

Where did my data go? Evaluation of Distributed Ledger Technologies' Suitability for Personal Data Provenance in Healthcare and Finance

Bachelor's Thesis of

Aleksandar Bachvarov

at the Department of Informatics, Institute of Information Security and
Dependability (KASTEL)
Decentralized Systems and Network Services Research Group

Reviewer:	Prof. Dr. Hannes Hartenstein
Second reviewer:	Prof. Dr. Ali Sunyaev
Advisor:	M.Sc. Oliver Stengele
Second advisor:	M.Sc. Jan Bartsch

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I declare that I have developed and written the enclosed thesis completely by myself, and have not used sources or means without declaration in the text.

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(Aleksandar Bachvarov)

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1 Introduction

With e-health [Eys01], e-finance [AMS02], cloud services, 'Internet of Things', social media, etc. spreading and growing by the day, data exchanged, analysed or produced by intelligent devices become more and more difficult to trace [17]. It is often unknown how information is collected, how it is further processed, by whom, and for what purpose [Zub15]. This kind of information is often referred to as *data provenance* (DP), where "The provenance of a data item includes information about the processes and sources that lead to its creation and current representation" [GD07, p. 3]. The purpose of provenance is to extract relatively simple explanations for the existence of some piece of data from some complex workflow of data manipulation.

With digitalisation, the concern with potential exposure of private and sensitive personal information is rising [TQV21], and with it, the significance of DP [BT19]. Also, information is not only personal and private, but also proprietary. Consumers should know if their data had been manipulated and how, in a network, that provides interoperability and connects actors in a secure, trustworthy, transparent and 'user friendly' way [Sun+14].

An increasing amount of research is being done to utilize DP technologies [BT19] in the fields of *healthcare* [Mar+20; LAC19; Le 18; HK21; Rah+20; Sun+14], *finance* [Sin+20; Liu+21; SAD19; Sir+19], supply-chain [Man+18], cloud services [Xia+17], scientific research [SPG05], storage systems [Mun+06], etc.

A lot of progress has been made recently regarding personal data and its protection [; 18; 19, TRND]. In European data protection law, everybody has the right to know where the organisation accountable got his data from, what the data was used for, where it was transferred to and how long it is stored, regardless of location [, GDPR]. However, laws and regulations alone cannot provide consumers with information about their personal data [CAG02]. The regulations created the need for tools, which can enable consumers to exercise their rights.

Unfortunately, many tools failed to meet the requirements of such technology [Hed08; Nor09; Hu+20]. In order for such tools to work, a combination of not only proper standards and legislation is needed, but also international adoption as well as mature and suitable technologies and architectures for their development [CAG02]. When improperly designed, DP tools can be a severe threat to the consumer and in a networked environment with a lot of actors this can be a complex and costly system to implement and manage [Hed08].

There are tools that partially solve some of the existing problems like owning your data, knowing where it is stored and what's happening to it [, MTM], others provide full access to all personal data along information flows [BKB16] or easy-to-understand visualization techniques [SS17]. However, these tools are still built in a centralised manner. While centralised databases provide advantages in terms of, for instance, maintainability, they have drawbacks in terms of their availability, performance (bottlenecks), and don't necessarily solve the issue with untrustworthiness [Sun20, p. 266-267].

To desire a one-fits-all solution is unrealistic. Recently, however, the *distributed ledger technologies* (DLTs) are on the rise and steadily becoming more versatile in terms of applicable

use cases [Mau+17]. DLT has been developed to keep a distributed immutable ledger of financial transactions [Sun20]. The ledger can be seen as a provenance record of, say, bitcoins; and it is therefore unsurprising that DLT could be used to record provenance in other settings. By leveraging the global-scale computing power of distributed networks, a DLT-based DP can provide integrity, authenticity, transparency, accountability, provenance and trustworthiness through its decentralized architecture, immutable record of transactions, lack of single authority, consensus mechanisms, smart contracts, tamper-proof storage of data, etc. [; Mar+20; Mun+06].

There are, however, different DLTs and they vary from each other in many ways such as their design, purpose, way of access, way of governance and so on [Cho+19]. So it is important to understand the characteristics, capabilities and trade-offs of individual DLTs [Kan+20] in order to select the most suitable approach for personal DP in the field of *healthcare* and *finance*. This leads us to the research question: *What are the characteristics of Distributed Ledger Technologies that make them beneficial/suitable for personal data provenance in healthcare and finance?*

In the next section, take a closer look at data provenance, the requirements of such approaches and the use cases selected in our work. In section three we describe distributed ledger technologies, their different designs, characteristics and properties, as well as DLTs' suitability for DP. Section four presents an evaluated mapping of our selected DLT approaches to the financial and healthcare DP requirements. This is followed by discussion in section five, consisting of principle findings, implications for practice, implications for research, limitations and future work. Then we end the work with a brief conclusion in section six.

2 Data Provenance

2.1 Definition

In this work we define *data provenance* (DP) as an approach/technology that can be used to record not only metadata, data origin and/or data operation, but also processes that act on data and agents that are responsible for those processes. Most importantly, this should be achieved in a secure, trustworthy and transparent way, that ensures accountability and is in accordance to international laws and regulation, with the well-being of the consumer in mind.

2.2 Requirements

DP approaches/technologies, suitable for tracing the origin and source of personal data and the processes that led to its current state, have to fulfil a number of requirements. Using the available literature, we derived and formulated the following requirements, which we then presented through the lens of the two use cases investigated in our work.

We combined the requirements into suitable groups: "User" contains requirements associated with the data of the individual user; "Data" contains the features that the data is required to posses in such approaches/technologies; "System" consists of requirements about the concrete DP approach/technology as an usable system; "Security" and "Other" include the fundamental security requirements and requirements that are necessary in almost every system.

Group	Requirement	Description
User	Identifiability	An unique identifier allows identification and lays the ground for accountability [Lee+13]. However anonymity, pseudonymity and unlinkability should also be possible [HPH11; Sen].
	Ownership	Allows Data Subjects to get an overview, request or perform changes and deletion of the data that they own. [ZN+15]
	Accessibility	Allows Data Subjects with access to view, store, retrieve, move or manipulate data, based on their access rights [ZN+15; BKB16].
Data	Traceability	Give information on what transmitting principle was used, what type of data, for what purpose and to whom the information was sent. How data is collected; how, when, where it is stored [Fre+08; ZN+15, p. 13].
	Completeness	Collecting complete provenance information can fully take the advance to track data and actions for identity management, error detection, etc. Incomplete provenance data may lead to detection missing and suppression of abnormal behaviors [GGM12; HPH11].
	Granularity	Not only the process derivation of a data file, but also the components of files such as paragraphs, shapes and images should be traced with regard to their origins. Fine-grained provenance information helps achieve highly precise anomaly detection and auditing [HWA10].

