Integration of ontologies with decentralized autonomous organizations development: A systematic review

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Abstract
During the last years, the industry has been experiencing an increasing interest of Decentralized Autonomous Organizations (DAOs), which has become a reference approach in blockchain-based decentralized software system development. DAOs are seen as a good alternative to become a business model truly global, reliable and transparent. However, the guidelines and models that provide support for the adoption and development of DAOs are almost non-existent and they are in natural language or graphical representations, both lacking the computational semantics needed to enable their automated validation, simulation or execution. This paper presents a systematic review of the literature related to the integration of ontologies into the DAO development process. The objective of this paper is to provide an unbiased and up-to-date framework that helps software development researchers identify new research activities and take advantage of this integration based on business models and blockchain-based decentralized technologies perspectives.

Keywords: Ontology, DAO, decentralized applications, Blockchain, smart contracts.

1 Introduction

In the last decade, Decentralized Autonomous Organizations (DAOs) have gained increasing attention in the industry and, in general, in the academic and public debate as a means to support organizations that are concerned with ensuring sharing, security, transparency, and auditability, making their business truly global without any central authority or middleman controlling it.

DAOs started to appear in the context of the decentralized solutions with the creation of Ethereum (Buterin, 2014), which could be automated, immutable and transparently embedded in a blockchain.

The term governance can be defined as “the use of institutions, structures of authority and collaboration to allocate resources and coordinate the effort and activity in society or in the economy” (Bell, 2002). In this vein, governance rules force organizations to think about and formalize their understanding of their current decision-making processes. In Ethereum, through the use of smart contracts (i.e., small pieces of code deployed on the blockchain and executed in a decentralized way by all the nodes in the network with no attached legal meaning
in this context), DAOs can implement their governance model, where the rules that are part of it could be decided based on proposals voted by their stakeholders, for example.

Therefore, a DAO can be understood as a group of people or an organization that use blockchain-based trustless decision-making frameworks. Decisions made by the DAO are self-actuating via interaction of smart-contracts which radically diminishes the need for middle-man or any intermediary (“DAOfest,” 2020).

As a decentralized organization, a DAO can “provide services (or resources) to third-parties or even hire people to perform specific tasks. Hence, individuals can transact with a DAO in order to access its service, or get paid for their contributions.” (Hassan, 2017).

Therefore, a DAO can be specified in terms of the following characteristics: (i) there is no central entity that owns or controls it; (ii) it can operate without human involvement (iii) the operations performed are unmodifiable (i.e., they cannot be removed or altered), which guarantees credibility; and (iv) it is shared, which provides transparency and public accessibility. Also, as stated in (Swan, 2015), the potential benefits of adopting this approach could range over not only economic issues, but political, humanitarian, social and scientific domains.

Therefore, the adoption and development of DAOs open new opportunities and presents new key research challenges focused on the industry that should be exploited. A uniform meta-modeling approach could enable us to build frameworks aimed at integrating governance/business models in blockchain-based decentralized applications, and to understand and manage complex relationships between the different artifacts that form a DAO development process.

In another direction, ontologies are also widely used in the area of Software Engineering addressing the process of software modeling aimed at the improvement of the software development process. An ontology is a formal explicit representation of a shared conceptualization (i.e., an abstract, simplified view of a shared domain of discourse) (Gruber, 1995) (Uschold and Gruninger, 1996). The term ‘shared’ indicates that an ontology captures some consensual knowledge, and the term ‘conceptualization’ means an abstract, simplified view of a shared domain of discourse. This definition is refined in (Guarino, 1998) where an ontology is considered to be a formal vocabulary with a specific meaning of the real-world and the related set of assumptions about that meaning. More formally, an ontology defines the vocabulary of a problem domain and a set of constraints (axioms or rules) on how terms can be combined to model specific domains. An ontology is typically structured as a set of concept definitions and relations between them. Ontologies are machine-processable models that provide the semantic context, enabling natural language processing, reasoning capabilities, domain enrichment, domain validation, etc. Ontologies have been used for decades to represent knowledge from our environment, producing
domain-specific abstractions and an agreed understanding of the domain that we are interested in (i.e., domain of discourse). Ontologies are the result of an extensive analysis and categorization of a specific domain.

