Combining Blockchain and Semantic Technologies: A Survey

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***Abstract*—We survey literature that combines blockchain and semantic technologies. Our findings identify main areas where the combination of blockchain with semantic technologies are considered, and answer key research questions, surveying existing challenges addressed, their advantages, technical perspectives, and future recommendations.**

***Index Terms*—Blockchain, Distributed ledger technology, Semantic web, Ontology, Knowledge graph.**

I. Introduction

Blockchain (BCT) is an emerging technology which has tremendous potential for data sharing application between untrusted entities. Semantic technology (ST) such as ontologies and knowledge graphs are well established and recognised for formalising meaning related to data, in particular in the context of the World Wide Web (WWW) [1]. Therefore, there is potential in combining both technologies and to study the impact they have on enhancing data with trust and meaning. In fact, the symbiotic relationship that supports both technologies, and the potential that can be reached by merging them, has been recognised [1]. BCT is seen as a perfect complement to ST to configure a big part of Tim Berners-Lee's vision of the Semantic Web, and it is claimed that BCT and ST must coevolve to achieve this vision [2].

In this paper, we provide an in-depth survey of the combination of BCT and ST in current research. The aim of this paper is to expose existing relationships between BCT and ST which also include technical aspects, rather than focusing solely on theoretical ideas. Amongst the papers we identified, we can distinguish four main application areas: in BCT industry, in organizations, for supply chains and in ST industry.

This paper is organized as follows: Sect. II provides a brief background on BCT and ST. Sect. III introduces research methodology and survey questions. Sect. IV summarizes the results of the selected papers. Sect. V answers our survey questions, while the final section concludes the paper.

II. Background

This section provides a brief background of BCT and ST.

BCT has shown opportunities in transforming traditional industries with its key features such as decentralization, persistency, anonymity and auditability [3]. In BCT, a third party is no longer needed. Consensus algorithms are used to support data consistency in distributed networks. Transactions send to a blockchain can be validated quickly and invalid transactions would not be admitted by honest miners. In this way, it is impossible to delete or rollback transactions once they are included on a blockchain. Blocks that include invalid transactions can be exposed immediately. Each user can interact with the BCT via a generated address, which does not reveal the real identity of the user; this process is known as *anonymity* [3].

Meanwhile, ontologies are used as tools to represent, name, and define categories, properties and relationships between concepts, data and entities of one or more domains [4]. The semantic web, originally intended for the WWW, provides a common framework for sharing and reusing data in different applications and domains. The vast majority of WWW data is readable for humans, but not for computers [5]. Knowledge graphs are used to describes entities – objects, events, situations or abstract concepts – and their interrelations, using graphs. They define possible classes and relations between entities in a schema. This allows for potentially interrelating arbitrary entities with each other and covers various topical domains [6].

III. Survey Methodology

In order to answer the survey questions proposed below, we have conducted a detailed review and discussion about the combination of BCT and ST. Our review adopts the methodological approach offered by Tranfield et al. [7]. It primarily involves three ordered stages: *planning*, *execution*, and *reporting*. In the planning stage, we define the research keywords and the execution procedure. Afterwards, we specify the database to execute the research. In the execution stage, we apply the previous planned protocol to find the related papers and information. In the final stage; reporting, we address the presented questions in this work by exploring all factors that impact on our findings.

1) Planning: The key terms used in this research are 'blockchain', 'distributed ledger technology', 'semantic web', 'ontology' and 'knowledge graph'. The research format terms are written in Scopus as follows: (TITLE-ABS ("blockchain") OR TITLE-ABS ("Distributed Ledger Technolog*")) AND (TITLE-ABS ("Semantic Web") OR TITLE-ABS("Ontolog*")

OR TITLE-ABS("knowledge graph")). This syntax means any of the first two terms must be combined with any of the last three terms. The first two represent BCT where the last three represent ST. TITLE-ABS let us search for the mentioned terms in titles and abstracts. The used digital library in this research is Scopus.