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System	Scalability	With the increase of the data volume and the number of operations, it should be possible to store and process provenance information efficiently and without risk of information loss [TBA16; Fre+08, p. 16].
	Interoperability	By definition - the capability to communicate, execute programs or transfer data between various systems in a manner that requires Data Subjects to have little or no knowledge of the unique characteristics of those systems [, IntOp].
	Trust	If the Data Subject trusts the system, they seem to be willing to share personal information [BHS02]. The willingness to share data can also increase if the Data Subject finds the advantages of engaging in such a transaction more valuable than the loss of privacy [BGS05; AG05].
Security	Confidentiality	Ensures non-disclosure of data traveling over the network to unauthorised Data Subjects [Asg+12].
	Integrity	Ensures that the Data Receiver may detect unauthorised changes made to the data [Tsa+07].
	Availability	Ensuring that data and its provenance is available to Data Subjects, when and where they need it [Lia+17].
Other	Policies	Enforce laws [] and regulations such as purpose limitation [FHS17], data minimisation [ASS17], etc.
	Usability	Provides clear interfaces and structures that display provenance information in an understandable way (usage of icons, graphs, etc.). Managing security (and privacy) is not the primary task of the user [Fre+08].

2.3 Use Cases

In this work we investigate DP approaches for both *healthcare* and *finance*. While all of the above mentioned requirements are important for such approaches, each requirement can have different level of significance and meaning in the specific use case. In this section, we will discuss these differences and why each requirement from table 2.2 is important in *healthcare* and *finance* respectively.

The marked fields in the following table show which of our DP requirements are of high importance or are more nuanced than the general description (table 2.2) for the particular use case.

Group	Requirement	<i>Healthcare</i>	<i>Finance</i>
User	Identifiability	x	x
	Ownership	x	
	Accessibility	x	x
Data	Traceability	x	x
	Completeness		
	Granularity		
System	Scalability	x	x
	Interoperability		
	Trust	x	x
Security	Confidentiality	x	x
	Integrity		
	Availability	x	
Other	Policies	x	
	Usability		

2.3.1 Healthcare

Actors: *Patient, Physician, Institution*

In regard to medical treatment and patient safety, the importance of data, its origins and quality have long been recognised in clinical research [Cur+17] [Muh14]. Creating trust relationships among the various actors is vital - e.g., evidence-based medicine and health-care-related decisions using third-party data are essential to patient safety [Mar+20]. DP is also crucial for solving confidentiality issues with healthcare information like accidental disclosures, insider curiosity and insider subornation [Rin97b]. In the following we discuss the important aspects of each of the DP requirements, specific for healthcare, pointed out in table 2.3.

Identifiability: There are important trade-offs between indentifiability and unlinkability/anonymity. For example, a patient feels that their physician misrepresented a test and wants to share this information, but is reluctant to do so, since casting the physician in a negative light can have repercussions in their care at a later time []. Another example is the perceived stigma of having a mental disorder acts as a barrier to help seeking. It is possible that patients may be reluctant to admit to symptoms suggestive of poor mental health when such data can be linked to them, even if their personal information is only used to help them access further care. There is a significant effect on reporting sub-threshold and non common mental disorders when using an anonymous compared to identifiable questionnaire [Fea+12]. Studies suggest that anonymity is strategically used and fosters self-disclosure among individuals who are embarrassed by their illness [Rai14].

On the other hand most people believe that, when a physician makes an error, an incident report should be written and the individual should be identified on the report. People are reluctant to accept physician anonymity, even though this may encourage reporting [Eva+04]. Also, Data Protection Act insists that patients must consent directly to participate in research or that patients' data must be completely anonymised. However, this causes particular problems for epidemiological research [War+04] which often requires access to routinely collected identifiable personal data, or requires identification of research participants from such data. Obtaining individual consent from large numbers of patients may be onerous or simply impossible, for example if patients have died or moved away, and participation bias may undermine the data. Anonymising data is difficult and expensive and greatly limits their future value [Wal06].

Ownership: A relevant issue is the ongoing debate about the ownership of patient data among various stakeholders in the healthcare system including providers, patients, insurance companies and software vendors. In general, the current model is such that the patient owns his/her data, and the provider stores the data with proprietary software systems. The business models of most traditional EHR (electronic health record) companies are based on building proprietary software systems to manage the data for insurance compensation and care delivery purposes. Such approach does not encourage or makes it difficult for individual patients to share data for scientific research, nor does it encourage patients to obtain their own health records that may help better manage their health and improve patient engagement [Adi+17].

Accessibility: It is important that the different actors can view, store, retrieve, move, request changes/deletion or manipulate medical data based on their access rights [Ber17]. For example, patients should be able to see what prescriptions they have so they know what medicine to

take; physicians should be able to alter the prescriptions of their patients and also to see what prescription a patient has gotten from other physicians so that they can correctly treat them and avoid medication errors; an institution should be able to verify a patient's prescription to make sure that they are not trying to purchase unintended pharmaceuticals [, Priv].

Traceability: Traceability in healthcare is at the crossroads of numerous needs. It is therefore of particular complexity and raises many new challenges. Identification management and entity tracking, from serialization of pharmaceuticals, to the identification of patients, physicians, locations and processes is a huge effort, tackling economical, political, ethical and technical challenges. There are growing needs to increase traceability for drug products, related to drug safety and counterfeited drugs [KS18]. Technical problems around reliability, robustness and efficiency of carriers are still to be resolved. Traceability is a major aspect of the future in healthcare and requires the attention of the community of medical informatics [Lov08].

Scalability: The amount of global healthcare data is expected to increase dramatically by the year 2020. Early estimates from 2013 suggest that there were about 153 exabytes (10^{18}) of healthcare data generated in that year. However, projections indicate that there could be as much as 2,314 exabytes of new data generated in 2020 (around 15 times more) []. However, because of the sensitive and private nature of healthcare data, it is important that scalability should not come at the expense of security and trust.

