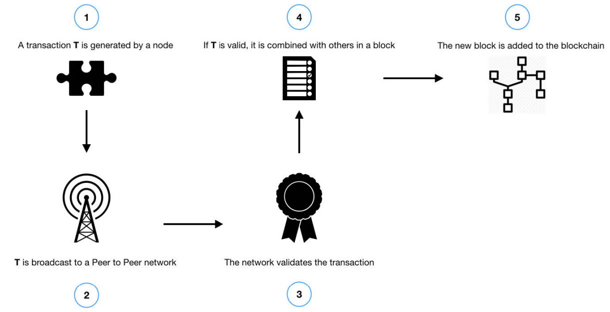

FIGURE 1. How a blockchain works.

The aforementioned challenges have attracted the attention of the financial regulators and provide the context and opportunities for modernisation and improvements.

C. WHAT IS BLOCKCHAIN?

In this study, we use the terms Blockchain or Distributed Ledger Technology (DLT) to mean the same thing. Although there is a thematic difference between those terminologies through their underlying architecture, it has become a common practice in the industry to combine all those meanings under the same umbrella. According to Hileman and Rauchs *et al.* [4], at its narrowest possible definition: "A blockchain is a special data structure - a database - that is composed of transactions, batched into blocks, that are cryptographically linked to each other to form a sequential, tamper-evident chain events that determines the ordering of transactions in the system. In this context, a transaction represents any change or modification to the database" [4]. More broadly, blockchain is a type of peer-to-peer (P2P) distributed network of independent participants that generally broadcasts all data to each other, each of whom may have different motivations and objectives. They may not necessarily trust one another, but reach a consensus (a consistent agreement about changes to the state of the shared database) on a linear history of operations of that shared database [4]. A high-level workflow of blockchain is presented in Fig. 1.

The key advantages of blockchain, in comparison to existing distributed systems and database technologies, is in the use of a specialised data structure which bundles transactions into blocks, and/or the broadcast of all data to all participants, in its automated reconciliation mechanisms, together with its resilience and transparent nature [4]. Some of the main components of a blockchain are: cryptography, P2P networks, consensus mechanisms, the ledger, validity rules and access or permission types. There are general permission type distinctions for current blockchain architectures:

- 'Permissionless', 'public' or 'open' refer to blockchains where access is not restricted to a specific set of vetted participants [4]. In these types of blockchain, participants do not know and trust each other, so the "good"

behaviour is incentivised through the existence of a native token;
- 'Permissioned', 'private' or 'closed' refer to blockchains where access is restricted to a specific set of vetted participants [4]. These blockchains operate in an environment where participants are already known, vetted and there is a level of trust amongst them; this removes the need for a native token to incentivise good behaviour. Participants are held liable through off-chain legal contracts and agreements and are incentivised to behave honestly via the threat of legal prosecution in the case of misbehaviour [4].
- 'Consortium' or 'federated' refer to a blockchain where the architecture could be private or hybrid (public and private) [2], [27]. This type of DLT uses features such as: permission restriction, multiple controlling authorities; they allow easy, yet controlled information sharing between various stakeholders and more.

Although we have identified a small number of research studies on the potential application of permissionless blockchain for business of central banks [77], [101], the predominant consensus amongst the research community is that the permissioned access model is the preferred type of blockchain by such institutions [21], [22], [27], [36], [51]–[55], [57], [58], [58], [61], [66], [69], [86], [101]. Consortium or federated blockchain access type was not available in the included peer-reviewed publications on DLT applications for the business of central banks.

D. OVERALL IMPACT OF BLOCKCHAIN ON BUSINESS MODELS OF CENTRAL BANKS

Business Model (BM) is a relatively new concept in management studies [91], [92]. Although a specific definition has still to be found [91], [93], a BM has been identified as the "story" that explains how an enterprise works [91], [94] and also as the way firms do business – i.e. the rationale of how an organization creates, delivers and captures value [91]. BM represents an intermediate layer – the link between a firm's strategy, processes and information technology (IT) [91].

The major cornerstone of any bank's operations is its business model, such as processes and activity around payment systems' infrastructure [91]. Blockchain innovation has the potential to circumvent central bodies or legacy infrastructures [8] that surround trading activity, e.g. CSDs, clearing houses, market data providers and so on [96]. Central banks could also innovate in those systems by creating new blockchain-based business models, which in itself is believed to be one of the major factors behind the push for DLT adoption by the banking industry [8]. These will allow for a fundamentally different way of conducting and tracking financial transactions and could thus challenge the centralised nature of existing financial systems in central banks [8].

Furthermore, for BMs related to current Big Data analytics, the importance of filtering and signal extraction for the banking industry grows [67], [89], [95]. The opportunity here is to improve current limitations in the trade processing life-cycle, such as problems of quality and completeness of messaging between systems, lack of reference data systems, various problems with trade book-keeping, manual or even paper-based confirmations in some cases [97]. Integration of a hybrid approach using elements of DLT in combination with more established technologies applied in new ways, plus elements of Big Data analytics is necessary [97] to improve automatic intelligent trading, where customer- and trading-related data is collected, stored and shared via an instantly accessible Blockchain-ed platform [90]. These will improve intelligent auditing / tracing functionality [90] for regulators. Additionally, innovative combination of blockchain, Big Data and banking could promote the creation of shared value systems and improve cooperation among regulatory agencies and overall financial markets. This hybrid approach, where DLT is combined with Big Data has the potential to replace the transparency and feedback loops, which would ultimately reduce costs and operational risk [97]. The impact that blockchain-based Big Data will have on banking data analytics in future shows the increasing importance of a set of common "harmonised industry standards" for data representation and consideration of costs for data storage and maintenance, as DLT will "make big data even bigger" [89].

All these potential capabilities for BM innovation promise to enhance the efficiency of the banking industry, have the possibility to optimise financial infrastructure and play an important role in the sustainable development of the global economy by creating shared value systems and improving cooperation among banks, technology companies, regulatory agencies, customers and the market overall.

E. RELATED AND EXCLUDED SURVEYS

Four existing surveys discuss literature in the area of application of blockchain as financial technology (FinTech) for the central banking business. However, none of those surveys focus solely on peer-reviewed publications about utilisation of DLT by central banks.

Firstly, the work of Rio [8] reviewed stages of acceptance of DLT by central banks between 2016 and 2017 for their various systems and functions. The review was based on grey literature, i.e., on a central bank's own available publications, reports and press releases. The subset of utilised countries were those that belonged to the Organisation for Economic Co-operation and Development (OECD) and to the G20 organizations, including the Bank for International Settlement (BIS) and the European Central Bank (ECB), but excluded European Union (UE) and countries outside the OECD. The work concluded that, despite all central banks used in the study expressing interest in DLT, not one had an operational DLT-based system [8]. The reasons for the current unavailability of live blockchain applications were due to issues with: "Speed, cost of processing, security, transparency and privacy, legal settlement finality, scalability, network effects and immature technology" [8]. The same research did not go into the specifics of research trends and thus differs from the research approach and results of our study.

Secondly, in a systematic literature review, Lutz [9] examined financial literature on the topic of: ''dual or multiple currency scenarios for privately issued cryptocurrencies'' coexisting or competing with the central bank issued fiat currency and suggested a coexistence theory [9]. The review was limited to a financial / economic perspective and excluded ethnological aspects of blockchain as well as its legal contributions [9]. The work provided a comprehensive, detailed overview and analysis of the relevant contributions on currency coexistence, competition and developed a theoretical framework of the main ideas and functions of cryptocurrencies. The work concluded that: ''little academic research looks closer on the existence, interaction and consequences, as well as on a possible set up of coexisting private cryptocurrencies and central bank issued fiat currencies'' [9]. This survey is different from our research since it focused on privately issued cryptocurrencies as competing and coexisting with fiat currencies.

Thirdly, the work of Thakor [10] summarised theoretical and empirical literature on the interaction between novel financial technologies such as blockchain, its cryptocurrencies and the banking industry. The study considered: ''Innovations in payment systems (including cryptocurrencies), credit markets (including P2P lending) and insurance, with blockchain-assisted smart contracts playing a role'' [10]. The work debated the consequences for central banks, its payments, clearing and settlement systems (PCS) from cryptocurrency, created privately or by the banks themselves as a competitor to fiat money. The survey focused on cryptocurrencies and wider financial markets and is thus different from the current research.

Lastly, Hassani *et al.* [89] presented an example of a comprehensive overview of increasing interest from a global banking industry towards the adoption of blockchain [89] and presented a wide-ranging taxonomy of existing applications and relationships between blockchain and the wider banking sector. The work summarised the opportunities and challenges from a banker's perspective on blockchain adaptation. Furthermore, they elaborated on what future impact from Big Data generated on blockchain could have towards existing practices of data analytics in banking. They highlighted the increasing importance of filtering and signal extraction for the banking industry and also highlighted the lack of academic interest in this subject area [89]. This work was different from our research, because it covered research into wider the banking business and blockchain adaptation, without specific focus on central banking and only peer-reviewed research; in addition to academic publications, they also included industry wide reports, blogs and wider media sources on blockchain applications.

Surveys excluded from our study focused on wider applications of blockchain other than those for central banks. More specifically, on economic aspects of cryptocurrency (without interaction with fiat currency), blockchain evolution and technological concepts, surveys that did not focus solely on the application of DLT for central banking or financial services and surveys on the application of blockchain by industries other than banking or financial services.

III. RESEARCH METHODOLOGY

A. MOTIVATION

We selected and applied a Systematic Mapping Study (SMS) research methodology with the aim of describing the state of knowledge about the interest in blockchain technology for, and by, the central banking business. An SMS is a form of Systematic Literature Review (SLR), described by Kitchenham and Charters [11] and aims to give a broader examination of a researched topic than an SLR. It is motivated by the need to understand trends through thematic categorisation, a spectrum of publications and common or important topics and gain an understanding of the evolution of the field. The objective of the SMS was to find and map all empirical and non-empirical peer-reviewed research on DLT to the various areas of central banking. The outcome of this study provides an overview of the scope of the researched area; this will allow identification of research gaps that could be considered for further examination. The study follows the guidelines of Petersen *et al.* [6], [7], utilising steps of the Systematic Mapping Process (SMP) [6], [7]. The high-level steps for the review were as follows: 1) define research questions; 2) conduct a pilot search for primary studies; 3) construct search string; 4) search for all relevant papers; 5) keyword all abstracts; 6) extract and classify data; 7) analyse the results.

B. DEFINITION OF RESEARCH QUESTIONS

The first step of the SMP was to define research questions (RQs), which, according to Petersen *et al.* [7] and Kitchenham *et al.* [12] allow for a wide overview of the available topics related to DLT for central banks. The research questions outlined below were motivated by the focus of this study - in other words, to review all peer-reviewed research available on the intersect of blockchain for central banks:

- RQ1 *What are the trends in research on blockchain application for central banks?* This research question is motivated by the need to understand the comparative maturity of the topic, by examining where, when, how and by whom the research was communicated.
- RQ2 *What potential blockchain-based use-cases for central banks are addressed by the research community?* This research question is motivated by the need to understand where DLT is seen to be suitable for application for the central banking.
- RQ3 *Why or why shouldn't blockchain be considered?* This question is motivated by the need to understand why DLT was considered for each of identified use-cases and what challenges the application of blockchain poses, but not to highlight or promote any specific approach.
- RQ4 *What is the depth / breadth of the research for identified use-cases?* This research question is motivated by the need to understand the comparative maturity and application specifics of each separate use-case.

C. PRIMARY STUDY SEARCH AND SEARCH STRING

To develop a rigorous search strategy, the next step of the SMP was to search for all relevant papers. A *pre-defined search protocol* that specified methods of undertaking the search for the literature was established, to reduce the possibility of researcher bias and to allow for subsequent validity evaluation [6], [7]. The final search was conducted on 22nd of June 2020 and included years between 2008 and 2020. The current study used two common *search strategies* [6], [7]: database search and manual search. Leading *academic databases* were searched to obtain the literature for the study, namely: IEEExplorer; ELSEVIER: Scopus, SSRN (including JEL - Journal of Economic Literature), ScienceDirect; arXiv.org; Web of Science; ACM.

The *steps of the search* were as follows:

1) following the guidelines of Petersen *et al.* [6], [7] an initial set of keywords was identified from the study title: ''blockchain'' and ''central bank'';
2) a pilot manual database search was first conducted using those keywords, where additional keywords were derived from the known papers [7] and categorised based on James *et al.* [13]. A Population Intervention Comparison Outcome (PICO) approach allowed the creation and structuring of the search string [6], [7];
3) improvements in the search were implemented to find more relevant papers *per* iteration [7] and update the search string.

According to Petersen *et al.* [7], Population (P) and Intervention (I) are the most relevant for a SMS, since the other dimensions may restrict the search too much and remove relevant articles. As a result, only P and I dimensions were applied for search string composition. In the current research context, those elements are defined as: *Population*: an industry group comprising a central banking business and its underlying products and services; *Intervention*: blockchain technology as a software engineering tool considered for the application and adaptations for central banking functions.

The decision not to use ''cryptocurrency'' and ''Bitcoin'' as keywords for the search string was based on our pilot search results. Papers collected by the search tended to be related to the economics of publicly issued cryptocurrencies such as Bitcoin rather than aspects of underlying blockchain technology and its applications. The steps of composing a search string and applying a database suitable variation of it, using the P and I dimensions were as follows [7]:

Step 1: Scope the search for banking industry related publication: *(''banking'' OR ''bank'' OR ''central bank'' OR ''reserve bank'' OR ''monetary authority'' OR ''monetary'' OR ''financial Intermediary'' OR ''financial Intermediation'' OR ''clearing'' OR ''clearinghouse'' OR ''settlement'' OR ''financial institution'' OR ''FinTech'' OR ''financial technology'' OR ''inter-bank'' OR ''IBPS'' OR ''real-time gross settlement'' OR ''RTGS'' OR ''payment settlement'' OR ''CBDC'' OR ''money supply'' OR ''monetary policy'' OR ''technocracy'')*
AND
Step 2: Search further in the population of papers obtained by the Step 1 for reference to blockchain technology - intervention: *(''blockchain'' OR ''distributed ledger technology'' OR ''DLT'' OR ''smart contracts'')*

D. SEARCH FOR RELEVANT PAPERS

Not all identified papers were relevant to the topic, so the next phase was to evaluate the actual relevance of obtained articles against what was known about the population of the topic of interest [7]. We achieved this by defining rigorous inclusion and exclusion criteria. Those criteria were applied to all titles, abstracts and keywords of articles obtained earlier with the goal of identifying papers that were clearly in or out of the scope of the mapping study [7].

Grey literature such as relevant government project reports, working papers and evaluation documents available through earlier pre-specified databases was also included. Garousi *et al.* [14], [15] underlined the importance of such literature to be used as an additional source for understanding the area of novel research. The topic of development, application and evaluation of blockchain technology for central banks is a novel research domain and inclusion of grey literature broadens the outlook for both the state-of-the art and the state-of-practice in the area [15] by including wider research sources.

Inclusion criteria:

1) English scientific and grey, empirical and non-empirical, peer-reviewed articles, conference papers, available through pre-specified databases;
2) publications between 2008 - 2020 inclusive;
3) papers with research scope of blockchain technology and sub-scope - the application of that technology for the domain related to the central banking business.

Exclusion criteria:

1) papers without full text availability;
2) papers that were not written in the English language;
3) studies that were duplicates of other studies;
4) studies that were an older version of studies already considered;
5) the study was not a scientific study, such as editorials, summaries of keynotes, workshops, and tutorials;
6) studies that were book chapters;
7) papers that had some other meaning other than one relevant to the application of blockchain technology for central banking.

The final 'Database Search Results' on 22nd of June 2020 with the database specific search strings and automated (if database functionality permitted) or manual application of inclusion/exclusion criteria on title, keywords and abstract is provided in Appendix A.

For *borderline papers* deemed relevant during the inclusion and exclusion, based on their title, abstract and

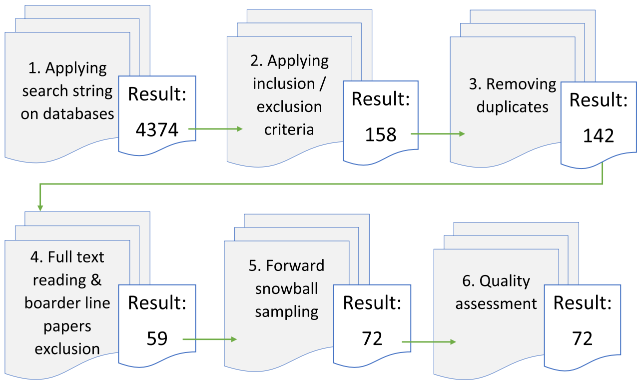

FIGURE 2. Number of included articles during the study selection process.

keywords, further reading of introduction, conclusion and, if the decision was still unclear, full text reading was conducted to establish relevance to the research questions [3]. Excluded borderline papers had a primary focus on 1) blockchain application for the wider financial sector other than central banks, i.e.: commercial banking, financial trading and/or exchanges (excluding Payment Clearing and Settlement (PCS) infrastructure operated by central banks), general economy, unbanked; 2) papers that provided publicly issued cryptocurrency economics and solutions, i.e., that described it as a digital asset or private sector money, such as Bitcoin, not issued by the central bank; 3) wider FinTech and blockchain regulation and legal implications for blockchain and cryptocurrency other than those concerned with central banking activity.

We also performed a *forward snowballing* sampling technique on the most cited papers [16]. Citing metadata is available through the majority of the databases. A further 13 studies were added through this technique [16]. The decision to use forward snowballing was underpinned by the focus on more recent and novel publications and to allow for theoretical validity evaluation.

Final *quality assessment* was performed on the set of 72 primary studies. According to Petersen *et al.* [7] and Kitchenham *et al.* [17], for SMS: "Quality assessment should not pose high requirements on the primary studies, as the goal of mapping is to give a broader overview of the topic area" [7], [17]. The criteria for paper evaluation was whether the knowledge claims made by the paper were interesting and justified by the research method Wieringa *et al.* [18]. Fig. 2 represents the final results for each step of the SMP.

E. KEYWORDING OF ABSTRACTS

The next stage of the SMP was the keywording of abstracts of the final set of relevant papers [6]. Keywording is a way to reduce the time needed for developing the classification schema and to ensure that the schema takes the existing scope of studies into account.

To build the current classification schema, we again followed the guidelines of Petersen *et al.* [6], conducted through the following steps:

1) Abstracts were read and searched for keywords and concepts that reflected the contribution of the paper; while doing so, the context of the research paper was identified. When the abstracts provided no meaningful category of keywords, the paper's introduction and conclusion were also read;
2) Sets of keywords from different papers were combined to develop a high-level understanding about the nature and the contribution of published research. This process produced a set of categories representative of the underlying included studies;
3) All selected papers were then read fully. If a paper revealed some new important keywords in the text, existing categories were updated [7];
4) The final set of keywords was then clustered and used for categories of the current SMS [6].