2) Execution: This phase started once we applied the previous research criteria, which in return found 361 paper. Next, we started the filtration process by removing all unrelated papers which gave 157 papers. The second step involved applying an inclusion/exclusion criteria. The inclusion criteria validates that the main focus of an included paper is the combination of both technologies (BCT and ST). Hence, all papers where the combination of BCT and ST is not the main focus, were excluded. This narrowed down the results to 119 relevant papers. Then, we run a second round criteria by reading carefully the abstract of each paper. Several papers discuss the combination of BCT and ST without identifying technical details—those were excluded as well. At the end of this selection process, we were focusing on 29 papers. The analysis process was performed iteratively. The reporting phase is explained in Sect. IV and Sect. V.

3) Survey Questions: We identified four key questions about the identified research that combines BCT and ST:

1) What are the main challenge areas addressed by combining BCT and ST?
2) What are the main advantages, disadvantages and limitations of combining both technologies?
3) What are the main technical ideas to combine BCT and ST?
4) What is the proposed future research on the combination of BCT and ST?

IV. Survey Overview

Through the study of the selected 29 papers, we identify four main areas where a combination of BCT and ST has been proposed. It shows that the area most affected by this combination is BCT itself, then organizations, next supply chain (CS) and last ST industry.

A. Blockchain Technology

Applications in the BCT industry can be divided into three subcategories: (1) data integration, storing, querying, searching, (2) data modeling and standardised information; (3) others, including hiding configuration process, creating custom structure, and simplifying block data structure.

1) Data integration, storing, querying and searching: Third et al. [8] suggest adding semantic indexing to reveal distributed ledgers (DL) data as Linked Data, because information relating to an entity may be scattered throughout multiple ledgers. Knez et al. [9] propose a transaction manager for ontology-based database manipulation that combines BCT and ST. Yang et al. [10] address the problem that most secure semantic searching techniques still perform precise matching on ciphertext after query expansion which produces weak search results. They propose a secure heuristic semantic searching scheme in which a privacy-preserving word nonlinear matching (PP-WNM) technique is developed, and a BCT-based verification is used to reach trustworthy search results with high retrieval accuracy. Wang et al. [11] study a scheme of processing file storage and traceability of knowledge graphs based on BCT and distributed file storage system. Sopek et al. [12] and Tomaszuk et al. [13] introduce and extend GraphChain as a framework for on-chain data management for BCT using the synergies between ontologies and BCT. This permits storing data in native semantic formats. Abu et al. [14] propose a data-graph service-layer which employs data graphs such as RDF-encoded data to permit utilising ST for reasoning on data, data retrieval and connections inference.

2) Data modeling and standardised information: ST is well-positioned to address information management in distributed ledgers. Garcle et al. [15] improve their Blockchain system named CopyrightLY, which is a secure heuristic semantic searching scheme with BCT-based verification to address the vocabulary mismatch problem when searching for arbitrary query words over encrypted data to get accurate research results. Rojas et al. [5] propose BLONDiE which is an ontology to permit semantic representation of knowledge to define the native structure and related information. Its use admits having common data formats of different platforms for further processing.

3) Others: Lun et al. [16] propose a novel data searching structure based on a height balanced Binary Search Tree (BST). Their approach retains the characteristics of the traditional ledgers, and adds quick query to create data structure as a doubly linked list. Shahbazi et al. [17] propose a new idea of creating a BCT compliant distributed database which exposes its data with explicit semantics. It applies BCT securitization mechanisms directly to the RDF graph data model. To hide the complex configuration of BCT, Li et al. [18] suggest Blockchain-as-a-Service (BaaS) approach where developers can pay more attention to knowledge graph constructions instead of struggling for mastering BCT. This facilitates the difficulty of creating, maintaining, using BCT and reducing the problems in smart contracts deployment. Maria et al. [19] develop a framework of ontology and blockchain models to assist practitioners to understand and apply new solutions. Jan et al. [20] propose a model to tackle issues in the peer reviewing process by using an approach of recording peer-review data on BCT, ST and linked data. Their system can be used to quantify, recognize and incentivize researchers' peer-review efforts.