Trust: Trust is, of course, essential to both physician and patient. Without trust, it is difficult for a physician to expect patients to reveal the full extent of their medically relevant history, expose themselves to the physical exam, or act on recommendations for tests or treatments [Saf+98; Mos+98]. Trust promotes efficient use of both the patient's and the physician's time. Without trust, the process of informed consent for the most minor of interventions, even a prescribed antibiotic, would become as time consuming as that needed for major surgery [Goo02]. Furthermore, physician-to-patient relationship is jeopardised when people do not trust that their personal health information will be kept confidential, and that these data will not be utilised for purposes other than medical [KLG03].

It is also suggested that it is morally important for doctors to trust patients. Doctors' trust of patients lays the foundation for medical relationships which support the exercise of patient autonomy, and which lead to an enriched understanding of patients' interests. It may not be possible to trust at will, the conscious adoption of a trusting stance is necessary as the burdens of misplaced trust fall more heavily upon patients than physicians [Rog02].

In terms of medical research, one of the three key factors to the patients willingness to share data is contingent upon trust who is accessing the data [KMR19].

Confidentiality: Trust and confidentiality between a physician and patient is not new: it is central to the practice of healthcare and has been focused on since Hippocrates. Whilst the concept of patient confidentiality has endured as an ideal throughout history. In the digital age, patient confidentiality is often framed within the context of electronic patient records and the potential involvement of third parties. While the involvement of institutions and other research organisations can resolve many practical issues for healthcare providers, it often involves the transfer of sensitive patient information to these institutions [Rin97b]. Therefore, it is important that there isn't any disclosure of medical data traveling over the network to unauthorised actors [Rin97a, p. 96]. Sometimes, however, difficulties with keeping the confidentiality of personal health information may arise, because of the often unclear position of family members and friends, in patient's health and medical treatment [Pet+04].

Availability: Medical data and its provenance should be available and ready for immediate use, especially in cases of emergency [KLG03]. The immediate availability of patient and resource oriented information is of great importance, in order for physicians and institutions to, for example, identify the most appropriate ambulance and healthcare setting; provide guidance to physicians as to the most appropriate management of the emergency case at hand; prioritize/classify the emergency case and overall improve the quality of the emergency care [PMV12].

Policies: Unfortunately, legal controls over data collection in European countries have badly affected the work of epidemiologists [WN94a]. While data protection laws, policies and regulations aim to protect the patients information, rights and health, they might cause harm to the patients well-being in the long run, by damaging the ability of institutions to conduct unbiased and reliable medical research [War+04; WN94b].

System **Usability**, **Scalability** and **Interoperability**; data **Integrity**, **Completeness** and **Granularity** are, of course, of great importance and the more requirements are fulfilled in a DP approach, the better. However, these requirements don't seem to have any specific aspects that differ from the general description in table 2.2, in terms of healthcare. Therefore, we concluded that they don't require that much of our further attention or detailed investigation.

2.3.2 Finance

Actors: *Consumer, Institution*

In online banking, digital money and digital financial services, the importance of information about transactions, money flow, money origin, credit scores and financial decisions is becoming bigger and bigger since the emergence of e-finance [AHS02]. DP is of great use not only in investigating money laundering [Ung+06], tracing donations [Sir+19], charities [Sin+20] or illegal funding [Tei18], but also loans and financing, mortgages, trading of currencies, insurance policies and others [But20]. However, 'big tech' are also venturing into financial services [Boi+21]. While being accused for abuse of market power and anti-competitive behaviour, they are also famous for not giving extensive information on how personal data is analysed, processed or interacted with by third parties and international or government organisations [, RV19], which has a negative impact on the consumers' ability to trace their personal data.

Identifiability: On one hand, in the last ten years there has been a tendency to introduce anonymity into stock, bond, and foreign exchange markets. Almost all the asset markets organized as electronic platforms are anonymous []. On the other, The last few years have seen an international campaign to ensure that the world's financial and banking systems are "transparent," meaning that every actor and transaction within the system can be traced to a discrete, identifiable individual []. Anonymity fosters crime, while identifiability challenges privacy. For example, there is a high degree of anonymity with Bitcoin [DL], however traceability is possible [RH13]. In connection to this, a study shows that the relationship between participants' views on anonymity and traceability as a disadvantage to bitcoin transactions was statistically significant [AW21]. Perhaps consumers should be able to perform operations in an pseudonymous way, that ensure ownership (pseudonyms are not improperly used by others)

and ensure individuals are held accountable for abuses created under any of their pseudonyms [Cha85].

Accessibility: Not all information in e-finance is private. Indeed, by law, many types of transactions must be made available to various institutions, ranging from the government to the public. As a practical matter, there will often be several parties to a transaction who must have access to the information [SWR97]. Another example is money inheritance, where an institution or another consumer can give access rights to their personal financial data or money. This shows consumers require and can attain more access rights to other consumers' or institutions' financial data, compared to patients in the healthcare use case.

Traceability: The term traceability may have a law enforcement implication suggesting, for example, the ability to monitor or track the activities of consumers. While transaction records and audit trails certainly can provide such a capability, this is different from using traceability to verify the accuracy of a measurement or the authenticity of a set of data [SWR97]. Traceability can discourage fraud, and criminal activities like money laundering [Ung+06], illegal funding [Tei18] or simply bring transparency in donation tracing [Sin+20; Liu+21; SAD19]. There is also a research that supports the notion that transparency is a desirable characteristic of financial reports - increased transparency reduces information risk and cost of capital [BS08].

Scalability: E-Finance is a constantly growing field. As of November 2021, there were over 10 000 fintech (financial technology) startups in the Americas, making it the region with the most fintech startups globally. In comparison, there were over 9 000 such startups in the EMEA region (Europe, the Middle East, and Africa) and over 6 000 in the Asia Pacific region. 25 000 new startups in 2021 compared to only around 12 000 in 2018 []. However, with big tech providing basic financial services through their low cost structures (especially where a large part of the population remains unbanked) [Boi+21], large-scale DP approaches should consider measures against discrimination, abuse of market power, anti-competitive and monopolistic use of data.