F. DATA EXTRACTION, ANALYSIS AND CLASSIFICATION

The aim of this step was to collect all the information required to structure the literature for this study in order to map it and to answer research questions. Following the guidelines of Petersen *et al.* [7], we developed a data collection form to enable data extraction from the included publications. Each data collection field was populated with a data item (the column header – a category) and its corresponding values. This allowed a check for the correctives of extracted data in the collection form by tracking it back to its original paper. The development of the form was achieved in two stages:

1) We itemised basic metadata available through predefined databases and populated the data form with corresponding values. The added data items were: *document title, authors, publication year, publication venue, publication type and publisher*. After reading all papers, we added further fields, such as *research type, research contribution*. This step allowed development of the facets for: *"Topic-Independent Classification Schema"* [7]. These facets enabled us firstly, to answer RQ1 and RQ4 and, secondly, to facilitate comparison of the similar or same research in the different fields [7]. This allowed us to gain insights into the comparative maturity of the study area [7] and helped to improve and clarify classification [7].
2) Further categories were then added to the data collection form headers that emerged from keywording of the abstracts. This stage developed a schema representative of the underlying publications: *"Topic-Specific Classification Schema"* [7]. This provided study specific categories [7] allowing us to answer RQ2 and RQ3 and to map findings against the facets, identified in the previous stage.

The topic-specific classification schema developed could be considered as an additional contribution on its own, since it provides a framework for categorising and describing the blockchain-based interest and application for central banking business in peer-reviewed literature. The full list of headers of the data collection form is provided in Appendix B.

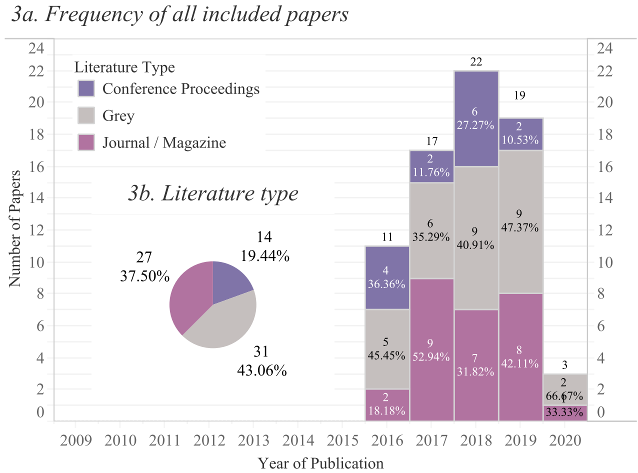

FIGURE 3. Frequency of publications.

Categorised data then was used to visualise, summarise, analyse and draw conclusions in relation to the research questions, to satisfy the aim of the research.

IV. MAPPING RESULTS

A total of 72 papers were used in the completed review, with three categories for topic independent classification schema and five categories for topic specific schema defined for each paper. The complete list of all included papers is provided in Appendix C. It is important to note that the current study does not represent a full and comprehensive review of how all central banks explore blockchain technology today. Such a review would require us, in addition to academic publications, to consider industry reports, press releases, white papers etc., with emphasis primarily on grey literature sources. A good example of one such review is in the work of Hassani *et al.* [89], where the authors summarised blockchain adaptation for the wider banking community largely utilising industry and media reports. The focus of the current study is to report the state of academic research.

A. TOPIC-INDEPENDENT CLASSIFICATION SCHEMA

This section provides an overview of the data from included literature allowing us to answer RQ1. This question is motivated by the need to provide a comparison of similar research in different fields [7]. Research facets identified in this section will be further used in Section IV.B and IV.D to enable the mapping of use-cases and to answer RQ2 and RQ4.

RQ1: What are the trends in research on blockchain application for central banks?

1) FREQUENCY OF PUBLICATIONS AND LITERATURE TYPES

Fig. 3 represents numbers for all publications identified between the beginning of 2008 and June of 2020. The colour categorisation communicates the type of the peer-reviewed literature published, distinguished between: 1) conference proceedings, 2) grey literature and, 3) journal and magazine academic articles. The bubble plot in Fig. 3b shows the count and percentage of the total for each of those literature types.

The data reveals that peer-reviewed grey literature contributed the most research to this topic - 31 papers (or 43.06% of total), with academic articles being a close second at 27 papers (or 37.5% of total), leaving just 19.44% (or 14 publications) for Conference proceedings (Fig. 3 b). Although the search included years 2008 - 2020, the data shows that, across all pre-specified databases and including manual search and forward snowball sampling, there were no publications available reflecting the interest of the research community in application of blockchain for central banks until 2016 (bar chart of Fig. 3a). During that year, a total of 11 publications (or 15.28% of total available literature) were shared, with almost half provided by industry (grey literature types), only two being a pure academic article and four communicated as Conference proceedings. Over the following two years, the overall number of available papers steadily grew and peaked in 2018 at 22 papers (or 30.56% of total). For that year, grey literature provided a slight majority of the research (nine papers or 40.91% for that year), closely followed by academic articles (seven papers or 31.82% of 2018). Availability of Conference proceedings fluctuated over the years peaking in 2018 to 6 papers. The greatest number of academic articles was found in 2017 (9 papers), showing a steady decrease thereafter. Academics provided more than half of all research for that year. For 2019, the results showed a total of 19 papers, almost half of which were grey literature sources (nine or 47.37% of 2019). In relation to 2020, only two papers were found as grey literature and one as an academic article, although it is difficult to judge with confidence about the final trend for 2020 as there is still a considerable amount of time left in the year. Overall, these results show, firstly, that the interest of the research community in the application of blockchain for central banks is a very young; secondly, that the overall trend of interest in this topic is potentially growing, and, finally, that there is a strong industry presence providing and potentially guiding such research, although participation of academics and industry practitioners in research is somewhat balanced.

2) FREQUENT PUBLICATION VENUES AND PUBLISHERS

Breaking down included literature by publication venue and a publisher provided an insight into which one has potentially the most similar research. Fig. 4 shows the most frequent venues (Fig. 4a) and publishers (Fig. 4b) for sharing peer-reviewed publications. Additionally, the bars are colour-coded to demonstrate what type of literature was available through each of those sources.

The data indicates that publications related to examination of DLT for and by central banks have been published in a very broad range of venues and by a wide variety of publishers. Our study includes literature from 57 different publication venues, including 48 venues that have only provided a single paper. Furthermore, the research was published through 31 distinct publishers and 19 of those had only published one paper on this topic. The most frequently targeted journal that published both academic articles and

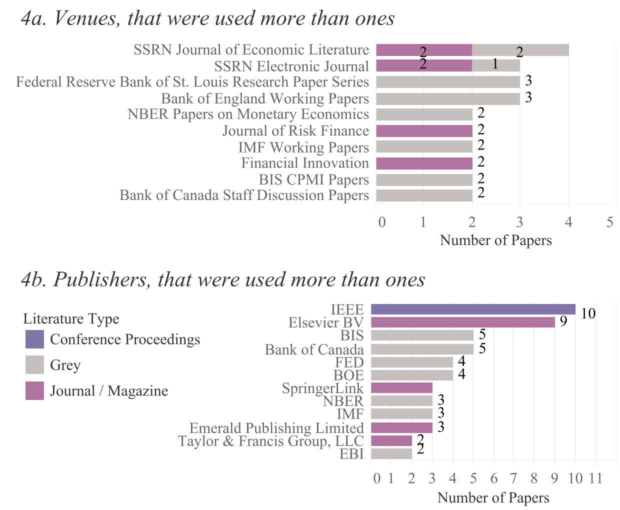

FIGURE 4. Frequent publication venues and publishers.

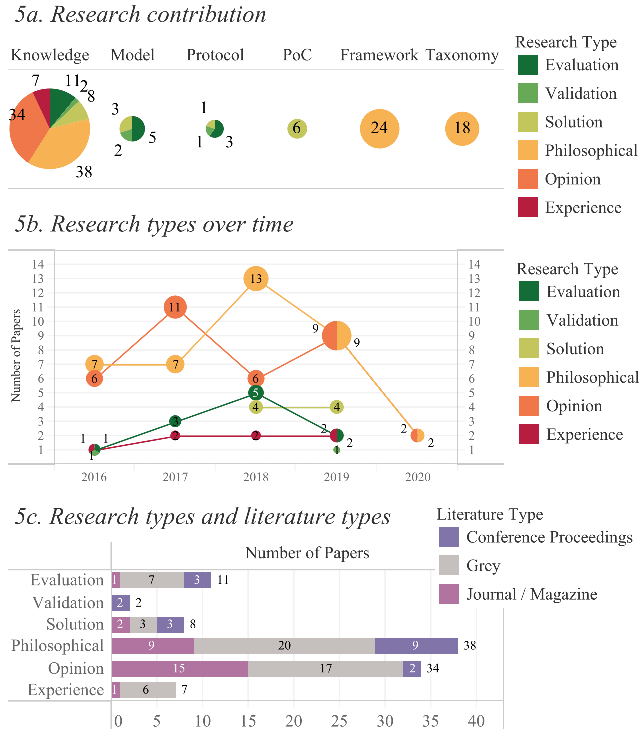

FIGURE 5. Frequency of publications.

grey literature was the SSRN Journal of Economic Literature (JEL) – totalling four publications overall (Fig. 4 a). No pattern for conferences was found, as all 13 provided one publication each.

Fig. 4b shows that IEEE and Elsevier BV were the most popular publishers and the former only focuses purely on conference proceedings and the latter only on academic articles; a total of 10 and 9 papers were found over the period, respectively. For the grey literature, the most frequently used channels for research outputs were the central banks themselves - Bank of Canada, FED, BOE, BIS and so on. The full list of venues and the publisher is provided in Appendix D.

3) RESEARCH TYPE AND CONTRIBUTION

In this study, we identified the *research type facet* that reflected classes of non-mutually exclusive research approaches (or types), to which all primary studies could be mapped. As this facet is general and independent of specific focus area [6], it allows for comparison with other fields. We utilised the research type categories from Petersen *et al.* [6] and Wieringa *et al.* [18] and this facet captured six categories in total, further grouped into two broader categories:

Empirical Research Types:

1) Validation Research;
2) Evaluation Research;

Non-Empirical Research Types:

3) Solution Proposal;
4) Philosophical Paper;
5) Opinion Paper;
6) Experience Paper.

Another facet was the *research contribution facet*, which represented non-mutually exclusive types of novel contributions provided by the included papers to the research field and captured six categories in total. Those categories could be more broadly divided into:

Practical (or technological) contribution:

1) Model;
2) Method;
3) Proof of Concept (PoC);

Theoretical (or knowledge) contribution:

4) Conceptual Framework;
5) Taxonomy;
6) New Knowledge.

This facet allows for comparison of papers with similar objectives.

As one paper can use more than one Research Type and provide more than one Contribution to communicate the work of its authors, overall numbers for each of those facets are greater than the number of included papers. An important distinction for Evaluation research is that it involves industry cooperation [6]. The contributions from Evaluation and Validation research types, in addition to new knowledge, could also include a novel technique, such as a model or a protocol. Although a Solution proposal is a non-empirical research type [6], [18], in addition to new knowledge, it sometimes provides a technological contribution in the form of Proof of Concept (PoC) – a model or protocol - but without "full-blown" validation [18]. Contributions of a Philosophical paper can be a new conceptual framework [6], [18] and / or taxonomy [6], both of which are theoretical contributions. Opinion papers and Experience papers both contribute to knowledge, but in contrast, Experience papers can involve experience reports from industry practitioners [18], so often utilised for grey literature.

Fig. 5a represents the frequency of all contributions (column headers), provided by each research type (colour coded pie charts). Results show that, overall, the dominating contributions to this topic are knowledge, framework and taxonomy. We see that, overall, there are 10 novel models provided, five of those are communicated using Evaluation research type, the other two from Validation research and three as Solution proposals. Evaluation research added the most novel protocols (three out of five). Solution proposals added thee models, one protocol and six PoCs as practical contributions, although those were not empirically validated. Philosophical papers added 24 new frameworks and 18 new taxonomies. The data shows that theoretical contributions dominate the field, with technological artefacts appearing less frequently and predominantly provided with industry cooperation.

Fig. 5b shows the distribution of identified Research Types, represented as colour codded pie-bobbles, for each year. The size of each bobble shows a total count of papers and the colour of the pie is relevant to different research types. For example, in 2016 and 2019, Validation research type was utilised once in each of those years. Uses of Evaluation type peaked to five in 2018 from three in 2017. Opinion papers peaked in 2017 at 11 and were utilised six times in 2018 and nine in 2019. Philosophical papers were used the most in 2018 (13 times) to communicate new findings, nine times in 2019 and twice in 2020. Experience papers were utilised the least overall. The data potentially points out, that, because the topic of this study is young, there is still little practical experience to report on - the majority of work is still theoretical. Communication of empirical findings on the other hand, although significantly lagging, seems to be slowly but steadily increasing over time.

In Fig. 5c, a distribution of the cohorts of Literature Types for each Research Type is given. Results show that, overall, the authors preferred to use non-empirical research types to communicate their findings. Only 13 times out of total (or 13%), was Empirical research used (11, or 11% of total, for Evaluation research and two, or 2% of total, for Validation Research). The other times a non-empirical research was utilised, with 38 (38%) for Philosophical, 34 (34%) for Opinion Papers, eight (8%) for Solution Proposals and seven (7%) for Experience papers. Evaluation and Experience research were mainly communicated via grey literature and the same applied to Opinion and Experience papers. Half of the Philosophical papers were provided by industry (grey literature). Solution Proposal cohorts of the researchers appears balanced. All Validation Research is available as Conference proceedings. This data suggests that empirical research was mostly used by industry participants to communicate their findings. Non-empirical research was also noticeably dominated by grey literature, making practitioners into prominent debate contributors.

B. TOPIC-SPECIFIC CLASSIFICATION SCHEMA: BLOCKCHAIN-BASED USE-CASES FOR CENTRAL BANKS

In this part of the study, we introduce a classification schema that emerged from reading all paper keywords, abstracts and full text [6], [7]. This classification is specific to the underlying research topic and maps the interest from the academic circles to utilisation of blockchain for services and operations of a central bank. The schema allows us to answer RQ2 by structuring the researched topic in terms of variability of themes in relation to the application of blockchain for central banks in general.

After reading all included papers, it was evident that they fell into the five following categories for DLT-based use-cases for central banks:

1) *Central Bank Digital Currency (CBDC)*;
2) *Payment Clearing and Settlement (PCS) systems operated by central banks*;
3) *Assets transfer and ownership (Assets)*;
4) *Audit trail (Audit)*;
5) *Regulatory compliance (Regulation)*.

These use-cases provided another facet of our classification to map all included primary studies against earlier identified facets of: *research type*, *research contribution* and *literature type* and to answer RQ2 - RQ4.

Furthermore, after reading all papers, an additional two sets of information emerged for each of the identified use-cases; these broadly answered the questions of:

1) *Why DLT was considered for each of those use-cases?* and
2) *What challenges the application of blockchain posed for those use-cases?*

A narrative summary answering those questions (for each use-case) will be presented in Section IV.C of this study and allows us to answer RQ3. Additionally, after reading all papers it was evident that a single paper could span multiple use-cases, could utilise more than one research type and provide more than one contribution. Therefore, the overall number of studies across all categories is larger than the total number of publications.

Lastly several technical variables emerged, most prominently discussed in the included papers. Tables 1 and 2 that summarise positive and negative opinions of the researchers about application of those variables in the central bank settings is presented in Section IV.C.6

RQ2: What potential blockchain-based use-cases for central bank are addressed by the research community?

Fig. 6 represents use-cases that were available in the included literature. Fig. 6b shows a distribution of identified use-cases for each year, represented and colour-coded in pie-bobbles for each use-case. The size of each bobble reflects a total count of use-cases in that bobble.

It is evident from the data (Fig. 6a) that *CBDC* is the most widely investigated and reported central bank use-case for blockchain, with 39 papers (or 30.23% of total) examining it. The number of those use-cases available in the included literature has been steadily growing over the years (Fig. 6b), with four papers discussing it in 2016, five in 2017, 13 papers in 2018, peaking to 15 in 2019 and twice in 2020 so far. Over half of overall research on CBDC was provided through grey literature (Fig. 6 a) – 24 publications (or 61.54% of all CBDC

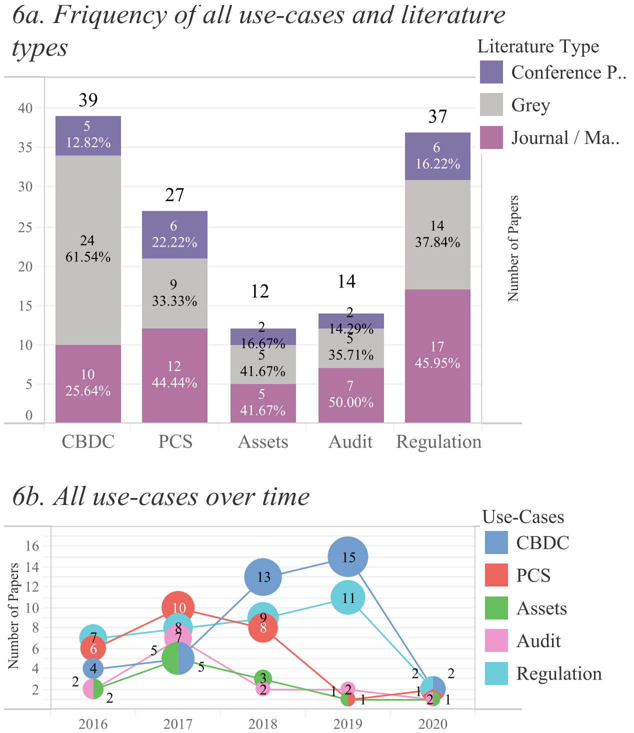

FIGURE 6. All blockchain-based use-cases for central banks.

research). The data indicates that interest in CBDC is growing and industry is leading and influencing the trend.

The second most popular use-case was *Regulation*, with 37 publications (or 28.68% of the total). The largest proportion of that research was communicated via academic journals (17 articles or 45.95%), with grey literature a close second. Over the years, availability of information on regulation in academic print was consistently growing, peaking to 11 in 2019 two more for the first half of 2020.The data suggests that interest in regulatory compliance is expanding and participation between industry and academia is more geared towards the academic side.