B. Organizations

Thanasis et al. [21] combine ontological knowledge and BCT to gain reliable service exchange and trustworthy content handling. It can be achieved by applying advanced knowledge management mechanisms for organizations such as health, economy, public services, energy and sustainability, news, media, entertainment, Industry 4.0 and tourism. Marathe et al. [22] suggest a framework to build a shared data view for effective collaboration inside organization boundaries using the combination of BCT and ST.

Legal organizations need to protect user personal identifiable information (PII) that they share with service providers. To maintain General Data Protection Regulation (GDPR) compliance in real time when the volume of shared data grows to exascale levels, Mahindrakar et al. [23] recommend a framework to ensure that data operations are only permitted when they are approved by data privacy policies that are compliant with GDPR privacy standards. Nguyen et al. [24] propose a hybrid method combining BCT and ST for validating the learning data and verifying the learning certificate with legal constraints that guarantees data and semantic transparency.

Iqbal et al. [25] propose HealthOn which is a web ontology language to build BCT based security ontologies to remove conceptual ambiguity and semantic gaps. This work is extended by Matulevicius et al. [26] by including blockchain-based healthcare application security threats. Chondrogiannis et al. [27] propose a distributed application (DApp) using BCT and ST that enable individuals and health insurance organizations to come into agreement during the implementation of healthcare insurance policies.

In recruiting organizations, Guoin et al. [28] propose a big data assisted ontology based BCT design (BDOBD) as an intelligent screening system for evaluating job candidates using ontological mapping.

C. Supply chains

Regarding supply chain (SC) industry, a common interpretation of data among SC enterprises to define the source of information is needed. Henry et al. [29] state that ontologies can contribute to develop BCT applications by analysing a traceability ontology and translating some of its representations to smart contracts. This executes a provenance trace and enforce traceability constraints on BCT. However, not all distributed databases are compatible with a BCT architecture. Therefore, there must be a common interpretation of data among enterprises. This interpretation can be formally enforced through the use of common data standards (i.e., models, dictionaries, and conventions). Ouf et al. [2] suggest to boost the representation capability of data through knowledge management and reasoning technologies by integrating BCT and ST. Shahbazi et al. [17] propose a BCT machine learning-based food traceability system (BMLFTS) to combine the new extension in blockchain, Machine Learning technology, and fuzzy logic traceability system that is based on the shelf life management system for manipulating perishable food. For low trust network, Braun et al. [30] propose the SoLiD system, which minimizes the data stored in BCT and is based on ST data modelling in knowledge graphs, decentralised management of interlinked data, and a light-weight smart contract. It stores information off-chain and confirms the information behind a supply chain using linked data and smart contracts.

D. Semantic Technologies

In connection with ST industry, the evolution processes become more complicated in large-scale ontologies due to different changes. Mohsen et al. [4] suggest to adapt BCT in building an ontology process to create a domain universal common ground. As a consequence, ontologies can be build in dynamic and automatic ways utilising worldwide consensus. BCT concepts and design principles exploit to construct a Worldwide Ontology Ledger (WOL) to evolve it in a collaborative novel algorithm. This leads to sharing ontologies globally. Another missing component in ST industry is the use of BCT mechanisms such as consensus protocols respectively mining algorithms for automatically determining whether concepts should be added. Furthermore, the multi-user-oriented design of ontologies and zero-knowledge proofs have not been considered in this context. Georg et al. [31] advise using Knowledge BCT which provides transparent monitoring of knowledge development for many purposes. Privacy protection and removing an intermediary can also be achieved in ST by BCT. Chen et al. [32] propose a first attempt to implement a knowledge graph in the OpenKG chain, a BCT-based trust network.

V. Survey Discussion

In this section we will answer our proposed research questions applied to the papers surveyed before.