Therefore, it seems that the integration of ontologies into the DAO development process may help software engineers and researchers understanding, managing and building this type of complex blockchain-based decentralized software systems. On the one hand, the use of models and meta-models for software development is an established practice in Software Engineering, and, on the other hand, the use of ontologies as modeling and reasoning frameworks for the management of models has been successfully reported and promoted by researchers over the last decades. Furthermore, focused on the DAOs domain, ontologies may provide shared domain conceptualizations representing knowledge that enable software engineers to model the problem as well as the solution under study fostering interoperability and supporting the extension of practices. In the existing literature, we can find works that discuss the contributions of ontologies to implementation of DAOs or smart contracts in general. It is worth the research done by (Norta et al., 2015b), (Kim and Laskowski, 2018), (Kim et al., 2018), and (Silva et al., 2019), among others.

Since we are interested in providing new solutions bringing a real benefit to the developers of DAOs using ontologies, it is important to determine what type of research it is being performed and how it is conducted. Therefore, a systematic review of the existing research related to the integration of ontologies into DAO development is presented in this paper. The systematic review has been performed following and adapting the protocols proposed in (Kitchenham, 2007) and (Evidence-based Software Engineering (EBSE), 2009).

The rest of the paper is organized as follows. Section 2 describes the plan of this systematic review: the research question of this systematic review, the sources that will be searched for the selection of primary studies, the search strings, the study selection criteria and process, and the data that were considered for each primary study. Then, Section 3 lists the selected primary studies. Based on the research questions, the discussion of the results is presented in Section 4. Finally, Section 5 draws the conclusions.

2 Systematic Review Planning

This section summarizes the systematic review protocol followed in this work. As stated previously, this plan is based in the guideline proposed in (Kitchenham, 2007) and in the template protocol defined in (Evidence-based Software Engineering (EBSE), 2009). The research objectives must be defined as well as the sources that will be searched for the selection of the papers, the search strings, inclusion and exclusion criteria for the papers selection, the selection process, and the extracted data for each primary study.
2.1 Research Question

In any systematic review, the research question(s) that the study tries to answer must be specified. Since the objective of this systematic review is the identification of solutions related to DAO development and ontologies, the research question that will be addressed by this work is the following: How can ontologies be used with blockchain-based decentralized technologies to aim the building of software frameworks that enable organizations to develop DAOs focused on understanding and leveraging all their potential?

2.2 Search Strategy

Once the research question has been defined for the systematic review, the sources that will be searched for the selection of primary studies must be specified. This work will be based only on a search of electronic sources. The primary studies selected for this systematic review have been acquired from the following sources (in alphabetic order): (1) ACM Digital Library, (2) Elsevier Science Direct, (3) Google Scholar (this source has been only used for searching specific papers that were cited in other primary studies), (4) IEEE Xplore, and (5) SpringerLink. These electronic sources have been selected because they represent an important reference for software engineers and the industry in general.

From the research question, several search strings have been defined: (1) “DAO” AND “Ontology”; (2) “Decentralized application” AND “Ontology”; and (3) “Smart contract” AND “Ontology”. It is worth highlighting that since sources include the complete set of results, even when they distinguish between singular and plural (e.g., ACM Digital Library), terms have been only searched in the singular.

2.3 Primary Studies Selection

Once the sources and the search strings are defined, the criteria for including and excluding papers and the selection process must be specified. The inclusion criteria consider studies where ontologies are used in blockchain-based decentralized approaches for the development of DAOs. These studies must provide contributions of ontologies to the DAO development process. On the other hand, the exclusion criteria consider studies about DAO development and ontologies where there is no relation between them or papers about blockchain-based decentralized approaches and ontologies where there is no relation to DAO development. Papers in which blockchain-based decentralized applications are used to improve ontology development, but whose improvement is not related to the development of DAOs, are also excluded.
The inclusion and exclusion criteria have been applied in general to the title and abstract in order to determine if the research work is considered relevant for the goals of this systematic review. However, when it was not enough, the full text has been reviewed.

The selection process for studies consists of several steps: (1) one researcher (the corresponding author of this paper) applies the search strategy to identify potential primary studies, (2) several researchers (the authors of this paper) check titles and abstracts of all potential primary studies against inclusion and exclusion criteria. If the title and abstract is not enough to determine how relevant a primary study is, then researchers will review the full text, and (3) any uncertainty in primary studies will be discussed among the researchers of this paper or with other researchers who have expertise in the domain under study.