PCS was researched 20.93% of the time, totalling 27 publications, where academic articles were leading the general trend (12 articles or 44.44%), with grey literature not far behind (9 papers or 33.33%). For this use-case, conference proceedings appeared to be proportionally popular, compared to some other use-cases, although still the least frequent venue for research communication. Year-on-year change for this use-case revealed that interest in this topic initially almost doubled from six papers in 2016 to 10 in 2017. 2018 provided eight papers, in 2019 there was only one publication available and two in 2020. The data indicates that, although PCS was a popular topic, participation of researchers is subsiding, potentially indicating underlying lack of interest and/or development of the gap in knowledge.

Two further categories had the least overall coverage in the literature, with 9.30%, or 12 papers, for *assets transfer and ownership* and 10.85%, or 14 papers, for *audit trail*. Research on assets was evenly divided between academic articles and publications from industry, with little input from conference proceedings. The majority of information on the topic of audit trail was available through academic articles. The year-on-year trend for both of those use-cases was similar, peaking for both in 2017 and slowing down thereafter. The data indicates that although these two topics show some interest from researchers, that interest seems to be lagging behind, unable to sustain an upward trend and potentially indicating another gap.

C. OPPORTUNITIES AND RISKS FROM BLOCKCHAIN ADAPTATION

This section provides a narrative summary of discussions in the included literature for each of the earlier identified use-cases answering questions of: 1)*why DLT was considered for each of those use-cases?* and 2) *what challenges the application of blockchain posed for those use-cases?*

RQ3: Why or why shouldn't blockchain be considered?

1) CENTRAL BANK DIGITAL CURRENCY (CBDC)

''Banknotes'' and ''commercial bank reserves/deposits'' - are both a form of central bank money, which is the main form of the central bank's liability and underpin nearly all other forms of money in the economy. In the UK, over 98% of sterling payments, by value, are made electronically, with less than 2% made by banknotes, coins or cheques [19]. BIS [26] states that the only way for the general public to own central bank money is through physical cash. ''If someone wishes to digitise that holding, they have to convert the central bank liability into a commercial bank liability (commercial bank money) by depositing cash in a commercial bank'' [26].

Why was blockchain considered for CBDC?

Currently, CBDC models receive more serious consideration [50] from the research community and central banks themselves. 28 included papers argue about the potential benefits from its hypothetical introduction, because CBDC is seen as a potential next milestone in the evolution of money [23]; it is believed to provide a more stable unit of account, a more efficient medium of exchange and a more secure store of value [25], [50]. The focus of many researchers is on its application to the domestic economy [23], monetary supply-side considerations [39] and for promoting financial inclusion [19], [43], [80] or as an enabler of cross-border payments [84], [87]. Some explore whether the introduction of CBDC could improve the efficiency of fiat currency function [41] by providing a way to directly transfer central bank funds to households and firms [19], [101]. Arner *et al.* [101] argue that the replacement of cash with a cash-like CBDC can lower the cost of maintaining the supply of physical currency and protect it against counterfeiting [101]. Thus, the social value of CBDC is believed to be in its ability to bring some of the anonymity of cash into the digital realm [101] or even blend the features of cash and deposits together [85]. In another example, after studying the macroeconomic consequences of issuing CBDC, the BOE states that its introduction could promote financial stability by permanently raising ''GDP by as much as 3%, due to reductions in real interest rates'' [22].

A large proportion of included papers focus on design features of a hypothetical CBDC because, from the perspective of central banks, the impact of CBDC introduction hinges on its design, country-specific economic and financial characteristics [23], [41], [101] and reasons for its introduction [20], [41]. For example, a CBDC designed to provide a secure payments service could serve a different core purpose to the one used ''as an instrument of monetary policy'' [20], or it could be designed in such a way as to blend a monetary and a payment systems into one [101] and it could have a ''separate operational structure to other forms of central bank money'', (BOE) [21].

In terms of payment economics, an important design consideration is what is verified on the blockchain – a token (an individual receiving a token will verify that the token is genuine [81]), or an account (an intermediary verifies the identity of an account holder [81]), i.e., an *account-based CBDC* versus *token-based CBDC*. A token-based CBDC could extend some of the attributes and functionality of cash for retail transactions [21], [23], [86], [101] and could be made widely available to the public as a general-purpose currency [50], [86]. Universal access to this CBDC could be obtained through a digital signature and privacy will be ensured by default [86]. Khiaonarong and Humphrey [39] believe that the role of cash in the economy should be maintained [39]. However, CBDC could reduce the demand for cash [4] or facilitate the gradual obsolescence of paper currency [25], effectively reducing costs associated with maintaining a cash-based system [4], [43], [101]. These would be helpful in discouraging tax evasion, money laundering and other illegal activities [4], [25], [43], [101]. An account-based CBDC could be utilised with payments through the transfer of claims recorded on an account [23]. It is the preferred design choice of central banks [23], [25], [50], [101], because it could provide them with a more reliable real-time window on economic activity to guide monetary policy [43], [50].

Academics further categorise account-based design depending on who has access to CBDC. The difference here is between *retail CBDC* which is issued for the general public and *wholesale CBDC*, issued by financial institutions holding reserve deposits with a central bank [38], [44], [50]. If anonymity is not seen as an issue, a central bank could provide bank accounts for the general public [23], [24], [26], in the same way deposit accounts are today [80] – the retail CBDC. Those types of accounts could be made available through public-private partnerships with commercial banks or could be held by private individuals directly at the central bank itself [25]. ''This is something that has been technically feasible for a long time, but which central banks have mostly stayed away from'' [80]. This type of a central-bank-run system would provide convenience, resilience, accessibility [86], opportunity to better track payments, making CBDC widely accessible, held by anyone for any purpose [20], with ease of use to per-to-per cross border payments [84], [86]. On the other hand, a wholesale CBDC issued for large-value wholesale interbank payments [24], [41] is considered when its design implementation can guarantee anonymity [34], provide restricted access to a predefined group of economic agents and is applicable to a limited range of purposes [20], [24], [38], [44]. This type of CBDC design could facilitate faster or immediate settlement [23], [41] or extended settlement hours [41] and could be accessed more broadly than central bank reserves [21]. Khiaonarong and Humphrey [39] provides an example of the Bank of Canada exploration of DLT for digital representations of the Canadian dollar (called a digital depository receipt), used for wholesale payments [39]. By improving efficiency and safety of both retail and large-value payment systems [41], [49], CBDC could aid central banks in easing liquidity pressures and potentially help to curtail bank runs [23], [35].

Another reported design feature of an account-based CBDC was that it could allow for interest payments - the *interest-bearing CBDC*, supplied by a central bank under either a monetary quantity rule or a monetary price rule [21]. When CBDC is designed as non-interest-bearing, its similarity to cash becomes the sole design choice [85]. If a return could be paid/earned on CBDC, the overall probability of its introduction increases [34], because an optimally designed interest-bearing CBDC could safeguard bank intermediation and protect the variety of payment instruments against network effects [85]. Furthermore, being a liability of a central bank [38], CBDC could be backed on the asset side of the central bank's balance sheet by liquid federal government risk-free assets [50], thereby serving as a secure store of value with a rate of return [25], [44] different to the rate on reserves [21]. By facilitating access to the balance sheet of a central bank, CBDC could promote contestability for banks and non-bank financial institutions [19]. It does not have to disintermediate banks in any way [35], [80]. If an account-based interest-bearing CBDC is used by the general public as a viable option to bank deposits [29], [44], [101] it could discipline behaviour of commercial banks [29], address competition problems in the banking sector [42], [43] and compel commercial banks to raise their deposit rates [80]. If CBDC is used as reserves, it can increase overall lending by reducing a banker's costs of holding those reserves in central banks via increases in the CBDC rate paid on those reserves [29]. As CBDC could also pay positive, zero or even negative rates at various points in the economic cycle [80], it could be utilised as a tool for conducting monetary policy [25], [43].

Lastly, the underlying architecture of CBDC could differ between *centralized*, *fully decentralized* and a *hybrid* system [101]. A centralised system would be characterised by a permissioned blockchain, be account-based and provide direct access to a central bank, but lack cash-like qualities such as anonymous exchange [101]. A decentralised CBDC could be based on a permissionless blockchain where full decentralization is achievable through tokenisation and could offer cash-like features [101]. A hybrid architecture is a blend of a centralized and decentralized CBDC. It may provide central bank accounts for financial intermediaries, where other participants could use intermediary services to access

CBDC-takens; these could represent the drawing rights on the funds stored in the central bank accounts [101].

What challenges could the introduction of CBDC pose?

A total of 32 papers discuss the potential negative side of CBDC introduction, as a large proportion of researchers agree that its net benefits for financial stability are not as clear cut. This is because, while its adaptation could reduce some of the existing risks, other novel and unknown risks could emerge and it is not certain which would be greater [22].

Despite a range of pilot CBDC projects and theoretical studies [101], a high price volatility [2], [3], [43] and low level of acceptance of cryptocurrencies demonstrated that they fail to satisfy full requirements of fiat money in their current form [2], [101]. If a hypothetical CBDC is to be introduced, it is still unclear what role should be taken by a central bank and eventual intermediaries [4]. There is a possibility that CBDC introduction could create a parallel monetary system [3], [87], which could pose risks to the central bank monopoly over issuing base money [49]. It is also uncertain whether CBDC should complement or serve as a substitute for existing central bank money [4]. If CBDC were to be designed as cash-like [85], it may lead to the reduction in demand or disappearance of cash, thus lowering the variety of payment instruments valuable to households with diverse needs [85]. Additionally, such a system creates a risk of permanent loss of funds if end users fail to keep their private key secret secure [86]. Furthermore, there are risks to price stability [49], to smooth operation of payment systems [49], [62] and to the conduct of monetary policy [49], [87]. CBDC also could have a negative effect on seigniorage, the interest rates [19] as well as face numerous legal challenges [49], [87].

The next important challenge, reported in the included papers was to establish who should get access to CBDC in the first place: only commercial banks, financial institutions in general or even citizens [4]? If CBDC was to be issued to the general public, who should run the nodes (end users or money providers) and how off-line payments should be processed [4].

Some researchers believe that disintermediated public access to the central bank balance sheet via interest-bearing CBDC could result in destabilizing consequences for the banking sector [49], [50], [85]. As a competitive and safe and convenient alternative to commercial bank deposits [23], [43], [44], [50], [85], CBDC would likely to have a disruptive effect on financial stability of credit institutions [23], [44], [49] and key financial market infrastructures [24], [50] with contagion to the overall financial system [49]. Disruption of commercial banks' business model [50] could lead to adverse consequences for the real economy [45]. With a sufficiently high CBDC interest rate [29] commercial bank reliance on customer deposits as a major source of their funding [45] may become less stable [23], [85] and more expensive [23], [29], [43], leading to additional reductions in lending activity [29], [43], [45], [85] or increased lending rates to general public [23], [43]. Since in times of financial distress, commercial customer deposits could far more easily take flight to a central bank [24], [43], [49], [85], [87], CBDC could act as an accelerant of bank runs [23], [24], [43], [50], [87], [101], "transforming an isolated concern about one bank's solvency into a system-wide crisis" [50].

Key characteristics of current blockchain architectures, i.e., the anonymity of a beneficial owner of CBDC [19], [37] – is another reported red flag [37] of CBDC design. If there were to be interest payments/charges on CBDC holdings [78], it would be impossible for a central bank to sustain that owner's anonymity [19], because the holder would need to be identified for income tax purposes [78]. Overall, a central bank cannot issue CBDC in the sense of a truly decentralised and permissionless asset that permits its users to remain anonymous [37], [101], because anonymous CBDC would facilitate criminal activity [19] leading to high reputational risks for central banks [37], [101]. Additional restrictions and compliance costs would have to be imposed [19], [43], such as KYC (Know-Your-Customer), AML (Anti-Money-Laundering) and CFT (Counter-Terrorist Financing) [37], [43]. Another issue is that novel CBDC system will have to contend with operational and security risks arising from technological disruptions [3], [23], [37], [51]–[53], [101]. Overall, there is an agreement in the research community that there is a need for more research on the impact of a potential deployment of CBDC on monetary policy and financial stability [4], [101]. More work is required to assess the full potential of CBDC [24], its technological feasibility and operational costs [23], [43], [101] and country-specific circumstances [23]. There is a growing consensus amongst researchers that, due to outstanding uncertainties regarding the design and architecture of the CBDC systems [4], [101], to technical constraints [38] of current blockchain architectures and maturing technology [3], [4], [19]–[25], [37], [40], [50]–[52], [64], [66], [75], that it is too early to draw firm conclusions on the real benefits of CBDC [19], [23], [101]. Today, the general view remains that such a move towards CBDC adoption would be premature [50] and the risks connected with issuing CBDC would outweigh the potential benefits for society [39]; currently, no central bank has a live and operating CBDC system [4], [21], [38].

2) PAYMENT CLEARING AND SETTLEMENT SYSTEMS OPERATED BY CENTRAL BANKS

Central banks play a fundamental role in supporting, regulating and supervising payment systems [101], because such infrastructure stands at the core of monetary and financial systems by creating a linkage between them [101]. "In its simplest form, the PCS of a financial transaction, regardless of the asset type, requires: 1) a network of participants, 2) an asset or set of assets that are transferred among those participants, and 3) a transfer process that define the procedures and obligations associated with transactions" [52]. Central banks facilitate settlement using central bank accounts to ensure finality [101].

Why was blockchain considered for PCS systems of central banks?

Overall, 31 papers argue about the potential benefits of hypothetical blockchain-based PCS systems, operated by central banks. Some researchers believe that DLT has the potential to improve efficiency [51], [101] and bring greater value [82] to PCS [46] by modernising financial market infrastructure [45], [101] and revolutionising the underlying technology [67] underpinning those processes today.

Researchers argue that DLT is capable of enhancing service and overall operational efficiency, safety [67], [101] and global reach [65] of *Interbank Payment Systems (IBPS)* [4], [41], [56], [57], [63], [68] for large-value wholesale payments [26], [31], [41], [101]. By allowing point-to-point transmission [67] and straight-through processing of global [36], [68] financial transactions [66], DLT could reduce complexity for multiparty, cross-border [52] inter-bank payments and settlements [39] and allow for transfers in multiple currencies with the use of a single transaction system [65]. Blockchain could enhance efficiency of IBPS for cross-bank money transfers [63] by speeding them up [2], [68], [101] to near-real-time updating and 24 × 7x365 processing [61], [65]. Also, for general application of Real Time Gross Settlement (RTGS), CBDC could be utilised to make it open access, allowing any financial agent to settle large value payments, achieving finality in virtually real-time [19], [61], [65], [101]. For the inter-bank market, each bank can be a participant in DLT-PCS and take part in the consensus process [56], thus eliminating the intermediary link of third-party financial institutions [4], [27], [67], [101]. Blockchain can also eliminate the need for centrally maintained back-up systems [51], [101], by creating decentralised, technology-led, automated IBPS [66] that no longer require reconciliation between different databases [56], [101]. By tracking on blockchain [63], [101], a central bank can oversee [75] payments, settlement and remittance transfers [4], [68] of inter-bank cash flow [63] and ensure a delivery-vs-payment (DvP) by linking transfers of assets with payments [51], [54].

Another potential benefit of DLT cited by researchers is that it could streamline a post-trade value chain [64] by simplifying and automating many of the processes currently involved in the post-trade cycle [51] such as clearing and settlement. For clearing, there is an opportunity to speed it up to almost immediate [26], where a collection of DLT nodes could clear payments on a continuous basis [62]. As an example, Tsai *et al.* [55] propose a framework for a permissioned multi-blockchain clearinghouse that could be shared with exchanges, banks and regulators, thus providing redundancy, high speed processing and scalability. In relation to the inter-bank settlement of assets, issued and controlled by a central bank, DLT could reduce back-office costs by automating various settlement processes [58]. It could enhance settlement efficiency [24], [26], [51] and simplify procedures by reducing the number of intermediaries [69] because blockchain is capable of facilitating direct connection [2] between transacting parties. DLT can enable settlement to occur through consensual reallocation of the balances [62] as a decentralised settlement of a transaction could be simultaneous with the validation process [69]. Furthermore, blockchain can improve end-to-end duration of the settlement cycle [51], [52], where transactions could happen in almost real-time and peer-to-peer [56], [101]. It could additionally provide a more flexible settlement [51], [54], by extending settlement hours [41] or shortening settlement periods [2], [19], [26], [41], [51], [54], [61], [69] from the current standard of 'trade date plus three days' (T+3), to near instantaneous settlement (T+0) [2], [26], [51], [58], [69]. Faster transfer will allow participants of inter-bank market to receive funds and securities more quickly, freeing up liquidity that could be tied up in collateral [53]. Improved availability of assets and funds [52], could illuminate the shortcomings of fractional reserve banking [45], by facilitating more effective use of collateral and regulatory capital [64], such as central bank reserves used for settlement of inter-bank payments [61]. These provide a real opportunity to address the separation between transactions (such as securities or derivatives transactions) and payment for those transactions, particularly at the wholesale level [101].

All the above have the potential for reducing costs of transactions [2], [4], [67], [69], reconciliation cost [4], [51], [64], clearing cost [63], processing cost [65] and overall settlement cost [4], [26], [41], [51], [52], [56], [68], [69]. Additionally, blockchain could promote reduction of risks inherent in PCS activities [52] such as legal and settlement risks [51], [52], [54], operational risks [51], [52] such as risk of fraud [2], and financial risks [52] such as liquidity [68] or counter-party risks [2], [4], [51], [56], [68], [69].

The challenges that blockchain-based PCS systems could face?

The multitude of possible designs for DLT is an indication that a one-size-fits-all approach is not appropriate for addressing the broad range of challenges in payment, clearing and settlement [53], [101]. 15 papers discuss the potential negative implications of blockchain adaptation for PCS.

Researchers are sceptical about full substitution [66] of existing and well-established PCS process by currently available DLT architectures and protocols. High barrier to entry was explicitly recognised as a critical factor influencing the adoption of DLT for PCS processes [52], [69]. In jurisdictions where banks have already built collective infrastructure [66] for PCS, the lack of incentive for alternative equivalent systems arises due to the inefficiencies of high set-up cost, duplication [66] and because of its already existent network effects [4], [46], [52]. Building these new networks through an alliance of incentives of different participants is a challenging task [4]. The rationale for it is that the creation of new networks of participants in such settings requires each party to give up some amount of existing control, combined with an unwillingness to change well-established business processes at their respective institutions [4]. The banking industry will require an uptake from a critical mass of those participants for any application of new technology to be successful [52].

Furthermore, faster blockchain-based PCS processing, reduced reconciliation work and real- or near-real-time transaction time [53] will remove netting benefits that clearing provides, thereby increasing the 'spot liquidity' demand for settlement [51]. A real-time (T+0) cycle would require prepositioning of cash or securities (collateral) in advance of a trade [51], thus increasing credit and liquidity needs associated with payment, clearing and settlement activity [51], [53].