A. Main Challenges

We structure the information presented in the selected papers using themes: The main theme is *interoperability between data sources*, which occurs in all areas. Another main theme is *data storage and retrieval*, which is not occurring in all areas but forms the biggest part of the published research. Side themes, which are occurring only in one area, are *GDPR compliance*, and *provenance and traceablitliy*.

Interoperability between data sources is seen in all areas. BCT data needs to integrate with other types of data on other technology stacks. Due to the large number of external data sources, BCT must process different types of data [8]. BCT needs interacting with other technologies and disclose their data [20]. For organizations, the heterogeneous nature of data and need for sharing makes the process of collaboration between organizations more complicated. Sharing business data across independent enterprises is a call [22]. SC and associated data are moving to BCT to enable inter-organizational processes in networks with low trust which provides a scaling issue for BCT [30]. ST organizations need evolving domain ontologies globally by using BCT as a platform relying on its features and capabilities [4], applying knowledge BCT to ontology and using BCT infrastructure for open knowledge graphs [32].

Our second main theme is data storage and retrieval, which we divide it into three sub-categories; *search*, *security* and *improving BCT data structures*. For search, a secure search on the BCT platform is required for reliable and accurate results. For example, there are discrepancies when searching for keywords through BCT-encrypted data [15]. The security sub-theme appears in organizations: BCT can tackle security threats and provide data integrity. This can be used to decentralise healthcare data operations and to make healthcare data transparent and immutable [25], [26]. Also, a multi-layer method is developed for a semantically-enriched blockchain software ecosystem named ONTOCHAIN. It enables the development of trustworthy distributed applications [21]. System security can be increased and potential attacks prevented [27], even under an assumed attack of quantum computing [24]. Also for SCs, the combination of BCT and ST allows storing larger files while keeping the security and transparency provided by blockchain [9]. The sub-theme improving BCT data structures can be recognised in BCT area. BCT's data storage structure is not efficient and the block data structure is complex [16]. BCT structures are missing hiding configuration processes and missing creating customs structures [18]. Developed data models are urgently needed to make clear connections and knowledge [19]. An official querying and data storage about BCT is essential [12]. Processing files in BCT requires file storage using Knowledge Graph traceability [10]. Representation capability of data can be boosted through integration of knowledge management and reasoning technologies with BCT [2]. Existing electronic recruiting mechanisms are primarily useful for storing contact details for qualified candidates but need to use BCT and ST combinations [28].

The side theme GDPR compliance appears in BCT area. Data protection in legislation organizations is difficult to maintain GDPR compliant in real time, when the volume of shared data grows to exascale levels. A GDPR knowledge graph has been integrated with BCT to have an audit log of every operation and the corresponding GDPR policy that permits the operation [23].

The another side theme, provenance and traceability, occurs in SC area. One of supply chain major concerns is defining the source of information. Several food manufacturing systems present food traceability systems that suffer from a low level of readability, scalability, and data accuracy [30]. BCT can facilitate ontologies to be used for much improved supply-chain provenance as metadata and ST enabled ontologies to be applied for knowledge provenance. For example, many systems of BCT and ST are proposed for supply chain management and provenance tracking [29].

B. Advantages, Disadvantages and Limitations

None of the papers surveyed mentioned disadvantages or limitations. However, many advantages through combining ST and BCT have been identified.