2.4 Data strategy

Each primary study remaining after the selection process of the systematic review has been reviewed in detail and a review summary was written for each paper. The information of a review summary is defined and in Table 1.

Table 1. Paper Review Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Primary study ID.</td>
</tr>
<tr>
<td>Source</td>
<td>The electronic source(s) that provided the primary study.</td>
</tr>
<tr>
<td>Relevance</td>
<td>The relevance of the primary study to the research question (i.e., how well the primary study meets the research questions): {low, medium, high}.</td>
</tr>
<tr>
<td>Title</td>
<td>The title of the primary study.</td>
</tr>
<tr>
<td>Authors</td>
<td>The author(s) of the primary study.</td>
</tr>
<tr>
<td>Publication</td>
<td>The details of the publication.</td>
</tr>
<tr>
<td>Abstract</td>
<td>A summary of the primary study.</td>
</tr>
<tr>
<td>Comments</td>
<td>Remarks and additional notes about the primary study.</td>
</tr>
</tbody>
</table>

3 Data Synthesis

In recent years, there has been a growing effort to formalize the knowledge that underlies blockchain-based decentralized domains. However, it is difficult to find relevant and significant contributions and real implementations in this field. Most of them are just conceptual or theoretical contributions pending for validation or implementation of the proposed solutions. The electronic sources provided 615 results. After applying the inclusion and exclusion criteria, 34 papers were considered to be primary studies for the research question. The total number of papers and the number of primary studies obtained from each electronic source can be seen in Table 2.
Table 2.
Relevant information obtained from the electronic sources.

<table>
<thead>
<tr>
<th>Electronic source</th>
<th>Papers (*)</th>
<th>Primary studies (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACM Digital Library</td>
<td>61 (“DAO” AND “Ontology”)</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>3 (“Decentralized application” AND “Ontology”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 (“Smart contract” AND “Ontology”)</td>
<td></td>
</tr>
<tr>
<td>Elsevier ScienceDirect</td>
<td>258 (“DAO” AND “Ontology”)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>15 (“Decentralized application” AND “Ontology”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>56 (“Smart contract” AND “Ontology”)</td>
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<tr>
<td>Google Scholar (***</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>IEEE Xplore</td>
<td>11 (“DAO” AND “Ontology”)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3 (“Decentralized application” AND “Ontology”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 (“Smart contract” AND “Ontology”)</td>
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<tr>
<td></td>
<td>77,555.00</td>
<td></td>
</tr>
<tr>
<td>SpringerLink</td>
<td>41 (“DAO” AND “Ontology”)</td>
<td>9</td>
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<tr>
<td></td>
<td>4 (“Decentralized application” AND “Ontology”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134 (“Smart contract” AND “Ontology”)</td>
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</tr>
</tbody>
</table>

(*) Date of search: June 2020.
(**) For a specific source, primary studies that were found in another source are not counted as primary studies.
(***) Google scholar has been only used for searching specific works that were cited in other studies.

The complete paper review summaries are too long to be included in this paper. Therefore, the list of the primary studies (Authors, Title, Relevance and Source) that were selected after the selection process is shown in Table 3.