Trust: It has long been recognized that trust is a key ingredient in fostering financial transaction and achieving business success. According to Nobel prize Kenneth Arrow, 'it can be plausibly argued that much of the economic backwardness in the world can be explained by the lack of mutual confidence'. Since then plenty of evidence has shown that aggregate trust and aggregate economic performance are linked by a strong positive relationship. In addition, in high trust countries, institutions can grow larger [La +96] and stock markets and financial markets can prosper [GSZ08]. Financial transactions, being all exchanges of money over time, should be particularly dependent on trust. In fact any financial transaction, being it a loan, a purchase of a stock of a listed company or the purchase of an insurance policy, has a fundamental characteristic: it is an exchange of money today against a promise of (more) money in the future. But what leads the consumer to believe that promise and make the exchange actually possible, is trust. The trust of a consumer who has invested in the stock of a company that his money will not be appropriated by the company's managers [Gui12]. Currently trust in finance is highly dependant on third parties and intermediaries [JSZ07; Bos01], which also has its risks [LJ09].

Confidentiality: According to a study examining the conflict between anti-money laundering and anti-terrorism finance law requirements and bank secrecy and confidentiality laws [], the duty of confidentiality is regarded as an essential feature of the institution-consumer relationship and it was enunciated at a time when crime was viewed as a local phenomenon.

However, the last two decades have seen the rise of transnational crimes such as money laundering [Ung+06] and terrorist financing [Tei18]. To counter these crimes a number of legislations were enacted which, require institutions to disclose their consumers' financial information in certain circumstances to law enforcement authorities. This is justified by the fact that institutions are used by criminals to launder criminal proceeds and the audit trail they leave behind helps criminal investigation and prosecution. However, this is still personal financial information and there exist the requirement for some level of confidentiality [Ber14].

Policies, system **Usability** and **Interoperability**; user **Ownership** of data; data **Integrity**, **Completeness** and **Granularity** are, of course, of great importance and the more requirements are fulfilled in a DP approach, the better. However, these requirements don't seem to have any specific aspects that differ from the general description in table 2.2, in terms of finance. Therefore, we concluded that they don't require that much of our further attention or detailed investigation.

3 Distributed Ledger Technologies

A distributed ledger (also called a shared ledger or distributed ledger technology or DLT) is a consensus of replicated, shared, and synchronized digital data geographically spread across multiple sites, countries, or institutions [Sun20]. Unlike with a centralized database, there is no central administrator [Sca16].

The distributed ledger database is spread across several devices (nodes) on a peer-to-peer network, where each replicates and saves an identical copy of the ledger and updates itself independently. The primary advantage is the lack of central authority. When a ledger update happens, each node constructs a new transaction, and then the nodes vote by consensus algorithm on which copy is correct. Once a consensus has been determined, all the other nodes update themselves with the new, correct copy of the ledger [Mau+17]. Security is accomplished through cryptographic keys and signatures [Sun20]. The literature [Kan+20] differentiates between:

DLT *concepts* - describe the basic structure and functioning of DLT designs on a high level of abstraction. For instance, blockchain is a DLT concept describing the use of blocks that form a linked list. Each block contains multiple transactions that have been added into the block by nodes [Kan+20].

DLT *designs* - specify an abstract description of DLT concepts by adding concrete values and processes for inherent DLT characteristics. There are important differences between DLT designs, which make them suitable for some applications and unsuitable for others [Kan+20].

DLT *characteristics* - represent features of DLT designs, which are of technical or administrative nature. The technical characteristics constrain future changes of the administrative characteristics (e.g., lack of scalability regarding network size of a distributed ledger) [Kan+20].

DLT *properties* - groups of DLT characteristics and shared by each DLT design. For instance, "throughput" and "scalability" are both associated with the DLT property "performance" [Kan+20].

The emergence of DLT, with strong support for data integrity, authenticity and provenance, has opened up the door of opportunities in different domains [; Mar+20; Mun+06; Lia+17; Wor+20]. With the increase in DLT application domains, the number of DLT designs has also increased steadily. These DLT designs vary from each other in many ways such as implementation, purpose, way of access, way of governance and so on [Cho+19]. Therefore, it is important to understand the characteristics of DLT designs and their properties, in order to determine which are more advantageous and most importantly, which properties make them suitable (or not) for a particular use case and its specific requirements.

3.1 Designs, Properties and Characteristics

3.1.1 Designs

DLT designs can be instantiated as a *public* or *private* [Xu+17; Yeo+17].

Public - DLT designs, where the underlying network allows arbitrary nodes to join and participate in the distributed ledger's maintenance. For example, consumers can execute financial transaction without registration or verification of the nodes' identities being required. Public DLT designs like, for example, Ethereum [] are usually maintained by a large number of nodes. Owing to the large number of nodes in the network, each of which stores a replication of the ledger, public DLT designs achieve a high level of availability. To allow many (arbitrary) nodes to find consensus, public DLT designs should be well scalable to not deter performance when the number of nodes increases [Sun20].

Private - DLT designs, that engage a defined set of nodes, with each node identifiable and known to the other network nodes. Consequently, private DLT designs require verification of the nodes that join the distributed ledger. Private DLT designs like, for example, Hyperledger [DMH17] are often used if the public should not be able to access the stored data [BM16]. For example, physicians can use a common ledger in Healthcare to collaborate, but do not want to disclose the data to other colleagues or institutions not involved in the collaboration [Sun20].

Besides the choice of going with *public* or *private*, we differentiate between *permissioned* and *permissionless* DLT designs [Yeo+17; Xu+17].

Permissioned - when consensus finding is delegated to a subset of nodes (which is usually small). Since only selected nodes can validate new transactions or participate in consensus finding, fast consensus finding can be applied, which enables a throughput of multiple thousands of transactions per second [CL+99]. Owing to the small number of nodes involved in consensus finding, they can reach finality, which means that all of a distributed ledger's permitted nodes come to an agreement regarding the distributed ledger's current state [Sun20].

Permissionless - when the nodes' identity does not have to be known [Yeo+17], because all of them have the same permissions. In permissionless DLT designs with a large number of nodes (e.g. Ethereum), consensus finding is usually probabilistic and does not provide total finality, because it is impossible to reach finality in networks that allow nodes to arbitrarily join or leave. Consequently, the consistency between all the nodes of a public, permissionless distributed ledger can, at a certain point in time, only be assumed with a certain probability. Furthermore, a transaction appended to a distributed ledger is only assumed to be immutably stored to a certain probability. In blockchains, this probability of a particular transaction's immutability increases when new blocks are added to the blockchain [DL] [Sun20].