Regarding BCT industry, the advantages achieved by the combination of BCT and ST are: *improved interoperability*, *improved search*, *improved security and traceability*, *more efficient BCT deployment*, and *use of ST tools*. Searching for information in DL will be improved, search property will be more accurate and will use domain specific terms across multiple ledgers with improved power, usability and BCT scope and services [10]. Furthermore, searching will achieve higher accuracy for ranked results [13]. Data can also be simply linked to other sources of information using ST approaches. It is possible now to connect domain-specific data from sources external to the chain, for example linking BCT Open Badge information with other Linked Data resources [12]. Interoperability will be simpler and complex domains will become easier to deal with [18]. Furthermore, interoperability can be used in privacy-preserving applications, such as privacy-preserving image retrieval [20]. Additionally, facilitating BCT-powered knowledge graph construction schemes greatly simplifies the building of new BCT systems. The ability to manage multiple BCTs for different domain specific knowledge graphs also becomes easier [18]. Faster and more robust, trustful, and reliable services can be achieved [27]. Users of BCT can work with standard tools developed in the domain of ST like SPARQL for querying, Linked Data mechanisms for accessing the nodes of the graphs reasons for ontologies and many others, while benefiting from BCT mechanisms in their capacity to guarantee data reliance [33]. Storing the process file of building a knowledge graph into BCT ensures their security and traceability. For example, process files of a certain period, which may store reasoning error or security issues, can then be obtained from the chain on demand [11].

In terms of organizations, the benefits accomplished are: *enhanced services*, *improved privacy*, *higher accuracy*, *increased productivity*, *improved security*. Advanced knowledge management mechanisms can provide reliable service exchange and reliable content handling [21]. Other benefits are to systematically improve temporal delay, data inconsistency, and lack of trust issues, to aid maintaining the scenarios where the user will always have access to their data as well as the ability to track it. This empowers consumers while ensuring their privacy and decent service quality [22]. In job requirements applications, the accuracy of information about competing applicants will be improved, the settings feature effectively increases overall productivity which leads to increase the organization's performance [28]. Furthermore, BCT with ST can overcome security challenges, improve data integrity, and transform the transacting process in a decentralised, transparent, and immutable manner. For example, HealthOnt supports the selection of BCT by security experts when designing healthcare applications. It encodes traditional healthcare applications' information security into a blockchain-based system development that can be extended, reused, or integrated with other security ontologies [25], [26].

Considering the advantages in SC industry, highly secure access to immutable supply chain data can be provided. Provenance can be evaluated even when no party claims ownership over all supply-chain data [29]. In addition to improving data representation capability, transparency and traceability is enhanced by its ability to query all systems in the supply chain network. For example, a shared understanding between humans and IoT in a BCT-based pharmaceutical supply chain can be enabled [17]. In addition, scalability and data sovereignty problems of BCT can be addressed with off-chain semantic data modelling [30].

The advantages for ST industry are, that automatic ontology validation and evaluation technique are enhanced. Knowledge, experiences, improvements and conflicts are quantifiable and measurable. The universal ontology process can be automated with increasing resilience and improving cross-domain collaboration [4]. Advantages of using an ontology management system based on combining BCT and ST include data loss protection, data restoration, change tracking, and automatic consistency checking. [9].

C. Technical Perspective

The main theme for technologies mentioned in the BCT area are *storage technologies*, with sub-themes *file storage* and *data storage*. Further technologies discussed less frequently are *data indexing* and *data matching*. Constructing an index for BCT using smart contracts to represent Open Badges, where the capacity to utilize related data and link it to pertinent external sources, is greatly improved by indexing the contracts, accounts and data relating to their external semantics [8]. For searching in BCT, a safe procedure for transforming the Word Nonlinear Matching (WNM) problem into a PPWNM problem is created. It is used to determine how similar a query and document are to one another. The encrypted documents are ranked using similarity metrics, which produces precise results [10]. The process files of building knowledge graph are pre-processed by distributed file system to advance the storage efficiency and save resources; then the processed files are stored in the BCT network to ensure their security and integrity. Through the combination of BCT and distributed file storage system, the safe storage and fast reading of files in the process of building knowledge graph are guaranteed [11]. Applying the GraphChain architecture in synergy with Ethereum BCT can create a distributed graph data storage to enhance BCT storage. Furthermore, a service-layer can be added that employs data-graphs, reasoning, and underlying inference rules to fulfill advanced requirements for handling sophisticated data models in BCT [13].