Table 3.
Selected studies grouped by source and publication date.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Title</th>
<th>Relevance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alex Norta, Anis Ben Othman, Kuldar Taveter</td>
<td>Conflict-Resolution Lifecycles for Governed Decentralized Autonomous Organization Collaboration</td>
<td>high</td>
<td>ACM Digital Library (Norta et al., 2015b)</td>
</tr>
<tr>
<td>Allan Third, John Domingue</td>
<td>Linked Data Indexing of Distributed Ledgers</td>
<td>high</td>
<td>ACM Digital Library (Third and Domingue, 2017)</td>
</tr>
<tr>
<td>Marco Crepaldi</td>
<td>Why blockchains need the law</td>
<td>low</td>
<td>ACM Digital Library (Crepaldi, 2019)</td>
</tr>
<tr>
<td>Leepakshi Bindra, Changyuan Lin, Eleni Stroulia, Omid Ardakanian</td>
<td>Decentralized Access Control for Smart Buildings Using Metadata and Smart Contracts</td>
<td>high</td>
<td>ACM Digital Library (Bindra et al., 2019)</td>
</tr>
<tr>
<td>Roberto García, Rosa Gil</td>
<td>Social Media Copyright Management using Semantic Web and Blockchain</td>
<td>high</td>
<td>ACM Digital Library (Garcia and Gil, 2019)</td>
</tr>
<tr>
<td>Manoharan Ramachandran, Niaz Chowdhury, Allan</td>
<td>Towards Complete Decentralised Verification of Data with Confidentiality:</td>
<td>low</td>
<td>ACM Digital Library (Ramachandran et al., 2020)</td>
</tr>
<tr>
<td>Authors</td>
<td>Title</td>
<td>Journal/Conference</td>
<td>Citations</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>Third, John Domingue, Kevin Quick, Michelle Bachler</td>
<td>Different ways to connect Solid Pods and Blockchain</td>
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</tr>
<tr>
<td>Haan Johng, Doohwan Kim, Grace Park, Jang-Eui Hong, Tom Hill, Lawrence Chung</td>
<td>Enhancing Business Processes with Trustworthiness using Blockchain: A Goal-Oriented Approach</td>
<td>ACM Digital Library (Johng et al., 2020)</td>
<td>high</td>
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<tr>
<td>Hongman Wang, Yongbin Yuan, Fangchun Yang</td>
<td>A Personal Data Determination Method Based On Blockchain Technology and Smart Contract</td>
<td>ACM Digital Library (Wang et al., 2020)</td>
<td>low</td>
</tr>
<tr>
<td>Athina-Styliani Kleinaki, Petros Mytis-Gkometh, George Drosatos, Pavlos S. Efraimidis, Eleni Kaldoudi</td>
<td>A Blockchain-Based Notarization Service for Biomedical Knowledge Retrieval</td>
<td>Elsevier Science Direct (Kleinaki et al., 2018)</td>
<td>low</td>
</tr>
<tr>
<td>Zhengxin Chen</td>
<td>Understanding Granular Aspects of Ontology for Blockchain Databases</td>
<td>Elsevier Science Direct (Chen, 2019)</td>
<td>low</td>
</tr>
<tr>
<td>Wout J. Hofman</td>
<td>A Methodological Approach for Development and Deployment of Data Sharing in Complex Organizational Supply and Logistics Networks with Blockchain Technology</td>
<td>Elsevier Science Direct (Hofman, 2019)</td>
<td>high</td>
</tr>
<tr>
<td>Alex Roehrs, Cristiano André da Costa, Rodrigo da Rosa Righi, Valter Ferreira da Silva, José Roberto Goldim, Douglas C. Schmidt</td>
<td>Analyzing the performance of a blockchain-based personal health record implementation</td>
<td>Elsevier Science Direct (Roehrs et al., 2019)</td>
<td>high</td>
</tr>
<tr>
<td>Hans Weigand, Ivars Blums, Joost de Kruijff</td>
<td>Shared Ledger Accounting - Implementing the Economic Exchange pattern</td>
<td>Elsevier Science Direct (Weigand et al., 2020)</td>
<td>high</td>
</tr>
<tr>
<td>Xiaochi Zhou, Mei Qi Lim, Markus Kraft</td>
<td>A Smart Contract-based agent marketplace for the J-Park Simulator - a knowledge graph for the process industry</td>
<td>Elsevier Science Direct (Zhou et al., 2020)</td>
<td>low</td>
</tr>
<tr>
<td>Henry M. Kim, Marek Laskowski</td>
<td>Toward an Ontology-Driven Blockchain Design for Supply Chain Provenance</td>
<td>Google Scholar (Kim and Laskowski, 2018)</td>
<td>high</td>
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<tr>