3.1.2 Properties

N. Kannengießer et al. [Kan+20] have extracted 277 DLT characteristics, which were eventually assigned to 40 master variables names and descriptions. These 40 resulting DLT characteristics were further grouped into 6 DLT properties:

Property	Characteristic	Description
Opaqueness	:	The degree to which the use and operation of a distributed ledger cannot be tracked
Performance	:	The accomplishment of a given task on a distributed ledger under efficient use of computing resources and time
Flexibility	:	The degrees of freedom in deploying applications on and customizing a distributed ledger
Security	:	The likelihood that functioning of the distributed ledger and stored data will not be compromised
Policy	:	The ability to guide and verify the correct operation of a distributed ledger
Practicality	:	The extent to which users of a distributed ledger can achieve their goals with respect to social and socio-technical constraints of everyday practice

3.1.3 Characteristics

Out of those 40 DLT characteristics, we identified 10 "main" and 13 "secondary" characteristics, which correspond to our DP approach requirements described in table 2.2. These 23 characteristics can help us determine whether DLT is suitable for DP and a potential solution some of its present issues, or not.

Main Characteristic	Description
User Unidentifiability	The difficulty of mapping senders and recipients in transactions to identities
Transaction Content Visibility	The ability to view the content of a transaction in a DLT design
Traceability	The extent to which transaction payloads (e.g., assets) can be traced chronologically in a DLT design
Scalability	The capability of a distributed ledger to efficiently handle decreasing or increasing amounts of required resources
Interoperability	The ability to interact between distributed ledgers and with other external data services
Confidentiality	The degree to which unauthorized access to data is prevented
Integrity	The degree to which transactions in the distributed ledger are protected against unauthorized (or unintended) modification or deletion
Availability	The probability that a distributed ledger is operating correctly at any point in time
Compliance	The alignment of a distributed ledger and its operation with policy requirements (e.g., regulations or industry standards)
Ease of Use	The simplicity of accessing and working with a distributed ledger

Secondary Characteristic	Description
Node Controller Verification	The extent to which the identity of validating node controllers is verified prior to joining a distributed ledger
Throughput	The maximum number of transactions that can be appended to a distributed ledger in a given time interval
Maintainability	The degree of effectiveness and efficiency with which a distributed ledger can be kept operational
Turing-complete Smart Contracts	The support of Turing-complete smart contracts within a DLT design
Non-Repudiation	The difficulty of denying participation in transactions
Durability	The property that data committed to the distributed ledger will not be lost
Authenticity	The degree to which the correctness of data that is stored on a distributed ledger can be verified
Consistency	The absence of contradictions across the states of the ledger maintained by all nodes participating in the distributed ledger
Censorship Resistance	The probability that a transaction in a distributed ledger will be intentionally aborted by a third party or processed with malicious modifications
Strength of Cryptography	The difficulty of breaking the cryptographic algorithms used in the DLT design
Auditability	The degree to which an independent third party (e.g., state institution, certification authority) can assess the functionality of a distributed ledger
Support for Constrained Devices	The extent to which devices with limited computing capacities (e.g., sensor beacons) can participate in a distributed ledger
Ease of Node Setup	The ease of configuring and adding a new (or previously crashed) node to the distributed ledger

3.2 DLT and DP

One of DLTs' properties is DP. The data storage process in any distributed ledger is facilitated by means of a mechanism called transaction. Every transaction needs to be digitally signed using public key cryptography (PKI) which ensures the authenticity of the source of data. Combining this with the immutability and irreversibility properties of a distributed ledger provides a strong non-repudiation instrument for any data in the ledger [Cho+19].

3.3 DLT in Healthcare

3.4 DLT in Finance

3.5 Considered Approaches

3.5.1 Hyperledger Fabric

Hyperledger Fabric [DMH17] is a distributed ledger platform for running chaincode (smart contract in Fabric). It is a specific blockchain platform, which is optimized for a specific task such as tracking assets, transferring values, etc. The modular architecture delivers high degrees of resiliency, flexibility, confidentiality, in design and implementation. The flexibility in design leads to achieving scalability, privacy, etc. Fabric is designed to support pluggable implementations of a different functions and chaincodes (using Go, Java, JavaScript). Transactions in Fabric are private and confidential thanks to its channelization features [Bal17]. Rather than an open, permissionless system, Fabric offers a scalable and secure platform that supports private transactions and confidential contracts. This architecture allows for solutions developed with Fabric to be adapted for any industry, thus ushering trust, transparency, and accountability for institutions [SSS18].

Other DLTs that were originally designed for ad-hoc, public use (where there is no privacy and no governance) had to be later significantly redesigned to add in support for permissions and privacy; Hyperledger Fabric was designed with these features as foundational. In this regard, Hyperledger Fabric has had a head start over many of the competing frameworks. For example, while there may be promise in some of the Ethereum 2.0 implementations, these are still mostly oriented to public network use [DMH17].

3.5.2 Ethereum

Ethereum [] is an open blockchain platform that allows anyone to build and use decentralized applications that run on blockchain technology. Financial interactions or exchanges could be carried out automatically and accurately using code running on Ethereum. It is a general purpose blockchain platform, which allows users to write their own algorithmic code and running customised logical processes. It was designed to be flexible and adaptable and has a powerful shared global infrastructure. The movement of assets around the network represents the ownership of property. In some ways, Ethereum is similar to that of Bitcoin, but there some technical differences between them. Bitcoin offers peer to peer electronic cash system, while Ethereum blockchain focuses on running the smart contract code of any decentralized application. Miners work to earn the crypto token Ether, this is also used to pay transaction fees and services in Ethereum network [SSS18].

The Ethereum network can be either public or private. Public DLT designs bring trust, security and transparency. Everything is recorded, public, and cannot be changed; also the more decentralized and active a public DLT design is, the more secure it becomes; and in terms of transparency - all data related to transactions is open to the public for verification.

3.5.3 Comparison

From Hyperledger Fabric's and Ethereum's white papers it becomes clear that both systems have differing views on future implementation areas. By comparison, Fabric aims to provide a comprehensive and extensible module architecture that can be used in various industries

(finance, healthcare, supply chain). However, Ethereum is totally outside of every particular area of application and serves more as a general interface for all types of transactions and applications. Ethereum executes random complexity codes through its EVM and is freely available without authorization to any person. Fabric has a scalable design that guarantees durability and hence scalability with an allowed operating mode. Smart contract codes are used by both implementations. The chaincode in Fabric is known and unique consumer networks exist where the communications and relevant transactions of the associated channels can be seen. Access to transactions that offer anonymity to transactions is also limited. Both use various consensus processes to make the conclusion. Ethereum has Ether, but Fabric would not need an integrated currency since there is no mining. Ethereum has a generic platform that runs powerful smart contracts which is public and transparent and Fabric's modular architecture allows a customized platform for a specific mode of operation [MAA21].