Another important issue is that an ultimate settlement of sovereign-backed currency, in accounts held at a central bank is fundamental to social confidence and trust [66]. A blockchain-based settlement is probabilistic [53], [58] - in other words, the payment is therefore never fully settled because there is always a small probability that the payment could be reversed [58] due to forking [46], [51], [54].

It is also suggested by some researchers that operational capacity and performance-based scalability of current blockchain designs is a further concern [3], [4], [53]. This is based on limits of the size of the blocks in a blockchain [47]. As only a limited number of simultaneous transactions can be written into the blockchain at any given time, a block's capacity to grow and accommodate more interactions is not promising [2]. Current PCS systems are capable of handling a significant fluctuation in volume of transactions, which impose a requirement on blockchain-based PCS systems to be operationally scalable to accommodate processing large daily volumes and peak volumes in times of market distress or volatility [53]. As hundreds of millions of daily transactions are processed through current PCS [52], any novel system that fails to meet these requirements will weaken the safety of PCS system activity [53].

Moreover, when DLT-based settlement is compared with existing centralised RTGS, BIS highlights that it may take longer to achieve settlement on blockchain [53], thus actually decreasing the speed of transactions [27], [51]. This is because technically, to update and synchronise state changes to a ledger, the process for validating a transaction and reaching a consensus across all nodes in DLT is potentially more complex than with a centralised entity [53]. Combined with cryptographic verification, such settings introduce latency and limit the number of transfers that DLT can process concurrently [52].

Another essential requirement of any PCS system is trade matching of transactions over a large number of attributes with complex rules and cross-dependencies [51]. Blockchain does not necessarily have the functionality to compare different data domains, to address contract mismatches or to process exceptions [51]. Furthermore, operational settlement becomes even more complex if it involves delivery-vs-payment (DvP), payment-vs-payment (PvP) systems [47] or delivery of one asset against another [53] and so on. "Central matching may continue to be required as pre-ledger processing" [51], because in arrangements involving an exchange of value, multiple financial market infrastructure is typically involved [53]. Hence, certain processes of the post-trade cycle in the securities markets will still require involvement of intermediary institutions, irrespective of the market players involved and technology used [64].

Despite the need for immutability that stems from irreversibility of a blockchain, there are further issues identified with self-executing code [3], [51], [53] where mistakes in coding may need to be corrected [53], [101]. In PCS systems, there is a requirement for error management [51]–[53], [101] in circumstances such as inadvertent errors [53], e.g., mistaken or unauthorized payments [47]. Also, there are requirements for maintenance [66] of PCS, management of technological failures or misuse [66] and fraud [52], [53], [101], as currently existing and well-established PCS systems secure public interest objectives in stability and anti-abuse and are subject to regulation as a critical financial market infrastructure [66].

3) ASSET TRANSFER AND OWNERSHIP

Comparatively smaller numbers of papers available in the included literature discusses how introduction of blockchain could effect current processes for asset transfer and ownership in central banks.

Why was blockchain considered for asset transfer and ownership of central banks?

Nine publications deliberate on the potential improvements from blockchain. The capabilities of DLT such as its ability to provide record-keeping, storage and transfer of any type of asset (such as securities, commodities, derivative transactions and so on), make it asset-agnostic [52].

A key innovation of blockchain is that it can offer, via shared database [54], a time-ordered and immutable record of transactional history [61], [69], security ownership [4], [52], [69] and all transfers among all participants in the payment system [2], [52], that can be updated without relying on multiple, specialised intermediaries or a third-party infrastructure [54]. When financial institutions trade with one another through IBPS, all relevant counterparties would have a copy of that ledger.

These could also involve asset issuance and servicing [2], [62] such as creation of assets, enablement of trading between partners and liquidation of positions [62]. For example, Chen *et al.* [71] outlined a blockchain-based financial product information management platform that allowed for multi-institutional update of multi-dimensional and diversified financial product information.

There are also implications when protection of business sensitive information, such as the appropriate level of information is shared on the ledger and which participants have the ability to read or write to [52]. Even if all nodes have a complete copy of the ledger, it is technologically possible that some of the data on the ledger is encrypted so that only authorized participants can decrypt and read the underlying information [52]. This way, the system could facilitate a tamper-resistant [71] direct ownership [52], reducing intermediation costs for investors, together with legal, operational and overall systemic risks [61]. "This will improve accounting, auditing and regulatory supervision functions while increasing transparency of ownership" [2], [51], [71].

What challenges could blockchain-based asset transfer and ownership impose?

There are also four papers that discuss potential issues with utilising DLT for assets transfer and ownership. The concern is whether a DLT entry legally constitutes a proof of ownership. For ultimate and legal settlement, there must be a formal, i.e. legally defined, indication of transfer of ownership, once securities and cash have changed hands [51]. There is an uncertainty in regards of legal validity of financial instruments issued on a DLT, because such legal ownership [45] is not defined and elaborated by law [47] and not assured by the regulators and supervisors [45]. Proprietary rights [45], [47], [53] and obligations, associated with DLT representation of assets [45], as well as the liabilities and enforceability [53] of the rights of transacting parties are unclear [47], [53]. However, it is a legal requirement for those to be articulated clearly, understood by all participants and supported by applicable law [53]. "As things stand now, there is not even a standard satisfactory definition as to what constitutes a digital asset, not to mention an elaboration of its relationship to the physical asset it represents" [47].

Furthermore, for transactions that take place across borders or in multiple jurisdictions [51], [53], there are currently no laws that underpin the activity "in ways that are mutually compatible" [53]. "Decentralisation further challenges traditional methods of the enforcement of ownership judgment, as well as of a security interest, because, without the cooperation of the owner of an asset, placed on the blockchain, the asset may not be accessible" [47].

4) AUDIT TRAIL

There are several papers that provide a high-level discussion on potential improvements or limitation to current auditing practices from blockchain innovation in central banking settings.

Why was blockchain considered for audit trail of central banks?

Thirteen publications mention some potential improvements. Researchers argue that blockchain can enhance audit and regulatory functions [2] by providing the opportunity to monitor, supervise and audit trades and agreements in real-time, which drastically improves regulatory systems in place today [4] and assists central banks with their supervision role [4], [73]. The global shared audit log [4], [52], provided by the use of a DLT ensures the integrity of records through the integrity of the ledger itself [51].

Another cited advantage is reduction of reconciliation cost [4], [51], [52], [64]. The majority of back office costs are tied to manual reconciliation of conflicting trade data [69]. Blockchain promises to eliminate manual reconciliation processes [51], [74] across multiple record-keeping infrastructures [52] of many of the hundreds of data intermediaries [74] that play a significant role in reconciling costly and potentially conflicting, risk prone non-standard data [69], [74] in different locations by automating that reconciliation.

Moreover, the immutable [51]–[53], tamper-resistant [33], [52] nature of the DLT enables greater transparency [4], [51], [73] and traceability [4], [33], [51], [53], [57], [58], [73] of history of any flow of funds or securities [51], [57], where data cannot be unilaterally changed once recorded [51], [53], [58]. Immutability is crucial for safety as it relates to data integrity [53] and gives participants the assurance that everyone is storing, seeing, using and processing the same data as everyone else [2], [4]. As any amendments to the ledger are traceable [51], there is a possibility of reduction of data falsification and manipulation [3] resulting in reduction of the risk of fraud [2], [4]. While this refers mostly to the payment systems currently operated by central banks, it could in theory be extended to any DLT-based system to which central banks would be granted access to, such as internal bank ledgers [4].

What challenges could blockchain-based audit trail impose?

Four publications also mention issues associated with DLT and audit. Although it is expected that integrity of records in the ledger is ensured by the integrity of the ledger itself, a trusted body may still be needed to guarantee the validity [51] of that data. The reason for this is because the existing legal regime cannot assure the reliability of those records [45] and that the entered common information is correct [52] when large number of participants have an ability to write to the ledger without some kind of supervision. The decisions on who and how provides accuracy checks on information stored in the system [52] and still requires regulation to accommodate record-keeping and to provide for the reliability and authoritativeness of those records [45] on blockchain.

5) REGULATORY COMPLIANCE

A comparatively larger proportion of publications provide a discussion of various aspects of regulatory compliance of blockchain adaptation for central banks. More specifically on blockchain's intersection with regulatory compliance, CBDC impact onto Monetary Policy and regulation of blockchain-based PCS systems of central banks.

Why was blockchain considered for regulatory compliance?

Overall, 25 papers present thoughts on general aspects of regulatory improvements through blockchain. Adoption of blockchain for central banking business depends on its ability to comply with the existing regulatory framework [45], [87], therefore wider financial industry participants ask for updates in regulatory guidance and legal structure [69], [78]. Researchers debate on how to facilitate "embedded supervision" [76] by automating mandatory regulatory reporting [88], a process which is currently complex and tedious [4], [76]. Central banks foresee the potential of DLT to ease regulatory compliance [88], e.g., automatically enforce market regulation [2], [4]. To create an algorithmic rules-following monetary policy [75] regulators could participate as a node in DLT [55] and have full authority to set initial blockchain rules, the right to veto against existing blockchain codes, the power to enforce, update and change rules when necessary [79].

Automation of 'terms and conditions' of legally binding agreements could reduce some legal risks [53]. To achieve those goals, researchers argue for development of shared technical interoperability standards [2], [4], [51]–[53], [65], [67], [69], [70], [73], [74] which can provide a base layer of connectivity; this could help lower implementation and integration costs [53], halt avoidance of regulatory arbitrage [2] and provide access to more granular standardized transactional data [73], [74], [88]. A current absence of standardization still makes necessary and important the manual post-trading validation processes [69]. Overall, establishment of technical standards may encourage broader adoption of DLT in the financial system that could potentially bring network scale efficiencies [53]. In combination with cost-effective and secure data storing solutions [65], there is an opportunity to facilitate quicker reconciliation, reduce data discrepancy and demanding back office activities [53] important for regulatory reporting. Additionally, some papers propose establishment of a regulatory 'sandbox' model [2], [28], [67] as a facilitative approach to FinTech; this eases regulation in the testing, development and partial delivery to the public of new technologies, promoting the most suitable approach to regulating blockchain technologies [2].

The traceability feature of blockchain could potentially reduce the risk of fraud [2] by designing a legal framework [2], [77] for automating the connection of real-world identities to cryptographic identities in a database [2] for customer protection, KYC rules [2], [24], [36], [53], [67], AML [2], [24], [36], [53], CFT regulations [2], [24], [53], tax, capital and credit management [2], [24], [53], [67], [77] and overall monetary policy [2], [24], [53], [77]. This would remove duplication efforts in identification across institutions and enable encrypted sharing [2], [60], [62], [77]

What challenges could blockchain pose to regulatory compliance?

A total of 18 papers discuss some regulatory frictions from DLT. First of all, traceability should be weighed against privacy and the need to keep certain information confidential [2], [24], [53]. On a blockchain, all information in the ledger is typically observed by all participants [58], [69]. When such arrangements are applied to financial markets, this information transparency might cause privacy loss, confidentiality or competition issues [3], [4], [50], [69] and should be balanced against data protection and applicable privacy laws [45], [51]–[53], [58], [69], such as the General Data Protection Act (GDPR), the Bank Secrecy Act (BSA) or others.

Furthermore, blockchains of today are incapable of being influenced by governmental controls and provide limited access to regulators - read-only mode [3]. In such a setting, the governance and regulatory enforcements are solely concentrated in the hands of coding experts who do not usually possess governance expertise in areas of risk location and determination, consumer protection rights, financial and legal expertise [66] etc.

Blockchain application for central banking business potentially generates new services and involves new players [47], [52] and therefore creates new legal issues [4], [49], [51], [53], [70], [87] that require additional supervision [27]. Current regulation and supervisory policies that govern financial systems and the prevailing financial market architecture are not generally intended to favour a particular electronic technology [52]; unclear regulatory environment [4] is one of the important reasons preventing blockchain from adoption [77].

Another important issue is that today, the interdependence of existing financial systems suggests that issues arising in any one area of the wider banking ecosystem could result in the transmission of risk to other financial market infrastructures, leading to systemic damage at national and even international levels [2]. There is a diverse set of participants interacting within a single financial market or across different financial markets [52]. Because of this interdependence of legacy payment systems, adaptation of blockchain-based solutions for one area of central banking business could interrupt existing processes [77] and drastically affect a wide range of interconnected financial markets and infrastructures, including payment systems, stock exchanges, central securities depositories, securities settlement systems, trade repositories and others [2]. Moreover, interoperability across blockchains [4], [52] or between DLT and legacy systems [51], [52], [66], [69] is crucial to the efficient functioning of the wider financial system [52]. Currently, interoperability is still in its infancy [4] and the risks are further enhanced by the technological complexity of blockchain systems, including use of strong encryption, decentralised governance structures and its status as software [2]. Furthermore, as market participants are developing their own niche DLT systems [69], the current landscape is fragmented and comprises a variety of incompatible protocols [4] leading to additional complexity, costs [52] and operational risks, due to incompatibility issues [69]. Should widespread implementation of these systems occur, the International Monetary Fund (IMF) [2] warns, scenarios where blockchain technologies become simultaneously "too big to fail, yet too complex to resolve", could potentially arise [2].

a: MONETARY POLICY AND CBDC

Monetary Policy is the macroeconomic policy laid down by the central bank. It involves management of money supply and interest rates and is used by the government of a country to achieve macroeconomic objectives like inflation, consumption and liquidity growth.

In total, 14 papers elaborate on positive implications from introduction of CBDC onto Monetary Policy operations. Overall, CBDC is seen by researchers as an appropriate policy response to payment innovations [41], [43], because a CBDC based monetary policy framework could foster true price stability [25], [87] by simplifying [37] and facilitating systematic and transparent conduct of it [25], [37]. CBDC could be utilised as an additional monetary policy tool [22], [24], [78] that could strengthen monetary transmission mechanisms and simplify conduct of monetary policy [87], because a central bank could use it as a transmission channel and directly manipulate account holder balances [20], [24], [43], [45], [50]. Account-based CBDC could support unconventional monetary policy [19] such as Quantitative Easing (QE) [20], contribute to the stabilisation of the business cycle [22] or bring fiscal advantages relating to seigniorage [19], [78]. Another example - a central bank could commit to an algorithmic rate of money creation [24], [43], [44] by directly manipulating account balances of electronic central bank money and/or the aggregate quantity of that money [20] via precise control over interest rates [22], [37], [46], [50] or overnight interbank rates [50], thus addressing or removing the limitations of the Zero Lower Bound (ZLB) on those rates [19], [23], [24], [44], [78], [87].

In addition, 23 papers debate the range of challenges to architectures and operations of Monetary Policy from CBDC introduction. Because a monetary regime with CBDC has never existed [22] and technology to make it feasible and resilient have not been available [2]–[4], [20]–[24], [37], [40], [50]–[52], [64], [66], [75], it is difficult to predict an impact of CBDC [19], [23], [44] on the monetary transmission mechanism [20]. From a monetary policy prospective, CBDC could provide a dangerous widespread balance sheet exposition of an economy [20]. Also, its introduction might unexpectedly affect the size and composition of the balance sheets of central banks, commercial banks, non-bank financial institutions, households and firms [20], [21]. It is also unclear how CBDC could effect a money supply and which algorithm or regulator/authority/group of entities would control the issuance of CBDC [101].

A central bank introducing CBDC would additionally face legal challenges [49], [87], [101] and have to ensure the fulfilment of AML / CFT requirements, as well as satisfy the public policy requirements of other supervisory and tax regimes [24], [43], [101]. Every jurisdiction considering a CBDC should carefully consider the implications before making any decision [24], [101]. "There is very little historical or empirical material that could help understand the costs and benefits of transitioning to such a regime, or to evaluate the different ways in which monetary policy could be conducted under it" [22], [24], [40], [101]. A move toward CBDC adoption would be premature [19], [20], [23], [37], [50], as further analysis of technological feasibility and operational costs / benefit is required [23]. So far, no central bank has a live operating CBDC system [4], [21], [38].

b: REGULATION FOR BLOCKCHAIN-BASED PCS SYSTEM OF CENTRAL BANKS

Central banks have an objective of maintenance of public policy interests through regulation of both large value and retail payment systems innovation [66]. There are some papers in the included literature that discuss regulatory approaches to DLT adaptation to central bank operated PCS systems. Only six of those outline benefits to regulators from blockchain-based PCS. For example, PCS system implemented on DLT could provide a central bank with an enhanced regulatory audit function, as information is more easily tracked and visible by all parties, enhancing resolution management capabilities [2], [56], [62], [101]. Furthermore, the laws and regulations applicable to DLT-based PCS can affect the manner, speed and extent to which any implementation or configurations of DLT can be adopted [52], [53] by financial services.

A further 11 papers offer a deliberation on legal challenges and risks from hypothetical DLT-based payment clearing and settlement. Application of blockchain technology to PCS activity is a new [53] paradigm, contrasting with current legal frameworks, e.g., statutes, regulations, policy and supervision that are well established [52], and have specifically been drafted to accommodate existing architectures of the system and hence the requirement for legislative adaptation to cover DLT-based PCS [47].

When entering into any financial transaction, the key risk is that the final/legal settlement will not materialise as expected [52]. "Settlement finality (or legal settlement) for post trade clearance and settlement is a legally defined moment in time at which the transfer of an asset, a financial instrument, or the discharge of an obligation is irrevocable and unconditional and not susceptible to being unwound following the bankruptcy or insolvency of a participant" [47], [52], [53], [58]. It is typically supported by a statutory, regulatory, and/or contractual framework underlying a given financial transaction [52]. Parties to a transaction and their intermediaries rely on that definition and timing of settlement finality when they update their own transactional ledgers to measure and monitor various risks and determine the ownership of assets [45], [52]. For a settlement to be achieved on blockchain, legal settlement finality may not be as clear. First, in arrangements that rely on a consensus algorithm to effect settlement finality [47], [52], there may not necessarily be a single point of settlement finality, as there can be a gap between the period in which new additions to the ledger are made and later confirmed into blocks [2]. Second, consensus protocols are probabilistic [45], [51], [52], [58], i.e., the payment is never fully settled because there is always a small probability that the payment could be reversed [58] due to forking [51], [54]. The existence of forks brings into question the nature of any claims and rights that depend on the ledger records for their proof and can pose serious legal risks for users [46]. If a group of nodes have a fundamental disagreement in the history of events and decide to create an alternative ledger causing a fork, it undermines the assumption that there always will be only one reliable and authoritative ledger [66], failing the settlement. Even though the settlement becomes increasingly certain as recorded transactions become immutable over time, it never reaches the point of being irrevocable [51], [52], [58]. The applicable legal framework does not support a legal settlement in such cases [47], [53]. As it is a critical element of risk management, a legal basis is required to clarify when settlement finality happens. This allows definition of the key financial risks and obligations in the system, including the point at which transactions become irrevocable [45], [47], [51], [53].