<td>Henry M. Kim, Marek Laskowski, Ning Nan</td>
<td>A First Step in the Co-Evolution of Blockchain and Ontologies: Towards Engineering an Ontology of Governance at the Blockchain Protocol Level</td>
<td>Google Scholar (Kim et al., 2018)</td>
<td>high</td>
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<tr>
<td>Darra L. Hofman</td>
<td>Legally Speaking: Smart Contracts, Archival Bonds, and Linked Data</td>
<td>IEEE Xplore (Hofman, 2017)</td>
<td>high</td>
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<tr>
<td>Olivia Choudhury, Nolan Rudolph, Issa Sylla, Noor Fairoza, Amar Das</td>
<td>Auto-Generation of Smart Contracts from Domain-Specific Ontologies and Semantic Rules</td>
<td>IEEE Xplore (Choudhury et al., 2018)</td>
<td>high</td>
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<tr>
<td>Alex Norta</td>
<td>Self-Aware Smart Contracts with Legal Relevance</td>
<td>IEEE Xplore (Norta, 2018)</td>
<td>high</td>
</tr>
<tr>
<td>Hamza Baqa, Nguyen B. Truong, Noel Crespi, Gyu Myoung Lee, Franck Le Gall</td>
<td>Semantic Smart Contracts for Blockchain-based Services in the Internet of Things</td>
<td>IEEE Xplore (Baqa et al., 2019)</td>
<td>high</td>
</tr>
<tr>
<td>Authors</td>
<td>Title</td>
<td>Journal/Source</td>
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<td>---------</td>
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<tr>
<td>Mengyi Li, Lirong Xiay, Oshani Seneviratne</td>
<td>Leveraging Standards Based Ontological Concepts in Distributed Ledgers: A Healthcare Smart Contract Example</td>
<td>IEEE Xplore</td>
<td>high</td>
</tr>
<tr>
<td>Wim Laurier</td>
<td>Blockchain Value Networks</td>
<td>IEEE Xplore</td>
<td>high</td>
</tr>
<tr>
<td>Seung-Min Lee, Soojin Park, Young B. Park</td>
<td>Formal Specification Technique in Smart Contract Verification</td>
<td>IEEE Xplore</td>
<td>high</td>
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<tr>
<td>Panos Kudumakis, Thomas Wilmering, Mark Sandler, Victor Rodriguez-Doncel, Laurent Boch, Jaime Delgado</td>
<td>The Challenge: From MPEG Intellectual Property Rights Ontologies to Smart Contracts and Blockchains</td>
<td>IEEE Xplore</td>
<td>high</td>
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<tr>
<td>Alex Norta</td>
<td>Creation of Smart-Contracting Collaborations for Decentralized Autonomous Organizations</td>
<td>SpringerLink</td>
<td>low</td>
</tr>
<tr>
<td>Alex Norta, Lixin Ma, Yucong Duan, Addi Rull, Merit Kölvart and Kuldar Taveter</td>
<td>eContractual choreography-language properties towards cross-organizational business collaboration</td>
<td>SpringerLink</td>
<td>high</td>
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<tr>
<td>Nanjangud C. Narendra, Alex Norta, Msury Mahunnah, Lixin Ma, Fabrizio Maria Maggi</td>
<td>Sound conflict management and resolution for virtual-enterprise collaborations</td>
<td>SpringerLink</td>
<td>high</td>
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<td>Elena García-Barriocanal, Salvador Sánchez-Alonso, Miguel-Angel Sicilia</td>
<td>Deploying Metadata on Blockchain Technologies</td>
<td>SpringerLink</td>
<td>low</td>
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<td>Joost de Kruijff, Hans Weigand</td>
<td>Understanding the Blockchain Using Enterprise Ontology</td>
<td>SpringerLink</td>
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<tr>
<td>Joost de Kruijff, Hans Weigand</td>
<td>Ontologies for Commitment-Based Smart Contracts</td>
<td>SpringerLink</td>
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<td>Jan Ladleif, Mathias Weske</td>
<td>A Unifying Model of Legal Smart Contracts</td>
<td>SpringerLink</td>
<td>low</td>
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<tr>
<td>Diogo Silva, Sérgio Guerreiro, Pedro Sousa</td>
<td>Decentralized Enforcement of Business Process Control Using Blockchain</td>
<td>SpringerLink</td>
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</tr>
</tbody>
</table>