Ethereum has been used in a variety of domains, including: energy (Electron [31]), finance and banking, sports, IoT (Slockit [32]), naming service (ENS [33]), healthcare (Patientory [34]), and crowd-funding (DAO and Initial Coin Offerings).

However, public DLT designs lack speed, face concerns over scalability, energy consumption, privacy, identity and cost [Cho+19]. The bigger the public network, the slower it is, as more transactions take place and clog the network. For example, Ethereum can handle 13 transactions per second, compared to 3000 by Hyperledger Fabric, compared to 56 000 by VISA. Furthermore, data stored in these ledgers are visible to any participant and therefore not suitable to handle sensitive data. All entities are identified via cryptographic pseudonyms that makes it hard to audit and are open to Sybil attacks [35]. Storing data also incurs expense and is therefore infeasible to store a large amount of data in the ledger. Smart contracts in Ethereum lack any upgradability feature, thereby making it difficult to update any smart contract in case a new feature needs to be added or a bug needs to be corrected. Public blockchain is also often criticized for lack of governance when it comes to cyber crime [36], [37], money laundering [38] and drug trading [39].

Private DLT approaches have been created to resolve the issues of public DLT designs. They do not rely on an energy-intensive consensus algorithm. They can process transactions much faster than any public DLT system. The identity of each entity within the network is verified, thereby enabling auditability and accountability. This also acts as a mechanism for protection against Sybil attacks. Private DLT systems afford federated access to data in the ledger, ensuring privacy by only allowing authorized entities to access any private and sensitive data in the system. Fabric, for example, supports the upgradability of smart contracts, which can be vital when new logic needs to be incorporated or a bug needs to be fixed. All these properties make the private DLT systems suitable for scenarios that need to deal with highly sensitive data.

However, the biggest disadvantages of private DLT designs is centralization. Private distributed ledgers inherently become centralized due to their private network. The credibility of a private network relies on the credibility of the authorized nodes, which means they need to be trustworthy as they are verifying and validating transactions. Private DLT systems cannot provide the same amount of security regarding the immutability of data and code in comparison to public DLT systems.

The reason we consider these DLT approaches is that many of the Ethereum's (public and private) and Hyperledger Fabric's complementing features overlap with our defined DP requirements (table 2.2). We will further discuss these relations in section 4.2.

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3.5.4 Trade-Offs

From N. Kannengießer et al. [Kan+20]:

A	B	<i>Ethereum</i>	<i>H. Fabric</i>
Confidentiality (+)	Integrity (+)	B	A
Consistency (+)	Availability (+)	B	A
Strength of Cryptography (+)	Support for Constr. Devices (+)	A	-
Maintainability (+)	Availability (+)	B	A
	Integrity (+)	B	A
Node Controller Verification (+)	Ease of Node Setup (+)	B	A
Turing-compl. Smart Contracts (+)	Confidentiality (+)	A	AB
	Transaction Validation Speed (+)	A	A
Throughput (+)	Consistency (+)	B	A
	Integrity (+)	B	A
User Unidentifiability (+)	Throughput (+)	A	B

A: DLT characteristic A out-weights DLT characteristic B

B: DLT characteristic B out-weights DLT characteristic A

AB: DLT characteristic A and B are both achieved (trade-off avoided by other means)