With regard to organizations, a semantically-enhanced BCT ecosystem is built which allows the creation of secure distributed applications [21]. Also, BCT, ontology and heuristic rules are used as infrastructure to share business data across independent enterprises [22]. For example in Data Protection Regulation, policies are applied by using ST, natural language processing (NLP) and Text Mining [23]. In healthcare, security risk management (SRM) domain model has been followed to develop a framework for exploring security threats of traditional healthcare applications. This framework is used in building a BCT-based healthcare security ontology [25], [26]. Further techniques in health organizations are providing access control to user data via BCT, and machine-processable health contract conditions via ST [27].

In SC industry, ontology-based BCT modeling approach based on informal or semi-formal ontologies offers BCT an enhanced interpretability [29]. The off-chain data is described in RDF and accessible in a RESTful manner (i.e. Linked Data). Only hashes, URIs, and links are stored on BCT. The hashes, URIs, and links allow for verification of the off-chain data using a link-traversal-based querying approach involving smart contracts [30].

In terms of ST industry, storing the explicit knowledge in a decentralized BCT enables the understanding of the concept of the model, and allows to set up a scheme that delegates model operations to other identities [31].

D. Future Work

A number of future areas for research have been proposed. The design of a secure semantic searching scheme under decentralized storage needs to be investigated more [10]. It requires development of concepts like sub-graphs and graph hashing (integrity proofs), and the partial replication of such graphs [11]. Work in future can be extended in aspects like providing support for further BCTs such as private Ethereum blockchains. The performance of BaaS system needs to be improved in high concurrency scenarios and the model of supporting cross-chain interaction needs to be researched [18]. A semantic block explorer is capable of querying using SPARQL [5]. Areas to investigate include cross blockchain data exchange, embedding of metadata standards in BCT, providing collaborative BCT, better connecting BCT with various search engines and web-based applications [14].

In organizations, to improve security, it should be investigated how the HealthOnt system might overcome challenges linked to human factors [26]. Other areas for future work are supporting semantic data retrieval on the blockchain, and testing systems with other consensus algorithms [24].

For supply chains, research is needed to make the conversion from ontology representations to BCT code more systematic. This may involve more granularly outlining conversion steps, developing custom APIs, or contributing to efforts to convert ST representations like OWL and RDF into BCT-compliant representations [21]. Also, while the proposed architecture of Pharmaceutical Supply Chain Semantic Blockchain (PSCSB) is flexible to incorporate different technologies, further research is needed on ST rules and SPARQL queries to infer new knowledge from PSCSB [22]. Two main aspects are suggested for food SC. The proposed system should not be limited to food traceability, and more analysis aspects should be added, e.g., managing risks and e-commerce transactions. Also, information flows, such as risk, material, and value, can be covered by an integrated approach [17].

In ST industry, investigation should be done of the Stellar Consensus Protocol (SCP) and its two sub-protocols: a nomination protocol, a ballot protocol and the hybrid consensus algorithm [4]. Data structures should be investigated to identify which one is the most adequate for the representation of ontologies in the context of BCT. In addition, the use of UUIDs may not be an optimal solution for ontologies although they provide several benefits in terms of a distributed and independent creation of elements [31]. Other areas for proposed investigation in ST industry are performance issues caused by fine-grained knowledge identification on the chain, decentralized storage of knowledge graphs, and trainable incentive models for knowledge crowd-sourcing [32].

VI. Conclusion

In this paper, we discussed the main challenges, benefits, technical perspectives, and future work that have been identified in current research for combining BCT and ST. Based on 29 papers, we identified BCT, organizations, supply chains and ST as the main areas in which research has been conducted. We found that the two main challenge themes are interoperability between data sources, and data storage and retrieval. Improvements, such as efficiency, security, privacy, have been proposed for all areas. Improvements were also derived from the use of ST tools. Most of the surveyed articles suggested to improve BCT by using ST features.

In conclusion, we can say that research into the combination of BCT and ST has only started, and that its full potential still needs to be explored.

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