4 **Data Extraction**

This section presents the extraction of the relevant information that answers the research question of this systematic review: How can ontologies be used with blockchain-based decentralized technologies to aim the building of software frameworks that enable organizations to develop DAOs focused on understanding and leveraging all their potential?
After the analysis and evaluation of the primary studies, we can find several approaches that could apply ontologies in DAO development processes. Most of the studies use ontologies in the context of governance. In this approach, for example, (García and Gil, 2019) propose the use of an ontology in order to formalize key copyright concepts that can be used to enable rights management through distributed ledgers and blockchain technologies. As another example, (Kim et al., 2018) propose a conceptual design of a governance ontology represented as meta-data tags to be embedded and instantiated in a smart contract at the blockchain protocol level. We can also find several studies related to the formalization of legal aspects involved in smart contracts such as (Crepaldi, 2019), (Hofman, 2017), (Norta, 2018) and (Kadumakis et al., 2020). In another line of research, (Norta, 2015), (Norta et al., 2015a), (Norta et al., 2015b) and (Narendra et al., 2016) investigate the lifecycle of cross-organizational business process aware collaborating governance that involves DAOs. In the same context, (Silva et al., 2019) present a proposal that tackles the problem of traceability and control in collaborative business processes.

Another common approach, related to governance, is the of use ontologies for domain modeling through the implementation of smart contracts which are part of a DAO. That is, they share the idea of adopting an ontological approach for the conceptualization of a business domain based on the blockchain technology (i.e., the formalization of smart contracts in terms of ontologies according to their associated business domain). Domain modeling can provide a general framework (i.e., the ontology) that then can be adapted to the specialized needs of individual enterprises (Berztiss, 1999). A good explanation of domain models can be found in (Génova et al., 2009). As an example of this approach, (Hofman, 2019) presents a formal ontology for business transactions focused on data sharing in supply and logistics domain. In the same way, (Roehrs et al., 2019) present Electronic Health Record ontology, openEHR, as an interoperability standard that integrates distributed health records using the blockchain technology. In another direction, (Zhou et al., 2020) presents a proposal where, given collections of semantic concepts (i.e., ontology), each of them formalizing a specific domain, a smart contract validates that those other smart contracts are conformed to their associated ontology.

Finally, another less explored approach proposes ontologies for the modeling of blockchain (and smart contract) concepts. These case studies share the belief that in order to be accepted as a technology standard in the industry, a basic and a shared understanding of the workings and impact of blockchain is of major importance. According to them, ontology-based blockchains (i.e., a modeling approach based on formal ontologies) could provide support in the development of smart contracts that execute on blockchains, and since smart contracts make it possible to have automated control of what happens with data and cryptocurrency on the blockchain, this
formalization could enable us to query and retrieve data stored on the blockchain in different locations, where the corresponding data could be easily linked to other sources of information using Semantic Web. Further, according to this approach. For example, (Third and Domingue, 2017) present a standard ontology to represent blockchain concepts, aimed at exposing distributed ledger data as Linked Data in order to support efficient access to data and smart contracts stored on Ethereum blockchains.

In conclusion, from a DAO development perspective, although we cannot find proposals that explicitly apply ontologies in the formalization of DAOs themselves, ontologies could be used in three ways: (1) using ontologies as a tool for the management of governance in the organizations; (2) using ontologies at a business domain modeling level; (3) using ontologies as a formalization of the blockchain technology.

Figure 1 shows the number of studies focused on each research topic according to the publication year. Since legal aspects and governance rules may be successfully described by ontologies, the ‘governance’ category is the most important research topic related to the DAO development (Risius and Spohrer, 2017). It is worth noticing that research related to governance started to gain importance especially since the appearance of the Ethereum platform. On the other hand, due to the proliferation of blockchain-based web applications, research related to domain modeling has been experiencing an increasing interest in the last two years.

![Figure 1: Number of studies covering each topic based on the publication year.](image)

4.1 Governance

*Alex Norta, Creation of Smart-Contracting Collaborations for Decentralized Autonomous Organizations* (Norta, 2015)
This paper presents an approach for the formalization of smart contracts under the perspective that the smart contract setup lifecycle DAOs use service-oriented cloud computing in a loosely coupled collaboration lifecycle that starts with the setup phase. To accomplish this, the author models the setup-lifecycle of cross-organizational business-process aware collaboration for DAOs. During the collaboration setup, the parties consent to establish a smart contract whose definition is formalized in terms of a specific choreography language for cross-organizational business collaboration, *eSourcing Markup Language* (eSML), a choreography language for cross-organizational business collaboration which is an extension of the *Electronic Contracting Markup Language* (ECML) foundation (SA (Samuil), 2006). The eSML language is detailed in another author’s paper (Norta et al., 2015a), since the definition of this language and the associated smart-contracting ontology is outside of the scope of this paper.

**Alex Norta, Lixin Ma, Yucong Duan, Addi Rull, Merit Kõlvart and Kuldar Taveter, eContractual choreography-language properties towards cross-organizational business collaboration** (Norta et al., 2015a)

In the same line of research than previous papers, in this paper the authors investigate the lifecycle of cross-organizational business process aware collaborating governance that involves DAOs, and a reference architecture that facilitates a technical feasibility evaluation for system implementation is proposed. In this context, governance is considered as a set of smart contracts that comprise machine-readable code for the parties in an *eCommunity* consent upon. For achieving a consensus and define the legal principles, economic theory, and theories of reliable and secure protocols associated with collaborating governance, they refer to ontological concepts and properties for the design of smart-contracting systems.