-: Trade-off not applicable

(+): DLT characteristic is aimed to be high

3.5.5 Suitability for Healthcare DP

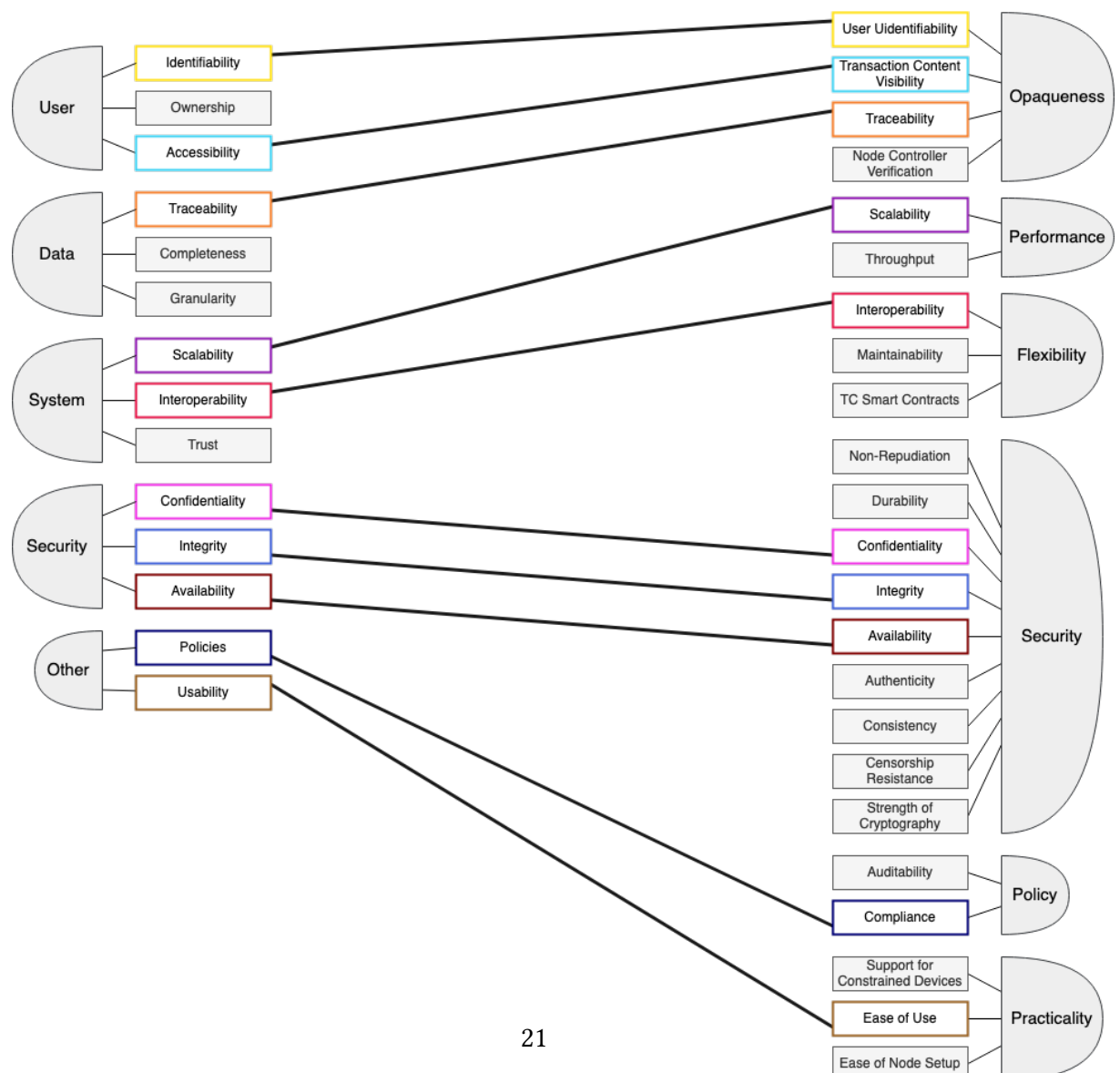
3.5.6 Suitability for Finance DP

4 Evaluated Mapping

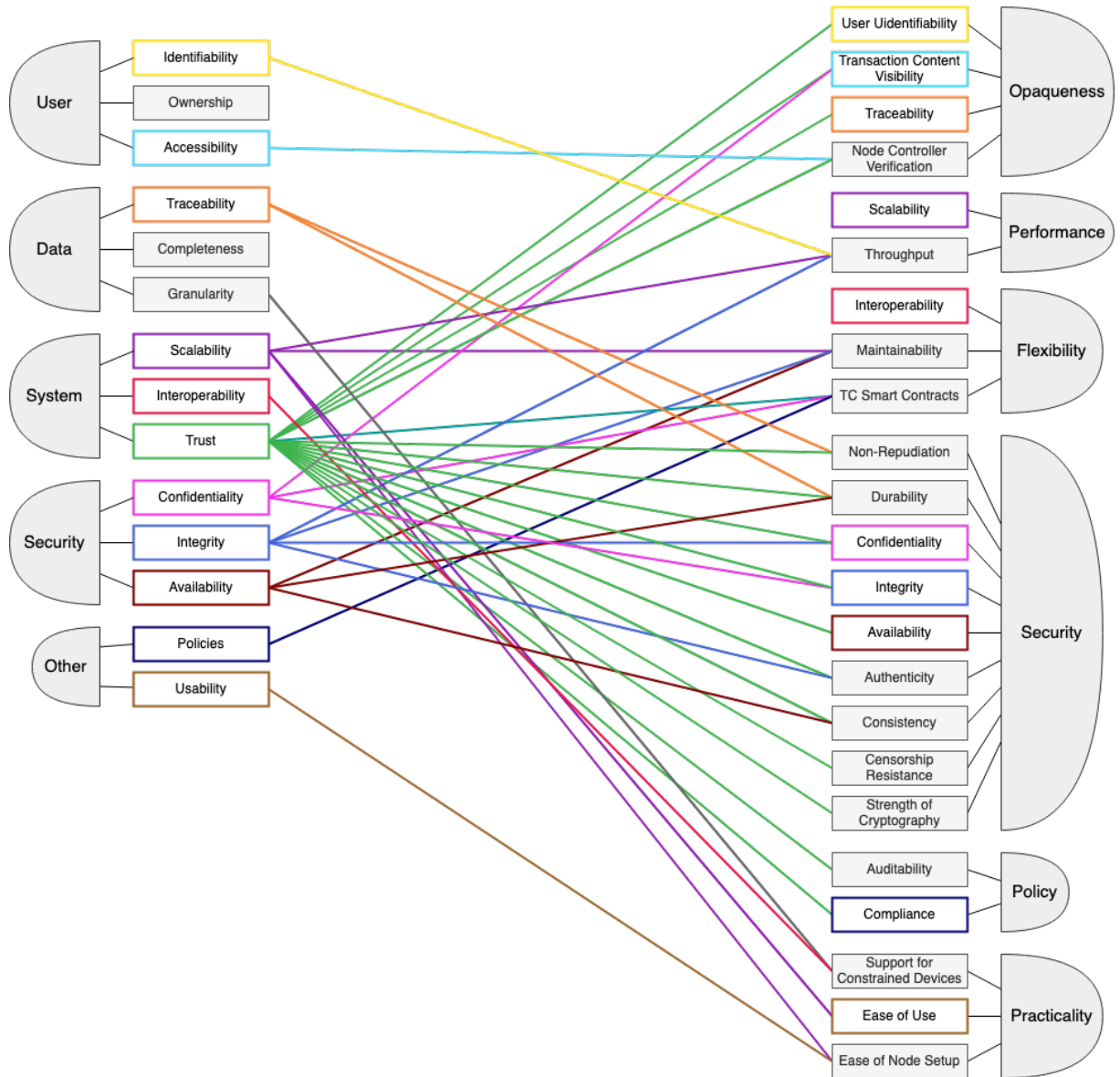
4.1 DP Requirements to DLT Characteristics

The 10 "main" DLT characteristics correspond directly to some of our defined DP requirements. The other 13 "secondary" DLT characteristics that we identified are rather concrete and specific. Furthermore, our defined requirements in table 2.2. can be influenced by one or more DLT characteristics. Here we aim to present in an easily visible way, which DLT characteristics seem to be related to which DP requirement.