Furthermore, DLT-based PCS systems are exposed to being hosted in multiple jurisdictions simultaneously [2] which opens them to the risk of regulatory arbitrage, whereby participatory nodes become concentrated in jurisdictions with loose regulatory controls [2], [53]. Additionally, for DLT-based PCS systems, compliance with the Bank Secrecy Act (BSA) [47], [52], AML [45], [47], [52], [66], KYC [45], [52], transaction monitoring and reporting of suspicious activity [52] is not currently provided. For a large value wholesale payment system, the need to keep transactional data private from other parties is fundamental [51], [58]. "This is necessary to prevent other participants from being able to take advantage of this information. A participant's clients may also prefer or require this privacy" [58].

Lastly, as these technologies are not fail-safe, further risk of greater expense in recovery or litigation if such technology fails [66] cannot be overlooked. Decentralised systems do not provide an independent regulatory party that can facilitate dispute resolution [3] functionality, raising questions about conflict of laws and jurisdictions [47] that determine the nature and extent of rights and claims [66].

All of above-mentioned issues are costlier in a distributed (no governing jurisdiction) and permissionless (no identifiable responsible party) environment [47]. The questions of how and when transactional certainty and security is achieved, as well as responsibility and risk allocation among participants [66] need to be considered prior to blockchain adaptation. By itself, this is a costly operation [47]. One path to manage those risks, could be an incremental adaptation of blockchain for PCS [66].

6) TECHNOLOGICAL FACTORS

Understanding technological factors (or variables) is important to any organisation whose business model relies on technology. It enables development and exploration of new opportunities and is an important source of competitive advantage [108].

Tables 1 and 2 provide narrative summaries of the opinions, expressed in the included papers. These relate to the most prominent technical variables applicable to blockchain technology in the setting of central bank application.

D. STATISTICAL ANALYSIS OF RESEARCH TRENDS FOR BLOCKCHAIN USE-CASES

This section provides a narrative summary and further statistical insight into each separate use-case. Appendix E of this study provides a matrix of our research.

RQ4: What is the depth / breadth of the research for identified use-cases?

TABLE 1. Technological benefits of blockchain.

Technical Variable	Opinion of the Researchers
Access types	Permissionless [77], [101]; Permissioned [21], [22], [27], [36], [51]–[55], [57], [58], [58], [61], [66], [69], [86], [101].
Verification Process	In the permissioned blockchains, an ultimate authoritative verification is needed to be performed by the trusted party, meaning that existing intermediaries, that perform such functions will still be required [66].
Use of Smart Contracts (SC)	Automated modification to the rate of money creation via contingent SC could streamline monetary policy operations [46]; SC based automation of 'priority' for payments could ease spot liquidity needs [4]; For securities markets: • could facilitate DvP [36], [54], [66]; • automatic execution and payment of certain derivatives [69], [101]; • automate certain transfers based on pre-specified events agreed to by counterparties to a transaction [52]; • automate certain non-elective corporate actions [69]; • automation of facilitation, execution, or enforcement of the performance of certain contract terms could significantly simplify back office processes and records management [53]; • creation of dynamic transactional document - a close-to-real-time "digital doppelgänger" for each financial contract during its entire life span [73].
Network Effects	•A larger DLT-based settlement network could allow users to settle trades with more counterparties [51], thus increasing network externalities; • Network resilience is provided through distributed data management [52], where having a distributed database enables faster recovery, as well as protection at the system level [4] in the event of cyberattack or failure [51].
Data Provenance Traceability and Transparency on Blockchain	• Provides data auditability and immutability and higher level of transparency [52], [69], [73], [101]; •Transparent nature of global audit log on blockchain enables traceability of anything represented on the ledger, preventing manipulation through the public auditability of the system [4], [73]; •Offers immutable, tamper-resistant transactional records [27], [61], [73], [101], by ensuring a high cost for dishonest actions [54]; •Reduces the possibility of data falsification and manipulation [3], [101] lowering the risk of fraud and enhance resolution management capabilities [2]; •Ensures immutable records of the history of any flow of funds or securities, with traceable amendments, where the integrity of the records is ensured by the integrity of the ledger itself [51], [101]; •Immutability of data recorded in the ledger is crucial to the safety as it relates to data integrity [53], [101]; •Increased traceability of records stored on the ledger though consensus mechanism, which ensures who can change records and how [58]; •Traceability could further be provided via reliance on the user account address protocol, where a central bank could separate the user's identity and transaction information [27]; •Traceability could be utilised for compliance with KYC rules, AML requirements and CTF regulations [53], [101]; Overall data management costs reduction [51].
Use of Oracles	•Computer servlets, that are programmed to store data feeds externally – Oracles - could be utilised for automation of validation of user-provided information which could then be added to a blockchain ledger [69] •Establishment of Oracles as a DC (Data Center) layer could promote stronger supervision [27]
Point-to-point Data Transmission	•An opportunity to improve, or illuminate data reconciliation processes of shared transactional data between financial institutions that could reduce data discrepancy, facilitate quicker reconciliation, improve or remove burdensome back office activities [51], [53], [67] and refocus many of the hundreds of data intermediaries and financial market utilities that play a significant role in reconciling risk prone and costly standard and non-standard data [74]; •For example, the inter-bank payments require reconciliation between the different databases [56]. That will no longer be required, as the blockchain consensus algorithm could become a single, authoritative general ledger [56]; •These will simplify operational processes and reduce the number of financial intermediaries or illuminate some (32), as DLT could eliminate the need for centrally maintaining back-up systems [51]; •Decentrality (44), or disintermediation of third-party settlement could lead to cost reductions [?], [2], [4], [26], [51], [52], [56], [64], [65], [68], [69], [96], as well as decreasing some of the risks [4], [52], [56].
Increased Automation	A key feature of DLT technology is its programmability to automate certain functions [53], that allows for: • straight-through processing of transactions [66]; • automatic recording of transaction from different locations combined with secure and cost-effective data storing solutions [65]; • automation of clearing and simplification and automation many of the back-office processes currently involved in the post-trade cycle [51], [58].
Enhanced operational Efficiency through Faster Processing	•Increased operational efficiency for settlement for cross-bank or cross-border transfers [26], [51], [63], could reduce complexity [52] and improve end-to end operational speed [52], [55], [68], [69], by, e.g., reducing duration of settlement cycle [51], [58], to near-real time [56], [58], [61], or even to 24/7/365 processing [65]; •Faster transfers suggest that financial market participants will receive their funds and securities more quickly, freeing up liquidity that could be tied up in collateral [53].
DLT as the Platform for CBDC	This is the most widely investigated use-case by central banks to use blockchain as the underlying platform to launch their own CBDC [4], [27].

TABLE 2. Technological limitations of blockchain.

Technical Variable	Opinion of the Researchers
Still Evolving Technology	Currently, not one central bank has implemented a "live", operational system based on blockchain, because the technology is still "maturing" [4], [21], [42], [50], [52] it still has not been properly evaluated or tested [2]–[4], [51], [64], [66], [101], meaning that the impact of its adaptations is still uncertain [19], [20], [37] and further analysis of technological feasibility and operational costs is needed [23], [24], [101].
Network Effects	Difficulties in building new participant networks because of reluctance to change already established complex business processes [77], combined with reluctance to give up various degrees of existing control and re-alignment of incentives of different participants [4], [52].
Interoperability	Lack of interoperability between blockchains and legacy financial market infrastructure and/or between numerous niche blockchain protocols is an important issue that creates fragmentation, friction and raised costs due to increased complexity of connections to and use of different systems, leading to more operational and systemic risks [2], [4], [51], [52], [66], [69].
Smart Contracts (SC)	• There are challenges with self-executing SC, as those are not immune to faulty or malicious code that could cause adverse and unpredictable behavioural patterns in the financial ecosystem [53] and latency in correction of errors; • Interdependencies between SC could result in a transmission channel for unforeseen risks [53]; • The legal status and nature of SC is not defined and is unclear [45], [47], [52], [53], [69].
P2P	There are significant drawbacks with P2P networks: • the design goal of a P2P network (t avoid all regulations) is in direct contradiction to a principal design goal for any financial systems with compulsory regulation [62]; • the multipath connection inherent in a P2P network creates barriers to regulation [62]; • difficult to monitor and control P2P applications as operations may be autonomous and decentralised [62]; • irregularities such as copyright infringement and security leaks [62]; • each node in a P2P network serves as a client as well as a server, the performance of a P2P network is inherently slower than a regular network [62].
Cost of Processing	Significant cost associated with running public permissionless blockchains in terms of network bandwidth, storage and processing power [2], [53], [73]
Scalability and Operational Capacity	There are significant concerns with operational capacity and scalability of blockchain's ability to process large volumes of transactions on a daily basis or handling unexpected pick volumes in times of market volatility – a crucial requirement of current PSC systems [3], [4], [50], [52], [53]. Only limited numbers of simultaneous transactions can be written in a block due to set limits on a block size [2], [47] and the consensus mechanism used [53].
Consensus Algorithms	Current consensus algorithms, combined with cryptographic verification and validation (44), from a technical point of view, introduce latency though complexity and limit the number of transactional transfers to financial data processing, when compared to existing PCS systems [3], [51], [52]
Mining	In a permissioned blockchain, mining is seen as irrelevant; participating banks maintain those ledgers and thus miners and the mining process are not needed [62] and seen as a dead-weight cost [54]
Immutability	Irreversibility of events born from immutability of blockchain is an important issue, as it prohibits error handling, transactions reversal in case of fraud, technological misuse or other events and hampers maintenance [3], [4], [51]–[53], [66], [101].

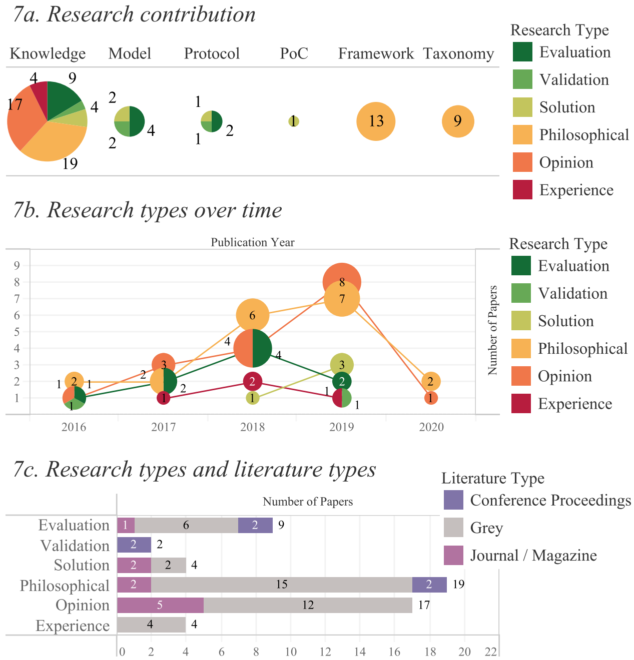

FIGURE 7. Central bank digital currency.

1) CENTRAL BANK DIGITAL CURRENCY

According to a generalised definition, a Central Bank Digital Currency (CBDC) is an electronic, 24 × 7, fiat liability of a central bank that can be used as a digital account or as an electronic token [19] to settle payments or as a store of value [19]–[23] and could provide access to a central bank's balance sheet [22]. It is an electronic central bank or narrow money [20]–[22], intended as legal tender [23], [24] that can be exchanged [25] in a decentralised manner, known as peer-to-peer (P2P). This means that all transactions occur directly between the payer and the payee, without the need for a central intermediary [26].

Fig. 7 shows representation of CBDC use-cases in the included literature. Out of 39 publications (Fig. 6 a) describing CBDC, 11 publications employ Empirical research types with nine publications using Evaluation and two Validation Research approaches (Fig. 7 c). As contribution to techniques (Fig. 7 a), Evaluation papers add four models [27]–[29], [85] and two protocols [27], [28]; Validation research adds two models [30], [31] and a protocol [30]. Interestingly, the majority of Evaluation research was provided via grey literature and all Validation research was communicated during conferences (Fig. 7 c). Over time (Fig. 7 b), the bulk of industry and data driven papers (Evaluation) were available in 2018, totalling 4. Validation research on CBDC was only published in 2016 and 2019 - a single paper for each year. The data indicates that empirical research on CBDC is steadily growing, predominantly includes industry cooperation and provides the largest contribution overall of novel techniques and technologies.

Amongst Empirical papers, the research of Hileman and Rauchs [4] provides a wide global benchmarking study on blockchain current areas of focus, attitudes toward the technology and outstanding questions. Researchers use surveys and focus groups to identify which overall blockchain use-cases were investigated by central banks (and a wider community of practitioners), maturity and future roadmap of that research. The authors establish that 82% of central banks were investigating DLT as a platform to launch CBDC [4]. Agur *et al.* [85] analyse the optimal CBDC design that maximises social welfare by comparing non-interest-bearing versus interest-bearing CBDC and the degree to which the CBDC resembles cash [85]. Researchers evaluate impact of those design choices onto cash, bank deposits and bank intermediation. The network effect lies in the core of their model. They show that when CBDC is designed as non-interest-bearing, its similarity to cash becomes the sole design choice [85]. If CBDC is designed as interest-bearing, it safeguards bank intermediation and provides households with a variety of payment instruments [85]. Chiu *et al.* [29], with cooperation of the Bank of Canada address implications of CBDC issuance for monetary policy and banking. They built a "tractable model" to represent imperfect competition in the deposits markets of the banking sector. Using quantitative analysis to demonstrate that an interest-bearing CBDC could promote bank intermediation, increase lending and aggregate output, they showed that the design choice of CBDC, competition level in the deposit market and the interest rate on CBDC does effect the banking system and real economy [29]. Kang and Lee [31] develop a "search theoretical model", where public cryptocurrency is used as a medium of exchange and coexists in an equilibrium and competes with central bank issued fiat money, thus affecting monetary policy, overall economic activities and welfare. Their quantitative analysis showed that, provided there is a sufficiently high inflation rate (to justify cryptocurrency mining fees), public permissionless cryptocurrency is able to compete with fiat money. However, due to the inefficient cryptocurrency mining process, the welfare in economy with both fiat money and cryptocurrency is lower than that in a money-only economy [31]. The rest of the Empirical papers use permissioned blockchain as a platform to launch CBDC, controlled by a central bank [27], [28], [30]. Two [27], [28] propose multi-blockchain models and evaluate their feasibility and scalability. Danezis and Meiklejohn [30] propose two "thread models", where transactions were processed with and without minters. Two papers use experiments [27], [30]; one use simulation [28]. Sun *et al.* [27] propose a protocol for "inter-blockchain transactions", design of which was influenced by the Practical Byzantine Fault Tolerance (PBFT) [32] algorithm and Bitcoin blockchain [5]; Tsai *et al.* [28] provide a consensus protocol for two types of blockchain - a "trading blockchain" and an "account blockchain"; Danezis and Meiklejohn [30] also use Bitcoin [5] as a consensus protocol for transaction validation.

Although not empirically validated, four Solution Proposal papers (Fig. 7), provide a novel protocol and PoC [33] and two models [34], [35]. Those contributions are communicated as purely academic articles and via grey literature and the first was available in 2018 following the other three in 2019. There are 19 Philosophical papers contributing 13 novel frameworks and nine taxonomies, as some of those contributed both. The majority of those are communicated from industry through grey literature and availability of those steadily growing each year, peaking in 2019 at seven publications and two papers for half of 2020. Opinion research is also heavily dominated by grey literature (12 out of 17 papers) and its availability grew constantly, with 2019 bucking the trend with eight papers and one in 2020. Experience papers only briefly appeared in 2017 (one paper), 2018 (two papers) and 2019 (one paper) and all are provided as grey literature. This data indicates that industry is also heavily involved in the theoretical discussion about CBDC.

Wu *et al.* [33] (Solution proposal) suggest using PoC, a Bitcoin blockchain [5] based electronic currency protocol to support anonymous payments. The protocol provides full access of transaction history to supervisors and auditors. The authors use blind signature technology, public key signatures and Proof-of-Work (PoW) consensus. In another Solution Proposal paper, Borgonovo *et al.* [34] provide a "primer model" to analyse demand for CBDC by identifying drivers of the political consensus in favour or against it. The research uses a "financial portfolio approach" and assume that the prospect of issuance of CBDC would influence individual portfolio choices. Brunnermeier and Niepelt [35] provide a "generic model of money and liquidity which identified sources of seigniorage rents and liquidity bubbles" and apply that model in the context of CBDC introduction for the use by general public. Their results imply that: "CBDC, coupled with central bank pass-through funding, need not imply a credit crunch nor undermine financial stability" [35].

Philosophical type is utilised in 19 papers to communicate research approach and contributions to knowledge. Amongst those, nine contribute taxonomies [23], [24], [26], [36]–[39], [86], [101] and 13 add new frameworks [19], [23], [24], [30], [35], [40]–[44], [84], [85], [101], three of which [23], [24], [101] contribute both. Out of nine novel taxonomies, two papers provide taxonomies of potential benefits and cost for a central bank from issuing CBDC [26], [39]; the other two propose taxonomies of existing forms of money in relation to CBDC [24], [37]; a further four offer taxonomies of CBDC projects and ongoing technical design efforts in other countries' by central banks [38], [39], [86], [101]; Auer and Böhme [86] sets out an additional taxonomy in the same paper for the underlying design trade-offs, that maps consumer needs hierarchy for designing a retail CBDC; Lipton [36] suggests a general taxonomy of potential blockchain applications to money and banking. Out of 13 novel frameworks, eight papers offer new conceptual frameworks to characterise various design features of potential CBDC: Arner *et al.* [101] consider design parameters for CBDC such as: users, scope, architecture and technology, within which they envisage three alternative CBDC architectural approaches: 1) central bank accounts with general access, 2) central bank accounts with intermediated access, and 3) new digital forms of fiat currency. By doing so, they analyse the impact of DLT and blockchain onto monetary and payment systems [101]; Engert and Fung [19] set out a framework of the features for a benchmark CBDC that are similar to cash; Agur *et al.* [85] build a theoretical framework tailored at analysing the relationship between CBDC design, welfare analysis, the demand for money types and financial intermediation; Han *et al.* [84] provide a theoretical guidance for a three layered blockchain-based CBDC framework that includes supervisory, network and user layers, incorporating account-based and wallet based mainstream models; Cœuré and Loh [24] and Pfister [44] propose conceptual frameworks for understanding the difference between a retail or general purpose CBDC and a wholesale CBDC; Kahn and Wong [42] provide a theoretical framework for account-based, token-based and delegated (i.e., as custodians and intermediaries) CBDC schemas; Koumbarakis and Dobrauz-Saldapenna [43] set out a framework and formulated broad design principles for CBDC in line with the central bank's function as a Lender Of Last Resort (LOLR). Furthermore, Griffoli *et al.* [23] offer a conceptual framework to compare different forms of money and another framework that provides an understanding about the roles of CBDC from a user prospective. Fung and Halaburda [41] propose a framework for central banks for accessing why and how they should consider issuing CBDC. The same framework can be used by the general public to make payments and could be implemented to improve the efficiency of retail payment system. Brunnermeier and Niepelt [35] provide a general framework for the analysis of monetary economics in the context of introduction of CBDC. Their framework: "Augments the standard asset pricing formula with a liquidity kernel". Danezis and Meiklejohn [30] present the first cryptocurrency framework "RSCoin" that provides control over issuance of CBDC and the monetary policy to a central bank.