**Alex Norta, Anis Ben Othman, Kuldar Taveter, Conflict-Resolution Lifecycles for Governed Decentralized Autonomous Organization Collaboration** (Norta et al., 2015b)
Nanjangud C. Narendra, Alex Norta, Msury Mahunnah, Lixin Ma, Fabrizio Maria Maggi, Sound conflict management and resolution for virtual-enterprise collaborations (Narendra et al., 2016)

In the same vein as previous works of these authors ((Norta, 2015) (Norta et al., 2015a) (Norta et al., 2015b)), this paper presents an ontology that solves the conflict modelling, management and resolution in cross-organizational collaboration under the perspective of DAOs, which are referred as Virtual Enterprises (VEs) in this work. Their conflict ontology formally represents conflict types in relation to the participating entities in a VE and the strategies for conflict negotiation and resolution. In this paper, they have focused on conflict modelling and management according to a lifecycle with distinctive stages. Also, via a detailed case study, the authors evaluate the realization feasibility and verify their approach using CPN Tools.

Darra L. Hofman, Legally Speaking: Smart Contracts, Archival Bonds, and Linked Data in the Blockchain (Hofman, 2017)

This paper proposes the creation of a semantic legal layer to support blockchain-based legal contracts. To do so, the author proposes the development of a robust, jurisdiction-specific legal ontology. According to the author, this proposal adds the precision, flexibility and enforceability to blockchain-based smart contracts to allow them to serve the same purposes at the traditional contracts.

Alex Norta, Self-Aware Smart Contracts with Legal Relevance (Norta, 2018)

This paper highlights that the problem with current systems based on smart contracts is the lack of suitable obligation and rights constructs for their execution and enforcement and the lack of the dynamics of legal relationships. Therefore, the aim of this paper is to address this gap by specifying a framework named Self-Aware Contracts (SAC) that enables blockchain-driven self-aware agents-assisted contracts for a decentralized peer-to-peer (P2P) economy. To do so, the author presents the formalization of obligations and rights in terms of an ontology. On the other hand, the approach uses a high-level state-transition automata in Colored Petri Nets (CPN) (Jensen et al., 2007) for processing obligations and rights. The SAC Ontology has been built using the Protégé editor tool (Knublauch et al., 2004) (“Protégé,” 2020), and they use the HermiT reasoner (Glimm et al., 2014) to check the ontology consistency and identify subsumption relationships between classes, among others.

Michal R. Hoffman, Can Blockchains and Linked Data Advance Taxation? (Hoffman, 2018)

In this paper, the author proposes a solution to the tax gap, or the inability to collect the full amount that is owed by a given entity to a particular authority, in terms of a permissioned blockchain-based tax reference generated by a smart contract. In this way, anyone with the right permissions could immediately investigate the
entire commercial chain for any taxable item on an ontology-based tax document. That tax document replicates real-world taxation governance structures and processes and it would be the result of combining an _Legal Knowledge Interchange Format_ (LKIF)-based tax ontology (Glaser, 2017) with a Glaser-based blockchain ontology (Hoekstra et al., 2007).

_Henry M. Kim, Marek Laskowski, Ning Nan, A First Step in the Co-Evolution of Blockchain and Ontologies: Towards Engineering an Ontology of Governance at the Blockchain Protocol Level_ (Kim et al., 2018)

In this paper, the authors propose a conceptual design of a governance ontology represented as meta-data tags to be embedded and instantiated in a smart contract at the blockchain protocol level. The design has been developed by examining and analyzing smart contracts from The DAO (“The DAO (organization),” 2020) (“Analysis of the DAO exploit,” 2016) one of the major hacks that occurred in the early development of the Ethereum blockchain which failed in autonomous self-governance.

_Marco Crepaldi, Why blockchains need the law_ (Crepaldi, 2019)

This paper is focused on the governance of blockchains from a legal point of view. That is, this study considers blockchains as a socio-technical system of rules in order to draw a comparison with legal systems. The author claims that governance structures of blockchains determine both their successes and failures, and contributes to the discussion on the governance of blockchains by leveraging the distinction between primary and secondary rules of law as established by legal theorists with respect to modern legal systems.