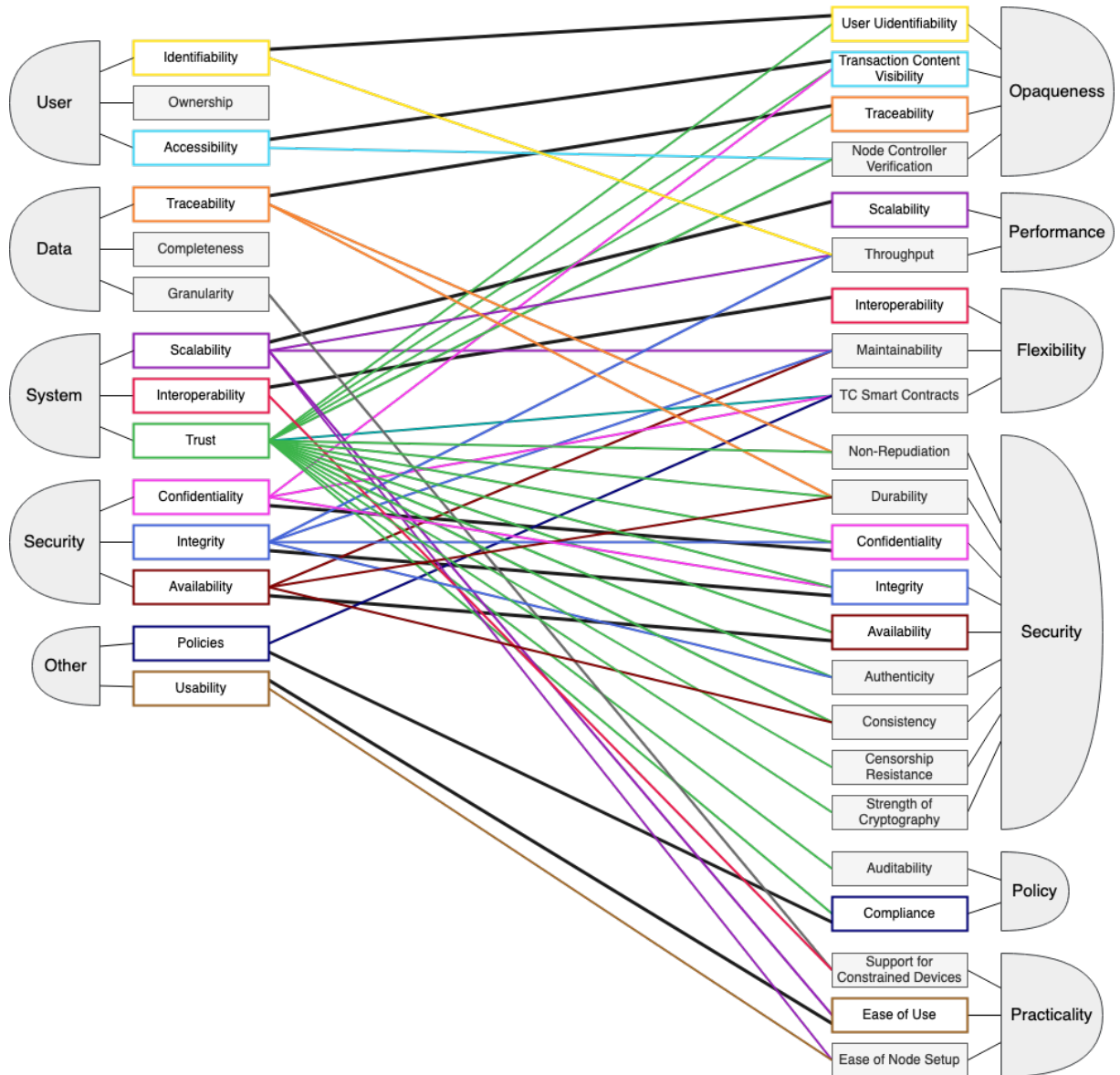
4.1.1 Main Relationships



4.1.2 Secondary Relationships



4.1.3 All Relationships



4.2 DP Requirements to the Considered Approaches' Features

4.2.1 Hyperledger Fabric

Since the network is permissioned, every user participating in a transaction must register in the network for getting their corresponding IDs, which can fulfil our **Identifiability** requirement [SSS18]. Another one of the many compelling Fabric features is the enablement of a network of networks. Members of a network work together, but because businesses need some of their data to remain private, they often maintain separate relationships within their networks [DMH17]. This can mean different **Accessability** rights for different users. Access rights and the nature of blockchain can provide **Traceability**. Its highly modular and permissioned architecture can bring **Confidentiality**, transparency and accountability which helps achieve high level of **Trust**. Its high throughput (3000 transactions per second) and low latency relate to **Scalability** and can ensure **Availability** in emergency situations. High degree of **Interoperability** can also be observed thanks to its multi-language smart-contract support (Go, Java, Javascript) and Fabric's support for EVM and Solidity. Queryable Data is also a feature which can positively impact **Usability**. **Policies** (and potentially other requirements) can also be implemented through chaincode [DMH17].

4.2.2 Ethereum

Ethereum (public), being a public ledger, has strong support for auditability and accountability in case the proper identity of entities can be verified and it provides pseudonymous identification via public key (**Identifiability**). Its immutable computer logic together with smart contracts, EVM, consensus mechanism, Ether (used to store, process and update data via transactions) and lack of necessity for trusted third parties, further increase the **Traceability** of information and **Trust** in the system. The immutability and irreversibility of the ledger can provide **Integrity**. Thanks to its customisability through Turing-complete smart contracts, its generalized purpose, flexibility, adaptability, current success and available tools, research and information for developers and users, it can be seen as accessible, relatively widespread and easy to use/setup (**Usability**). Ethereum provides also the possibility of decentralised applications (DApps) and decentralised autonomous organisations (DAOs), which can create or enable users to vote for **Policies** and regulations. In terms of **Availability**, the public Ethereum network is best suited to storing long-term static data that need to be widely available, such as the Ethereum Registration Authority information [Rob20].

In spite of its attractive potential, however, the mass adoption of this technology is prevented by its inherent limitation in scalability and due to Ethereum's probabilistic finality [Vuk15], it is not well suited to information that needs to be available and acted upon immediately [Rob20]. From the scalability perspective, Blockchain-based systems like Ethereum, are commonly compared [Cro+16] with conventional systems like VISA (2000-56000 transactions per second vs. 13 of Ethereum). This quantitative comparison shows that Ethereum is quite far from offering a viable implementation platform for all transaction-based systems [BFV19].

However, Ethereum can also be used as a private network. Approaches like sharding [], side-chains [21a] or choosing non-default values for the chain parameters can affect throughput, latency and drastically increase **Scalability** [SDS19]. Private Ethereum sidechains promise

also to ensure **Confidentiality** [JRB19]. While researchers and developers recognise it as challenging and complex, some solutions to cross-chain **Interoperability** have been proposed by a number of private Ethereum approaches [; 21b; Cle19].

4.2.3 Overview

Requirement	<i>Hyperledger Fabric</i>	<i>Ethereum (public)</i>	<i>Ethereum (private)</i>
Identifiability	x	x	x
Ownership			
Accessibility	x		
Traceability	x	x	x
Completeness			
Granularity			
Scalability	x		x
Interoperability	x		x
Trust	x	x	
Confidentiality	x		x
Integrity		x	x
Availability	x	x	x
Policies	x	x	x
Usability	x	x	x

5 Discussion

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5.1 Principle Findings

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5.2 Implications for Practice

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5.3 Implications for Research

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5.4 Limitations and Future Work

6 Conclusion

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