The remaining papers – Opinion [19], [25], [37]–[39], [42], [43], [45]–[50], [87], [101] and Experience [19], [24], [42], [44] papers provide a discussion on design characteristics of CBDC [25], [37], [38], [43], [44], [47], [50], [101], why and how a central bank should issue CBDC [19], [24], [42], [45], [48] and potential hazards from CBDC issuance [19], [46], [47].

2) PAYMENT CLEARING AND SETTLEMENT SYSTEMS OPERATED BY CENTRAL BANKS

Payment Clearing and Settlement (PCS) systems of a central bank are characterised by processes, such as payments (i.e. order management, including trade validation [51]), post-trade securities clearing (i.e. the calculation of counterparties' obligations [51]), and post-trade settlement (i.e. the final transfer of assets [51]). Those systems also involve several different types of financial intermediaries [52], [101] and infrastructures invoked from the time a trade in a financial security is agreed to the time when it is finally settled [51].

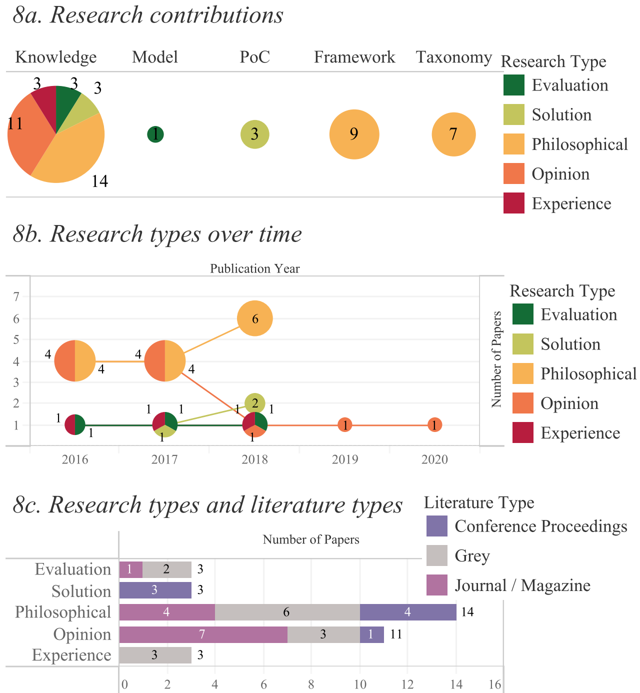

FIGURE 8. Payment clearing and settlement systems operated by central banks (PCS).

"Central banks have traditionally played an important catalyst role in payments and settlements" [53]. PCS processing systems of today are cumbersome and involve lengthy reconciliation tasks [51]. Finally, operational, settlement, legal and financial risks are inherent in the conduct of PCS system activities [52], [101].

Fig. 8 represents a blockchain underpinned PCS usecase in the included literature. There are 27 papers (Fig. 6 a) providing various contributions (Fig. 8 a). Empirical Research is only presented in three Evaluation papers [4], [52], [54] – 9% of all papers on blockchain applications for PCS and those papers were available between 2016 - 2018; two of them are grey literature. There is no Validation research available in the included publications. One model is added as a technological contribution by Chiu and Koeppl [54]. The remainder of all research only make theoretical contributions. The data indicates that, although comparatively small, all empirical research has industry input or drivers, because the Evaluation research approach involves industry participation [6].

As a step towards understanding the implications of DLT deployment to PCS systems and to identify the opportunities and the challenges facing its long-term implementation and adoption, a research team of the Federal Reserve Bank (FED) [52] conducted interviews with focus groups interested in participating in, or otherwise contributing to, the evolution of DLT [52]. In their report, the team summarised the approaches taken by industry to investigate the potential of blockchain [52]. Hileman and Rauchs [4], also based on the results of surveys and focus groups, report that overall: "55% of central banks are exploring DLT-based payment systems for remittance transfers, inter-bank payments, and other uses'' [4]. The only model contributed by Chiu and Koeppl [54] investigates the extent of potential financial gains or losses, if financial securities were to be settled on blockchain. The distinctive technological features of blockchain are explicitly modelled for asset settlement [54]. They investigated, both qualitatively and quantitatively, using mathematical analysis: its feasibility, optimal block size and time. The authors chose to consider a permissionless blockchain, which ensures delivery-vs-payment (DvP) by linking transfers of assets with payments and where updating of records is based on a proof of work (PoW) protocol.

Three papers utilise Solution Proposals for research communication of PoCs [55]–[57], all of which are proceedings of conferences, one in 2017 and two in 2018 (Fig. 8). 42.42% (or 14 publications) are Philosophical papers which provide nine novel frameworks and seven taxonomies, with two adding both [24], [53]. Over time, the addition of those papers to research was steady, with four for each of 2016 and 2017, increasing to six in 2018; the variety of literature types is relatively balanced, with grey literature slightly leading that trend. A third of publications (or 11) are Opinion Papers rising in availability in 2017 and being the only paper published for 2019 and for 2020. Those papers are principally shared as pure academic articles. Three experience papers [24], [52], [58] are all shared as grey literature, one for each of 2016 - 2018. This data indicates that the theoretical elaboration on the topic of utilisation of DLT for PCS is consistent and well-balanced between academics and industry. However, there are potential early signs of reduction in interest due to lack of availability of new research and the creation of a gap in the state of knowledge; as for the majority of 2019, there were noticeably few new research engagements on this topic.

Out of three Solution proposals, two [56], [57] explore application of blockchain for ''inter-bank payment systems (IBPS)'' and one explores use of blockchain as a ''clearinghouse'' [55]. For their project, Tsai *et al.* [55] adopt a permissioned DPT (Double-chain Parallel-processing Technology) developed at Tiande to facilitate a ''multi-blockchain clearinghouse'' experiment and demonstrate its feasibility via PoC. Wu and Liang [56] utilise a Bitcoin blockchain [5] to build a distributed ledger prototype system for credit matching of trading system for X-Swap and [57] use Hyperledger Fabric [59] to develop an end-to-end IBPS prototype to design a fund transfer functionality enabling gross settlement for Real Time Gross Settlement (RTGS) systems. A total of 14 papers use Philosophical methods to communicate new knowledge. Amongst those, nine add new frameworks [24], [41], [53], [55], [57], [60]–[63] and seven contribute taxonomies [24], [36], [51]–[53], [64], [65], with two of them [24], [53] contributing both. Out of nine frameworks, two papers offer multi-blockchain frameworks for integrating DLT into PCS processes [55], [62]. Three papers consider blockchain-based IBPS frameworks [57], [60], [63]. The remaining papers, such as 11 Opinion [2], [3], [45], [51], [64], [66]–[70], [101] and three Experience papers [24], [52], [58] provide a discussion on the potential impact of DLT on PCS processes.

3) ASSET TRANSFER AND OWNERSHIP

Any financial instrument, such as a monetary instrument, security, commodity or derivative is an asset [52]. ''PCS systems are typically organised around a specialised third-parties called Central Securities Depository (CSD), which are responsible for transfers of legal ownerships of securities/assets against payments'' [54]. Additionally, a variety of financial intermediaries, on behalf of their clients, can hold or trade those assets or securities [52]. In today's markets, it is a common occurrence that investors are not the direct owners of the traded assets, but they hold them indirectly through chains of financial intermediaries that operate between asset issuers and those investors [51]. ''This is partly a legacy from the time where securities were issued as paper certificates and had to be immobilised to facilitate their trading through book-entry transfers'' [51].

Fig. 9 shows a representation of the assets use-cases for blockchain in the included literature. Out of 12 papers (Fig. 6 a), describing assets transfer and ownership, one adds a model (Fig. 9a). There are only two Evaluation papers published [4], [54] as an article and as a grey literature, one in 2017 and another in 2018; one contributes a model [54]. There are no Validation papers on this use-case. Overall, the data on empirical papers does not provide a particular pattern, apart from that its availability is low and all available research has industry involvement. This might indicate a potential knowledge gap for empirical research.

Out of two Evaluation papers, Hileman and Rauchs [4] state that only 23% of central banks were investigating the ownership record management capabilities of blockchain. Chiu and Koeppl [54], whilst explicitly modelling feasibility of blockchain for assets trading, establish that the key innovation from blockchain to their model is that it provides a shared database of security ownerships [54] that can be updated without relying on multiple, specialised intermediaries or a third-party infrastructure [54].

One solution proposal [71] provides a PoC in 2018 via a conference (Fig. 9). The same paper also adds a framework. The majority - 69.23% or nine - are Opinion papers, four of which were published in 2017, with 2018-2020 supplying one additional papers for each year. One of those papers came from a conference, with industry and academics providing an additional four each. There is no Experience research available for this use-case. This data indicates that theoretical discussion on this topic is mainly hypothetical as there is no practical experience available upon which to draw justifiable conclusions.

Chen *et al.* [71] utilise two research types for their paper to communicate two contributions, a Solution Proposal for PoC, where they propose a ''financial product management platform'', that provides capabilities for multi-function financial data inquiries, routine maintenance of financial products

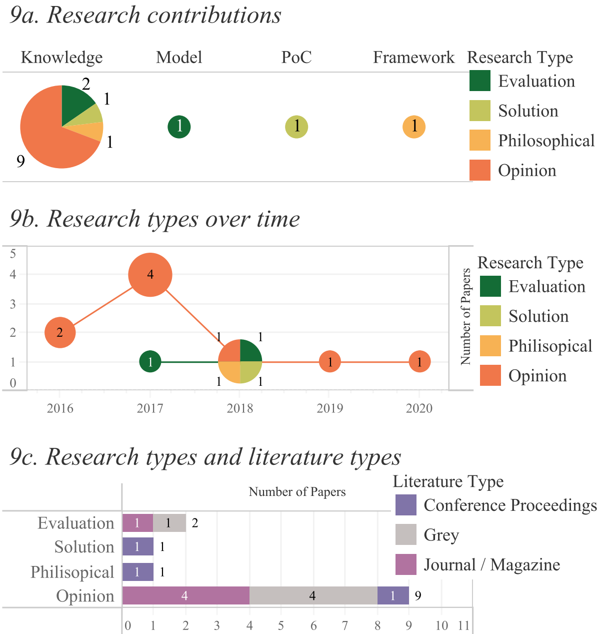

FIGURE 9. Assets transfer and ownership (Assets).

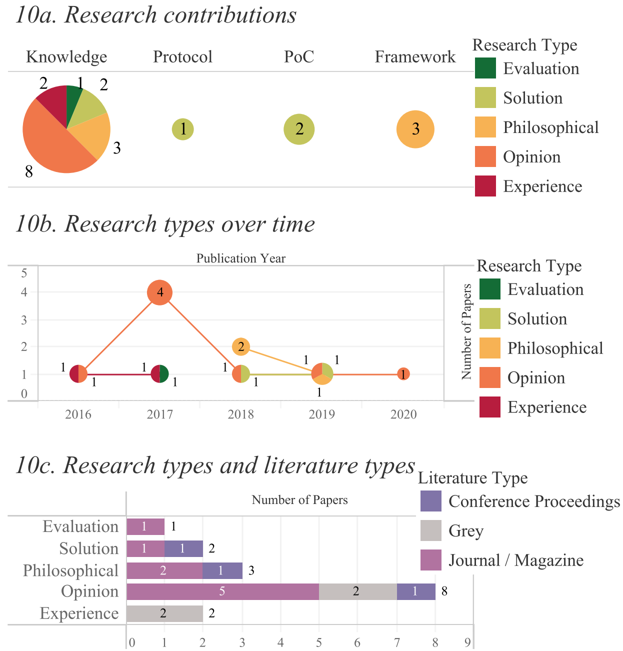

FIGURE 10. Audit trail (audit).

and multi-institution traceability. Their platform is based on Hyperledger Fabric [59]. The researchers also construct a "financial product management framework" for deployment of transactional logic for blockchain. Opinion papers provide a high-level discussion of both hypothetical benefits and limitations from application of blockchain to asset transfers and ownerships [2], [45], [47], [51]–[53], [62], [69].

4) AUDIT TRAIL

The BOE states that as part of a central bank's accounting reporting procedures, it: "Has a responsibility for reviewing the findings of internal and external auditors and monitoring outstanding actions. It receives and reviews reports on the risk profile of a central bank and inter-bank market participants" [16]. A large number of auditing processes believed to be simplified or even eliminated by automation of the audit trail on blockchain [72].

Fig. 10 provides a representation of the audit trail use-cases for blockchain in the included literature. Out of 14 papers (Fig. 6a), exploring the influence of blockchain on auditing performance of a central bank (Fig. 10 a), one adds a protocol. There was only one Evaluation paper available in 2017 which only contributes to discussion via an academic journal [4]. There are no Validation papers for this use-case. The data indicates that empirical research is comparatively low (signalling a potential knowledge gap), purely theoretical and, again, only with industry cooperation. The only available Empirical paper by Hileman and Rauchs [4] established that only a comparatively small proportion of central banks (18%) had specifically mentioned that audit trails, e.g., tracking of payments, are under investigation [4].

Two papers provide Solution proposals (Fig. 10), via PoC [57], [71] through a journal and a conference in 2018 and 2019, and one of them provides a protocol [71]. Three Philosophical papers all add frameworks in 2018 and 2019, two in journals and one through a conference. 50% of all papers are Opinion papers, peaking in 2017 at four publications; one more was added for 2018 - 2020. Interestingly, there are two Experience papers published as grey literature at the beginning of the period in 2016 and 2017. The data indicates that, although comparatively low, theoretical discussion on this topic has been underpinned by some practical experience from industry practitioners, although academic journal articles are now leading the conversation.

Both Solution proposals utilise Hyperledger Fabric [59] for their underlying architecture. Chen *et al.* [71] propose a "financial product management platform" that provides a multi-institution / multi-function data audit capability. Wang *et al.* [57] introduce an "end-to-end IBPS protocol" - that provides provenance tracking functionality for auditors. By leveraging the immutability of blockchain ledger, their protocol equips auditors with the ability to trace back the history of records and conduct reconciliation [57]. There are three papers that contribute via frameworks. Chen *et al.* [71] and Wang *et al.* [57] construct frameworks for auditors to track financial product data provenance on a blockchain. Kavassalis *et al.* [73] provide a framework for financial transactions as well as financial risk reporting; they report a transactional audit trail to the qualified authorities about all significant circumstances under which a transaction took place [73]. Eight Opinion papers [2], [3], [45], [51], [53], [64], [69], [74] and two Experience papers [52], [58] provide a high-level discussion of how implementation of DLT in central banks could affect their auditing capabilities.

5) REGULATORY COMPLIANCE

Hayes [75] states that the most visible function of a central bank is that of a monetary authority. A generalised legal

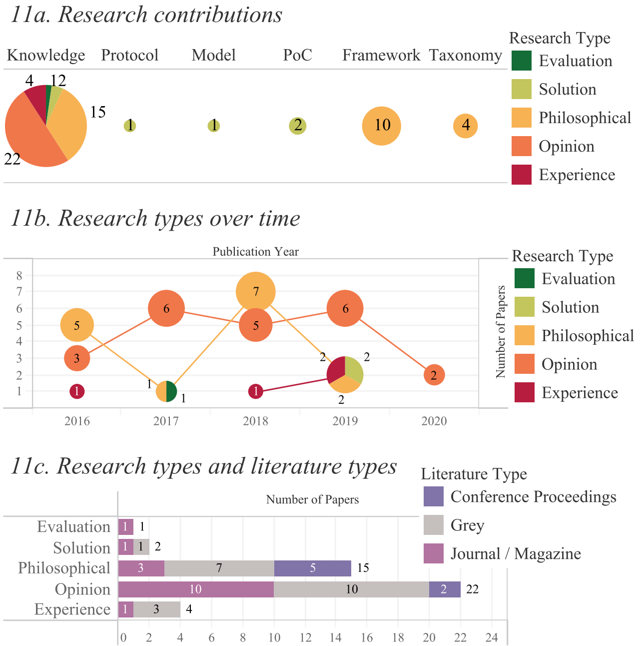

FIGURE 11. **Regulatory compliance (regulators).**

consideration for a central bank acting as a financial regulator consists of a legal framework which includes general laws, regulations, rules, procedures and contracts [53].

Fig. 11 represents the regulatory compliance use-cases for blockchain in the included literature. In total, 37 papers (Fig. 6 a) examine the impact from blockchain on the functionality of a central bank as a financial regulator (Fig. 11 a). Only one publication is empirical - an Evaluation paper [4] in 2017 via a journal. The only Empirical paper of Hileman and Rauchs [4] reports a response from surveys and focus groups that: "36% of central banks have been investigating DLT for regulatory compliance, such as automatically enforce market regulation" [4]. This data reveals that empirical research is comparatively low and only with industry cooperation, signalling a potential knowledge gap.

Two Solution Proposal papers [33], [76] contribute two PoCs and a model in 2019 as a pure academic article and as grey literature (Fig. 11). Over a third of all papers on this topic (15 publications) are Philosophical papers adding nine novel frameworks and four taxonomies via diverse literature cohorts. Most of those papers were published in 2016 and 2018. Over half of all regulation use-case papers are Opinion papers (22 in total), with almost half of those available as academic articles, presenting a somewhat steady trend in popularity over the years. There are also a total of four Experience papers added in 2016, 2018 and 2019, with three of those represented by practitioners via grey literature and one as a purely academic article. This data indicates that the theoretical discussion on this use-case is ongoing, diverse and potentially underpinned by practical experience from industry practitioners and academics. Auer [76] using PoC, models a blockchain based automated "embedded supervision" functionality for novel distributed markets. The model provides for economic finality in a permissioned market with decentralised verification. A CBDC protocol proposed by Wu *et al* [33], based on a Bitcoin blockchain [5], provides supervisors with ability to oversee unanimous payments via unrestricted access to the blockchain ledger. 15 Philosophical papers mostly contribute frameworks - 10 papers [40]–[42], [55], [60], [62], [73], [75], [76], [84], vs. four taxonomies [24], [51], [52], [77]. Four of those papers [40]–[42], [84] propose frameworks that utilised CBDC as a transparent transactional ledger visible to regulators, e.g., "custodians and intermediaries CBDC schemas" of Kahn and Wong [42] or the three-layered CBDC framework of Han *et al.* [84] that includes a supervisory layer. Two other papers utilise a blockchain-based PCS architecture as "a promoter of regulatory informant" [62] or as a participating regulatory node in DLT-based PCS [55]. Two further papers offer frameworks for central banks and regulators to assess legal risks from blockchain, such as risks to legal settlement finality, issues with a management and protection of data, connectivity with legacy systems, standards development [53] and suitability for KYC compliance [60]. Hayes [75] provides a conceptual framework for a workable decentralised central bank (DAO bank) to perform functionality of a "technocratic, rules-following monetary authority". Kavassalis *et al.* [73] propose a novel framework for a "regular technology (RegTech) approach for financial transactions, as well as financial risk reporting, which is based on distributed computing, decentralised data management technologies such as blockchain, distributed storage, algorithmic financial contract standards, automated legal text and document engineering methods and techniques" [73]. The researchers provide a proposal of: "How to develop a new layer of algorithmic regulation functionality, that enhances a supervisor's capacity to monitor the evolution of risk in the system" [73]. Auer [76] makes a "case for embedded supervision, i.e., a regulatory framework that provides compliance in tokenised markets to be automatically monitored by reading the market's ledger, thus reducing the need for firms to actively collect, verify and deliver data" [76]. Out of four taxonomies Nguyen [77] classifies overall legal and policy challenges about potential blockchain applications for banking. In relation to potential implications from the regulatory point of view onto blockchain-underpinned PCS, Benos *et al.* [51] provide a taxonomy of potential regulatory improvement, whereas Mills *et al.* [52] offer a set legal challenges. Cœuré and Loh [24] categorise Monetary Policy aspects for CBDC issuance.

Out of 22 Opinion Papers, seven discuss various ways of how DLT could be approached from a regulatory perspective [2], [37], [45], [67], [69], [74], [88], four examine impact of blockchain on Monetary Policy and Monetary Reforms [2], [3], [69], [78], seven deliberate on regulatory motivation for CBDC issuance and its effects on Monetary Policy transmission [24], [25], [42], [49], [50], [87], [101] and four reflect on the role of regulators for DLT-based PCS [51], [53], [66], [70]. Also, four Experience papers [24], [44], [52], [79], discuss questions that need to be considered by the regulators when assessing adoption of DLT for financial markets [67], legal considerations for PCS and blockchain [52] and Monetary Policy implications of CBDC [24], [44].

V. DISCUSSION

A. THREATS TO VALIDITY

For any empirically-based research, we need to consider the threats to the validity of the work Petersen *et al.* [7]. The following types of validity have been considered, enabling awareness of the potential limitations to the classification schema: theoretical validity, descriptive and interpretive validity and possibility of missing relevant articles.

Theoretical validity: there is potential for *researcher bias* in the selection of the studies and reporting of the results as the majority of work for this SMS was conducted by an individual researcher. To reduce this threat and gain confidence in the results, study identification was additionally evaluated through forward snowball sampling, where only 13 new studies were identified, indicating no measurable change to the search results. Additionally, one should keep in mind potential for the *publication bias*, as new controversial negative views are less likely be published [7]. To minimise this bias, only well-known scientific databases, in combination with rigorously designed search protocol were used to collect as many as possible available papers. However, as the research topic has proven to be a rather young research area, it is conceivable that further research has been administered by the industry and potentially either published as the ''white papers'' or kept confidential. SMS research on this topic using focus on grey literature as its source, could be an area for additional future research direction.

Descriptive and interpretive validity: there is a potential threat to accuracy of data extraction, recording and description, since in this qualitative study those processes are partially underpinned by the researcher's knowledge and understanding of the domain. To increase the descriptive validity of the study and following the guidelines of Petersen *et al.* [7], a data collection form was designed and implemented. This allowed us to make the data extraction process objective and, if necessary, amendable.

Possibility of missing relevant articles: The decision to limit this mapping study to the literature published since January 2008 does mean that there is a possibility of missing some relevant publications from before this time. However, given that the results show that there was no literature available even before 2016 on this topic, it is highly unlikely that even if there were potential unidentified papers available before 2008, that they would significantly impact final conclusions. Furthermore, creation of a search phrase was a challenging task, in particular the differences in functionality and sophistication between the different mainstream search engines, because each search engine required a different search expression syntax. To mitigate the challenges of the search phase the search for relevant literature was conducted as thorough as possible, by including an automated database search, followed by manual search, followed by forward snowball citation checking. Despite this thoroughness, there is always a possibility that some relevant articles were missed.

B. RESEARCH MATURITY

Although the hype about the capabilities of the blockchain started between 2008 - 2009, when its novel implementation through Bitcoin cryptocurrency reached worldwide news channels, it is evident from the data that the attention of research community to this topic is very recent, where first publications were first available from 2016 (Fig. 3b). This falls in line with other researchers' opinions, that the application of blockchain to the business of central banks is at a very early stage [3], [4], [19]–[25], [37], [40], [50]–[52], [64], [66], [75]. Industry is still providing large proportions of empirical technological and theoretical contributions to the field, with participation of academia predominantly on the non-empirical side of the research. Furthermore, the data implies that the overall trend of the engagement from the research community is growing, although it is difficult to judge with confidence about the trend for 2020 since our database search was done during the beginning of the second quarter, where a proportion of papers are still unpublished, but this does not invalidate the results we have presented.

As the topic of this study is a comparatively new area, there is also a distinct lack of validated research or data to support hypotheses. As described in Section IV.A.3, Empirical Research was only used 13% of the times and the majority of that research was Evaluation Research, involving participation of industry experts. The study has identified a clear need for more quantitative/empirical work in the area to evaluate aspects of blockchain. A common criticism of many areas of software engineering is that academic studies fail to appreciate the demands and pressures exerted on industry. As a result, there is almost a chasm between what academic studies do and what industry wants. The trend seems to be being repeated in this relatively new area. Empirical studies should involve industry and academia, address pressing issues in industry and focus on industrial impact. The results in this paper show a mixed picture thus far.

C. USE-CASES

Section IV.B showed that uses-cases for application of blockchain for central banks belonged largely to CBDC, Regulation or PCS. The largest proportion of empirical research and novel technological contributions were applicable to CBDC use-cases, where again, we can see a heavy presence of grey literature. The regulatory compliance use-case for blockchain closely follows CBDC by the amount of interest, although the majority of that research is done utilising non-empirical methods to generate large ongoing discussion from a diverse cohort of researchers. Interestingly, although a very popular use-case from the onset of the research availability, DLT-based PCS systems exhibit a sudden knowledge gap between 2019 and 2020. Further evaluation of the reasons for this lack of interest from the research community could reveal some hidden insights. In relation to asset transfer and

TABLE 3. Database search results (Appendix A).

D*	Database Applicable Search String	R*	I/E*
IEEExplorer	(“banking” OR “bank” OR “central bank” OR “reserve bank” OR “monetary authority” OR “monetary” OR “financial Intermediary” OR “financial Intermediation” OR “clearing” OR “clearinghouse” OR “settlement” OR “financial institution” OR “FinTech” OR “financial technology” OR “inter-bank” OR “IBPS” OR “real-time gross settlement” OR “RTGS” OR “payment settlement” OR “CBDC” OR “money supply” OR “monetary policy” OR “technocracy”) AND (“blockchain” OR “distributed ledger technology” OR “DLT” OR “smart contracts”)	995	30
Scopus	(“banking” OR “bank” OR “central bank” OR “reserve bank” OR “monetary authority” OR “monetary” OR “financial Intermediary” OR “financial Intermediation” OR “clearing” OR “clearinghouse” OR “settlement” OR “financial institution” OR “FinTech” OR “financial technology” OR “inter-bank” OR “IBPS” OR “real-time gross settlement” OR “RTGS” OR “payment settlement” OR “CBDC” OR “money supply” OR “monetary policy” OR “technocracy”) AND (“blockchain” OR “distributed ledger technology” OR “DLT” OR “smart contracts”) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008)) AND (LIMIT-TO (ACCESSTYPE(OA)))	1002	7
SSRN	bank blockchain	99	40
	banking blockchain	90	
JEL E4	blockchain	301	29
JEL E5	blockchain	198	13
JEL G01	blockchain	40	5
ScienceDirect	blockchain OR “distributed ledger technology” OR DLT OR “smart contracts” search within: banking OR bank OR “central bank” OR “reserve bank” OR “monetary authority” OR clearing OR clearinghouse OR settlement OR “real-time gross settlement” OR RTGS OR “inter-bank” OR CBDC OR “money supply” OR “monetary policy”	493	4
arXiv	bank* AND blockchain*	35	4
Web of Science	(bank* OR “central bank” OR “reserve bank” OR “monetary authority” OR monetary OR “financial Intermedia*” OR clearing OR clearinghouse* OR settlement* OR “financial institution*” OR FinTech OR “financial technology” OR “inter-bank*” OR IBPS OR “real-time gross settlement” OR RTGS OR “payment settlement” OR CBDC OR “money supply” OR “monetary policy” OR technocracy) AND (blockchain* OR “distributed ledger*” OR DLT OR “smart contract*”)	690	24
ACM	(+bank* +blockchain)	431	2
	Total	**4,374**	**158**
	Removing Duplicates		**142**

audit trail use-cases, both present somewhat similar trends, showing comparatively low engagement from researchers, providing non-empirically validated, theoretical views in the main.

Discussion of each of the separate use-cases in Section IV.C indicates that, although there are numerous advantages from application of DLT to the business of a central bank, potential limitations and issues constitute a comparatively large proportion of the debate:

CBDC models receive attention from the research community and central banks. Researchers are focusing on design characteristics of CBDC such as account versus token based CBDC or those designed for retail or wholesale money customers. If CBDC could pay interest on its holdings, researchers argue that it could remedy competition problems in the banking sector and promote financial inclusion. However, the questions of the role for central banks, disruption of commercial banks' business models, risks to smooth operation of payment systems, conduct of monetary policy and numerous legal challenges still remain unanswered.

In relation to hypothetical blockchain underpinned *PCS operated by central banks*, it is argued that for inter-bank, large-value wholesale payments blockchain could provide faster, close-to-real time 24×7x365 processing, reducing the need for centrally maintained back-up systems and reducing the number of intermediaries. By streamlining and speeding up post-trade value chain, PCS systems on DLT could free up collateralised liquidity quicker, thus improving availability of assets and resolving shortcomings of fractional reserve banking. On the other hand, faster processing will abolish the net benefits for liquidity provided by the (T+3) days settlement cycle. Furthermore, the probabilistic nature of blockchain-based settlements is a serious issue. Other limitations of current blockchains are its operational capacity, performance-based scalability, limitation of block size and issues with self-executing code. Immutability of DLT is also a problem, since PCS systems require a capability for error management, maintenance and management of technological failures or misuse.

Transfer and ownership of the assets through central bank-maintained systems has also been argued as a hypothetical beneficiary from blockchain adaptation. The tamper-resistant nature of blockchain could reduce legal, operational and overall systemic risks. Business sensitive information could be protected through encryption, while improving regulatory supervision and increasing transparency of asset ownership. On the other hand, issues with proprietary rights and obligations of assets on DLT and enforceability of the rights of the transacting parties in single or multiple jurisdictions are not assured by the current financial regulators and supervisors. There is not even a standardised definition of what constitutes a digital blockchain-based asset.

Small amounts of research are devoted to the enhancements to the *audit trail* for regulatory purposes from blockchain application. The immutable, tamper resistant nature of DLT promises to ensure traceability and transparency of audit for any history of funds and securities. However, blockchain-based auditing still requires regulators to accommodate record keeping by providing authoritativeness and reliability checks for those records.

Blockchain innovation for *regulatory compliance* is also extensively covered by the research. Development of blockchain-based technical interoperability standards, as a base connectivity layer promises to lower technological integration cost, provide access to more granular standardized data, thus bringing network scale efficiencies. Moreover, establishment of regulatory sandbox models should ease regulation in testing, development and delivery of blockchain solutions for central banking. Nevertheless, if blockchain application were to create risks in one area of central banking through interconnection of existing financial markets and interdependence of legacy payment infrastructures, these risks will be transmitted to the whole financial system. Furthermore, interoperability between blockchains and legacy financial systems or even between different niche DLT architectures is still in its infancy, leading to additional complexity, incompatibility and operational risks.

TABLE 4. The full list of headers of the data collection form (Appendix B).

Classification Schema	Data Types	Column Headers
Topic-Independent Classification Schema	Basic metadata	ID (Paper ID)
		Publication Year
		Publication Venue Name
		Publisher
		Literature Type
	Type of Empirical Research	Evaluation
		Validation
	Type of Non-Empirical Research	Solution Proposal
		Philosophical Paper
		Opinion Paper
		Experience Paper
	Research Contributions	Protocol
		Model
		PoC
		Framework
		Taxonomy
		New Knowledge
Topic-Specific Classification Schema	Blockchain-Based Use-Cases for Central Banks	CBDC
		PCS
		Assets
		Audit
		Regulation

Influence of *CBDC regime onto Monetary Policy* operations is also discussed by the research as another aspect of financial regulation. On the positive side, CBDC is seen as an appropriate policy response to the payment innovation, where it could be utilised as an additional monetary policy tool used e.g., as a policy transmission channel, simplifying systematic and transparent conduct of it, or a type of QE. A Central Bank can also commit to an algorithmic rate of money creation. On the negative side, the highly discussed issues are the immaturity of current blockchain architectures for CBDC adaptation and lack of empirical research on the impact of such CBDC regimes onto monetary policy performance. This leads to the conclusion that the move towards CBDC adaptation would be premature.

Lastly, the discussion on how *PCS application on blockchain can improve regulation* concludes that there is an opportunity for central banks to enhance their regulatory auditing functions, utilising data visibility offered by blockchain, hypothetically improving resolution management capabilities. On the other hand, issues arising from such novel systems attracts more attention from researchers as

TABLE 5. All included papers (Appendix C).

Reference ID	Document Title	Authors
[4]	2017 Global Blockchain Benchmarking Study	Garrick Hileman and Michel Rauchs
[40]	A 9-Dimension Grid for the Evaluation of Central Bank Digital Currencies	José Parra-Moyano and Arthur Macherel and Adrien Treccani
[84]	A Blockchain-based Framework for Central Bank Digital Currency	Xuan Han and Yong Yuan and Fei-Yue Wang
[63]	A Cash Flow Blockchain Based Privacy-Preserving	Xiaojun Zhai and Chongyang Zhang
[101]	After Libra, Digital Yuan and COVID-19: Central Bank Digital Currencies and the New World of Money and Payment Systems	Arner, Douglas W. and Buckley, Ross P. and Zetzsche, Dirk Andreas and Didenko, Anton
[28]	A Multi-Chain Model for CBDC	Wei-Tek Tsai and Zihao Zhao and Chi Zhang and Lian Yu and Enyan Deng
[66]	A New Era in Fintech Payment Innovations? A Perspective from the Institutions and Regulation of Payment Systems	Iris H-Y Chiu
[33]	A Regulated Digital Currency	Yanbing Wu and Haining Fan and Xiaoyun Wang and Guangnan Zou
[62]	A System View of Financial Blockchains	Wei-Tek Tsai and Robert Blower and Yan Zhu and Lian Yu
[73]	An Innovative RegTech Approach to Financial Risk Monitoring and Supervisory Reporting	Petros Kavassalis and Harald Stieber and Wolfgang Breymann and Keith Saxton and Francis Joseph Gross
[55]	Application of Blockchain to Trade Clearing	Wei-Tek Tsai and Enyan Deng and Xiaoqiang Ding and Jie Li
[60]	Applications of Blockchain Technology in Banking and Finance	Tejal Shah and Shailak Jani
[80]	Assessing the Impact of Central Bank Digital Currency on Private Banks	David Andolfatto
[47]	Banking in the Digital Age: Who is Afraid of Payment Disintermediation?	Benjamin Geva
[82]	Banking on Blockchain: Costs Savings Thanks to the Blockchain Technology	Luisanna Cocco and Andrea Pinna and Michele Marchesi
[34]	Between Cash, Deposit and Bitcoin: Would We Like a Central Bank Digital Currency? Money Demand and Experimental Economics	Emanuele Borgonovo and Alessandra Cillo and Stefano Caselli and Donato Masciandaro
[77]	Blockchain – A Financial Technology For Future Sustainable Development	Quoc Khanh Nguyen
[67]	Blockchain Application and Outlook in the Banking Industry	Ye Guo and Chen Liang
[68]	Blockchain Based Fnancial Case Analysis and its Implications	Soonduck Yoo
[79]	Blockchain Finance: Questions Regulators Ask	Peterson K Ozili
[45]	Blockchain, Securities Markets and Central Banking	Alexandros L. Seretakis
[71]	Blockchain-Based Implementation for Financial Product Management	Bihuan Chen and Zhixiong Tan and Wei Fang
[54]	Blockchain-based Settlement for Asset Trading	Jonathan Chiu and Thorsten V. Koeppl
[36]	Blockchains and Distributed Ledgers in Retrospective and Perspective	Alexander Lipton
[20]	Broadening Narrow Money: Monetary Policy with a Central Bank Digital Currency	Jack Meaning and Ben Dyson and James Barker and Emily Clayton
[39]	Cash Use Across Countries and the Demand for Central Bank Digital Currency	Tanai Khiaonarong and David Humphrey
[23]	Casting Light on Central Bank Digital Currency	Tommaso Mancini Griffoli and Maria Soledad Martinez Peria and Itai Agur and Anil Ari and John Kiff and Adina Popescu and Celine Rochon
[26]	Central Bank Cryptocurrencies	Morten L. Bech and Rodney Garratt
[24]	Central Bank Digital Currencies	Benoît Cœuré and Jacqueline Loh
[21]	Central Bank Digital Currencies: Design Principles and Balance Sheet Implications	Michael Kumhof and Clare Noone
[41]	Central Bank Digital Currencies: A Framework for Assessing Why and How	Ben S. C. Fung and Hanna Halaburda
[49]	Central Bank Digital Currencies: Preliminary Legal Observations	Hossein Nabilou
[29]	Central Bank Digital Currency and Banking	Jonathan Chiu and Seyed Mohammadreza Davoodalhosseini and Janet Hua Jiang and Yu Zhu
[25]	Central Bank Digital Currency and the Future of Monetary Policy	Michael D. Bordo and Andrew T. Levin
[43]	Central Bank Digital Currency: Benefits and Drawbacks	Antonios Koumbarakis and Guenther Dobrauz-Saldapenna
[19]	Central Bank Digital Currency: Motivations and Implications	Walter Engert and Ben S. C. Fung
[44]	Central Bank Digital Currency: One, Two or None?	Christian Pfister
[48]	Central Bank Issued Digital Cash	Andreas Furche and Elvira Sojli
[87]	Central Banks and Regulation of Cryptocurrencies	Hossein Nabilou and André Prüm
[50]	Central Banks and the Future of Money	John Murray
[30]	Centrally Banked Cryptocurrencies	George Danezis and Sarah Meiklejohn
[9]	Coexistence of Cryptocurrencies and Central Bank Issued Fiat Currencies - A Systematic Literature Review	Julia K. T. Lutz
[61]	Cryptocurrencies from an Austrian perspective	Alistair Milne
[75]	Decentralised Banking: Monetary Technocracy in the Digital Age	Adam Hayes
[85]	Designing Central Bank Digital Currencies	Itai Agur and Anil Ari and Giovanni Dell'Ariccia
[70]	Developing Blockchain Real-Time Clearing and Settlement in the EU, U.S., and Globally	Joanna Caytas
[46]	Digital Currencies, Decentralised Ledgers and the Future of Central Banking	Max Raskin and David Yermack
[64]	Distributed ledger technologies in securities post-trading: Revolution or evolution?	Andrea Pinna and Wiebe Ruttenberg
[69]	Distributed Ledger Technology for Securities Clearing and Settlement - Benefits, Risks and Regulatory Implications	Randy Priem
[53]	Distributed ledger technology in payment, clearing and settlement - An analytical framework	Benoît Cœuré
[52]	Distributed Ledger Technology in Payments, Clearing, and Settlement	David C. Mills and Kathy Wang and Brendan Malone and Anjana Ravi and Jeffrey Marquardt and Anton I. Badev and Timothy Brezinski and Linda Fahy and Kimberley Liao and Vanessa Kargenian and Max Ellithorpe and Wendy Ng and Maria Baird
[76]	Embedded Supervision: How to Build Regulation into Blockchain Finance	Raphael Auer
[3]	Everything and its opposite: Socio-economic implications of Blockchain technology: Case of monetary policy	Soumaya I. Ben Dhaou and Ibrahim Kholilul Rohman
[56]	Exploration and Practice of Inter-bank Application Based on Blockchain	Tong Wu and Xiubo Liang
[10]	Fintech and Banking: What Do We Know?	Anjan V. Thakor
[57]	Inter-Bank Payment System on Enterprise Blockchain Platform	Xin Wang and Xiaomin Xu and Lance Feagan and Sheng Huang and Limei Jiao and Wei Zhao
[78]	Monetary Reform, Central Banks and Digital Currencies	Sheila Dow
[38]	Money and Central Bank Digital Currency	Sayuri Shirai
[31]	Money, Cryptocurrency, and Monetary Policy	Kee-Youn Kang and Seungduck Lee
[27]	Multi-Blockchain Model For Central Bank Digital Currency	He Sun and Hongliang Mao and Xiaomin Bai and Zhidong Chen and Kai Hu and Wei Yu
[35]	On the Equivalence of Private and Public Money	Markus K. Brunnermeier and Dirk Niepelt
[58]	Project Jasper: Are Distributed Wholesale Payment Systems Feasible Yet?	James Chapman and Rodney Garratt and Scott Hendry and Andrew McCormack and Wade McMahon
[74]	Rebuilding Financial Industry Infrastructure	Allan D. Grody
[88]	Regulatory Technology: Replacing Law with Computer Code	Eva Micheler and Anna Whaley
[42]	Should the Central Bank Issue E-Money?	Charles M. Kahn and Francisco Rivadeneyra and Russell Wong
[37]	The Case for Central Bank Electronic Money and the Non-Case for Central Bank Cryptocurrencies	Aleksander Berentsen and Fabian Schar
[65]	The Impact of the Distributed Ledger Technology on the Single Euro Payments Area Development	Elżbieta Jantoń-Drozdowska and Alicja Mikołajewicz-Woźniak
[22]	The Macroeconomics of Central Bank Issued Digital Currencies	John Barrdear and Michael Kumhof
[2]	The Security and Financial Implications of Blockchain Technologies: Regulating Emerging Technologies in Canada	Evangeline Ducas and Alex Wilner
[86]	The Technology of Retail Central Bank Digital Currency	Raphael Auer and Rainer Boehme
[51]	The Economics of Distributed Ledger Technology for Securities Settlement	Evangelos Benos and Rod Garratt and Pedro Gurrola-Perez
[8]	Use of Distributed Ledger Technology by Central Banks: A Review	César A Del Río

current legislation is not adopted to cover DLT-based PCS. The other issue is the importance of legal settlement finality for PCS activities as a key element of risk management. Blockchain's ability to sustain settlement is not clear, as current consensus protocols are probabilistic, further imperilled by the existence of forks. Furthermore, the ability to host those PCS systems in multiple jurisdictions opens them up to the risk of regulatory arbitrage, complications with compliance with BSA, KYC, ALM, CFT, GDPR etc. As these novel blockchain technologies are not fail-safe, operational risks, recovery and litigation expenses could be greater than the promised potential rewards from DLT-based PCS systems.

In fact, the blockchain implementation for the central banking industry is one where practical application and theory *both* have integral roles to play in moving forward. The theory can be supported well by research in best practice and accompanied by sound and rigorous empirical studies that evaluate and compare different strategies. We are at a timely stage in blockchain's evolution for these to be now mandated. One other criticism of some academic studies is that they are often not trialled in the field and are conducted in the rarefied and some would say artificial atmosphere of the student classroom. While there is no disadvantage to using non-industrial subjects *per se*, the industry knowledge transfer this creates is limited. If there is one over-riding

TABLE 6. All publication venues (Appendix D).

Publication Venue Name	Number of Papers	Paper Reference ID
SSRN Journal of Economic Literature	4	[4], [51], [54], [61]
Bank of England Working Papers	3	[20]–[22]
Federal Reserve Bank of St. Louis Research Paper Series	3	[37], [42], [80]
SSRN Electronic Journal	3	[40], [43], [48]
Bank of Canada Staff Discussion Papers	2	[19], [41]
BIS CPMI Papers	2	[24], [53]
Financial Innovation	2	[67], [69]
IMF Working Papers	2	[39], [85]
Journal of Risk Finance	2	[36], [73]
NBER Papers on Monetary Economics	2	[25], [46]
Asia Pacific Journal of Innovation and Entrepreneurship: 'Blockchain on business and entrepreneurship'	1	[68]
Asian Development Bank Institute Working Paper Series	1	[38]
BAFFI CAREFIN Centre for Applied Research on International Markets, Banking, Finance and Regulation Research Paper Series	1	[34]
Bank of Canada Staff Working Paper	1	[29]
Banque de France Research Paper Series	1	[44]
BIS Quarterly Review	1	[86]
BIS Quarterly Review Special Features Series	1	[26]
BIS Working Paper Series	1	[76]
Board of Governors of the Federal Reserve System Finance and Economics Discussion Series; Divisions of Research and Statistics and Monetary Affairs	1	[52]
C.D. Howe Institute - Monetary Policy Research	1	[50]
CESifo Working Paper Series	1	[35]
Columbia Journal of European Law	1	[70]
Enfoque UTE (Universidad Tecnológica Equinoccial)	1	[8]
Equilibrium. Quarterly Journal of Economics and Economic Policy	1	[65]
European Banking Institute (EBI) Research Paper Series	1	[101]
European Banking Institute (EBI) Working Paper Series	1	[47]
European Business Organization Law Review	1	[88]
European Central Bank (ECB) Research Paper Series - Occasional Papers	1	[64]
FiDL Working Papers	1	[9]
Financial System Review	1	[58]
Future Internet	1	[82]
IEEE International Conference on Cloud Computing (CLOUD)	1	[57]
IEEE International Conference on Cloud Computing and Intelligence Systems (CCIS)	1	[63]
IEEE International Conference on Parallel and Distributed Computing, Applications and Technologies (PDCAT)	1	[27]
IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)	1	[84]
IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C)	1	[55]
IEEE Symposium on Service-Oriented System Engineering (SOSE)	1	[62]
IMF Staff Discussion Notes	1	[23]
International Conference on Computer Science and Education (ICCSE)	1	[56]
International Conference on Dependable Systems and Their Applications (DSA)	1	[28]
International Conference on Green Technology and Sustainable Development (GTSD)	1	[77]
International Conference on Theory and Practice of Electronic Governance (ICEGOV)	1	[3]
International Finance Review	1	[79]
International Journal (IJ)	1	[2]
International Journal of Political Economy	1	[78]
International Telecommunication Networks and Applications Conference (ITNAC)	1	[71]
Journal of Banking Regulation	1	[49]
Journal of Financial Intermediation	1	[10]
Journal of Risk Managment in Financial Institutions	1	[74]
Law, Innovation and Technology	1	[66]
Mediterranean Conference on Information Systems (MCIS)	1	[75]
NDSS (Network and Distributed System Security) Symposium	1	[30]
Regulating Blockchain. Techno-Social and Legal Challenges, Oxford University Press, 2019	1	[45]
Research Gate	1	[60]
Review of Banking and Financial Law	1	[87]
Science China Information Sciences	1	[33]
SNB-CIF Conference on Cryptoassets and Financial Innovation (Swiss National Bank)	1	[31]

TABLE 7. All publishers (Appendix D).

Publisher	Number of Papers	Paper Reference ID
IEEE	10	[27], [28], [55]–[57], [62], [63], [71], [77], [84]
Elsevier BV	9	[4], [9], [10], [40], [45], [48], [49], [74], [79]
Bank of Canada	5	[19], [29], [41], [54], [58]
BIS	5	[24], [26], [53], [76], [86]
BOE	4	[20]–[22], [51]
FED	4	[37], [42], [52], [80]
Emerald Publishing Limited	3	[36], [68], [73]
IMF	3	[23], [39], [85]
NBER	3	[25], [35], [46]
SpringerLink	3	[67], [69], [88]
EBI	2	[47], [101]
Taylor and Francis Group, LLC	2	[66], [78]
ACM	1	[3]
ADBInstitute	1	[38]
AISeL	1	[75]
ArXiv	1	[30]
BAFFI CAREFIN	1	[34]
Banque de France	1	[44]
C.D. Howe Institute	1	[50]
CJEL	1	[70]
ECB	1	[64]
EQUILIBRIUM	1	[65]
MDPI	1	[82]
PwC	1	[43]
RBFL	1	[87]
ResearchGate	1	[60]
SAGE	1	[2]
SciELO	1	[8]
SCIENCE PRESS	1	[33]
SNB	1	[31]
SSRN	1	[61]

lesson that this mapping study shows, it is that a co-ordinated and collaborative approach should be adopted between industry and academics to avoid the pitfalls of the past and to generate knowledge that progresses blockchain application, rather than widening the chasm that often emerges between the two.

VI. CONCLUSION AND FUTURE WORK

The purpose of this mapping study was to examine existing peer-reviewed publications concerning the influence of blockchain technology on the business of central banks. The particular emphasis was on identifying what type of use-cases were considered for blockchain adaptation, what the research trends were and who provided that research. Discussion about why those use-cases were considered and potential benefits, risks and issues arising from blockchain adaptation to those use-cases were summarised using relevant literature.

The Systematic Mapping Study identified a spectrum of existing blockchain-based use cases for central banks covered

TABLE 8. Matrix of the research (Appendix E).

Reference ID	Publication Year	Literature Type	Evaluation	Validation	Solution Proposal	Philosophical Paper	Opinion Paper	Experience Paper	Protocol	Model	PoC	Framework	Taxonomy	New Knowledge	CBDC	PCS	Assets	Audit	Regulation
[4]	2017	Journal / Magazine	*											*	*	*	*	*	*
[40]	2018	Journal / Magazine				*						*		*	*				*
[84]	2019	Conference Proceedings				*						*		*	*				*
[63]	2018	Conference Proceedings				*						*		*		*			
[101]	2020	Grey				*	*					*	*	*	*	*			*
[28]	2018	Conference Proceedings	*						*	*				*	*				
[66]	2017	Journal / Magazine					*							*		*			*
[33]	2019	Journal / Magazine			*				*		*			*	*			*	*
[62]	2016	Conference Proceedings				*						*		*		*	*		*
[73]	2018	Journal / Magazine				*						*		*					*
[55]	2018	Conference Proceedings			*	*					*	*		*		*			*
[60]	2018	Journal / Magazine				*						*		*		*			*
[80]	2018	Grey	*											*	*				
[47]	2018	Grey					*							*	*		*		
[82]	2017	Journal / Magazine					*							*					
[34]	2018	Journal / Magazine			*					*	*			*	*				
[77]	2016	Conference Proceedings				*							*	*					*
[67]	2016	Journal / Magazine					*							*		*			*
[68]	2017	Journal / Magazine					*							*		*			
[79]	2019	Journal / Magazine						*						*					*
[45]	2019	Journal / Magazine					*							*	*	*	*	*	*
[71]	2018	Conference Proceedings			*	*					*	*		*			*	*	
[54]	2018	Grey	*							*				*		*	*		
[36]	2018	Journal / Magazine				*							*	*	*	*			
[20]	2018	Grey	*				*							*	*				*
[39]	2019	Grey			*	*	*						*	*	*				
[23]	2018	Grey				*						*	*	*	*				
[26]	2017	Grey				*	*						*	*	*				
[24]	2018	Grey				*		*				*	*	*	*	*			*
[21]	2018	Grey	*											*	*				
[41]	2016	Grey				*						*		*	*	*			*
[49]	2019	Journal / Magazine					*							*	*				*
[29]	2019	Grey	*							*				*	*				
[25]	2017	Grey					*							*	*				*
[43]	2019	Grey				*	*					*		*	*				
[19]	2017	Grey				*	*	*				*		*	*				
[44]	2019	Grey				*		*				*		*	*				*
[48]	2018	Journal / Magazine					*							*	*				
[87]	2019	Journal / Magazine					*							*	*				*
[50]	2019	Grey					*							*	*				*
[30]	2016	Conference Proceedings		*		*			*	*		*		*	*				
[9]	2018	Journal / Magazine				*							*	*					
[61]	2017	Journal / Magazine				*	*					*		*		*	*	*	
[75]	2016	Conference Proceedings				*	*					*		*					*
[85]	2019	Grey	*			*				*		*		*	*				
[70]	2016	Journal / Magazine					*							*		*			*
[46]	2016	Grey					*							*	*				
[64]	2016	Grey				*	*						*	*		*		*	
[69]	2020	Journal / Magazine					*							*		*	*	*	*
[53]	2017	Grey				*	*					*	*	*		*	*	*	*
[52]	2016	Grey				*	*	*					*	*		*	*	*	*
[76]	2019	Grey			*	*				*	*	*		*					*
[3]	2018	Conference Proceedings					*							*		*		*	*
[56]	2017	Conference Proceedings	*						*					*		*			
[10]	2019	Journal / Magazine				*							*	*					
[57]	2018	Conference Proceedings			*	*					*	*		*		*			
[78]	2019	Journal / Magazine					*							*	*				*
[38]	2019	Grey				*	*						*	*	*				
[31]	2019	Conference Proceedings		*						*				*	*				
[27]	2017	Conference Proceedings	*						*	*				*	*				
[35]	2019	Grey			*	*				*		*		*	*				
[58]	2017	Grey						*						*		*		*	*
[74]	2017	Journal / Magazine					*							*				*	*
[88]	2019	Journal / Magazine					*							*					*
[42]	2018	Grey				*	*	*				*		*	*				*
[37]	2018	Grey				*	*						*	*	*				*
[65]	2017	Journal / Magazine				*							*	*		*			
[22]	2016	Grey	*											*	*				
[2]	2017	Journal / Magazine					*							*		*	*	*	*
[86]	2020	Grey				*							*	*	*				
[51]	2017	Grey				*	*						*	*		*	*	*	*
[8]	2017	Journal / Magazine				*							*	*					

by academic research and presented a detailed statistical and thematic analysis of those use-cases and of the overall topic. Narrative summaries of contents of the research for each of the identified use-cases was also provided. In respect of the topic of this study, overall research maturity was established by presenting frequency of publications over time with papers categorised by research channels; research depth and breadth is demonstrated via research types, research contribution and cohorts of researchers.

A critical discussion point in this review is the understanding of which exact areas and functionality of the central banking business is under the academic lens of interest. However, as the goal of the SMS was to provide an overview and to be a guiding input for SLR, a trade-of between effort and reliability of the outcome has to be made [7]. For more informed decisions and to provide a deeper understanding of each of the areas, performing a more focused review of each separate central bank uses-case for blockchain category is needed. Further work will explore a number of avenues. Firstly, this mapping study will be under continuous review as more research is undertaken and the review will need continuous updating. Secondly, the work opens up a number of research opportunities and highlights a number of gaps in our knowledge of blockchain; it would be useful to pursue these emergent areas. Thirdly, the scope of the review will be expanded, focusing on the blockchain application for the segment of central banks and also including a wider banking sector comparison, such as commercial, investment banks, un-banked population etc. Furthermore, such a review could be produced for each of those banking sectors and for comparison between sectors. Next, the integration of Big Data and AI practices with the blockchain environment for the activities and operations of central banks was found to be under-reported in the academic literature, signalling a knowledge gap for future exploration by researchers and practitioners. Finally, our text mentions areas which deserve further exploration (either through new mapping studies or through SLRs); as a relatively new concept, it is important to understand the area through these mediums before complementary research can start.

Our mapping is a reflection of the state-of-knowledge in blockchain for central banks at present. One valuable activity would be to update our mapping study with new publications as they arise. The concept of a *living review* (i.e., one that evolves over time and is current at all times) is one that we feel would be useful to follow.

APPENDIX A
DATABASE SEARCH RESULTS

Database Search Results: D* - Database Name; R* – Results on 22nd of June 2020; I/E* – application of inclusion / exclusion criteria on title, keywords and abstract (automated, if available via database, or manual). Table 3

APPENDIX B
FULL LIST OF HEADERS OF THE DATA COLLECTION FORM

Table 4

APPENDIX C
ALL INCLUDED PAPERS

Table 5

APPENDIX D
PUBLICATION VENUES AND PUBLISHERS

Table 6 and Table 7

APPENDIX E
MATRIX OF THE RESEARCH

Table 8 - the complete matrix of the research of all included papers.

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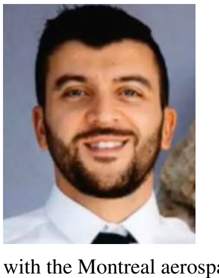

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