_Roberto García, Rosa Gil, Social Media Copyright Management using Semantic Web and Blockchain_ (García and Gil, 2019)

In this paper, the authors present a first attempt to adapt an existing proposal based on Semantic Web technologies for the copyright management domain, the _Copyright Ontology_, to the Ethereum ecosystem. The aim of their proposal is to model a formal representation of key copyright concepts that can be used to enable rights management through distributed ledgers and blockchain technologies. This model can be used, for example, when copyright actions are registered in the Ethereum network. The representations of the agreements are actually stored in the _Inter-Planetary File System_ (IPFS), a peer-to-peer distributed and immutable file system (Labs, 2020).

_Diogo Silva, Sérgio Guerreiro, Pedro Sousa, Decentralized Enforcement of Business Process Control Using Blockchain_ (Silva et al., 2019)
This paper presents a meta-model of integration conceptualization between business ontologies and blockchain applications that tackles the problem of traceability and control in collaborative business processes. Since their objective is to provide an ontological solution for business transactions they use DEMO (Dietz, 2006), an Enterprise Ontology, that models an organization as a network of responsibilities and interactions in order to understand and model human interactions in organizations. On the other hand, they use Hyperledger Composer (HC) (“Hyperledger Composer,” 2020), a toolset to develop Blockchain applications, in order to implement the modeled business transactions and provide traceability over them. The proposed meta-model of integration conceptualization has been designed in a Unified Modeling Language (UML) domain model (“Unified Modeling Language Specification Version 2.5.1,” 2017), that maps the key concepts existent in DEMO business transactions with the key concepts existent in HC.

Haan Johng, Doohwan Kim, Grace Park, Jang-Eui Hong, Tom Hill, Lawrence Chung, Enhancing Business Processes with Trustworthiness using Blockchain: A Goal-Oriented Approach (Johng et al., 2020)

This paper presents a framework for systematically using blockchain towards enhancing business processes with trustworthiness. This work lies in the use of blockchain under the context of goal-oriented Business Process Reengineering (BPR). The framework contains a reference ontology that offers essential concepts, relationships among the concepts, and constraints for BPR using the blockchain technology. It also contains a reference process for using the ontology in helping BPR with blockchain, where key business concerns are represented as (soft-) goals, problems are diagnosed, alternative business processes are explored as solutions and the most suitable selection is made, and all these with more explicit and (semi-) formal representations.

Panos Kudumakis, Thomas Wilmering, Mark Sandler, Victor Rodriguez-Doncel, Laurent Boch, Jaime Delgado, The Challenge: From MPEG Intellectual Property Rights Ontologies to Smart Contracts and Blockchains (Kudumakis et al., 2020)

The authors propose the use of Moving Picture Experts Group (MPEG) and Intellectual Property Rights (IPR) ontologies (MVCO (Rodriguez-Doncel and Delgado, 2009), AVCO (“ISO/IEC 21000-19,” 2018); (“ISO/IEC 21000-8,” 2018) and MCO (Rodríguez-Doncel et al., 2016)) to implement smart contracts that enable music and media value chain stakeholders to share and exchange all metadata and contractual information connected to creative works, in a standardized and therefore interoperable way. Their approach leads to transparent payment of royalties and reduced time spent searching for the right data. In this way, this solution bridges the interoperability gap between MPEG IPR ontologies (and consequently the Semantic Web) and blockchains.
4.2 Domain modeling

Athina-Styliani Kleinaki, Petros Mytis-Gkometh, George Drosatos, Pavlos S. Efraimidis, Eleni Kaldoudi, A Blockchain-Based Notarization Service for Biomedical Knowledge Retrieval (Kleinaki et al., 2018)

In this paper, the authors present a blockchain-based notarization service that uses smart contracts to seal a biomedical database query and the respective results. The goal of their approach is to ensure that retrieved data cannot be modified after retrieval and that the database cannot validly deny that the particular data has been provided as a result of a specific query. Biomedical evidence data versioning is also supported. Risk factors are described in a structured way following the CARRE risk factor Ontology (Third et al., 2015).

Henry M. Kim, Marek Laskowski, Towards an Ontology-Driven Blockchain Design for Supply Chain Provenance (Kim and Laskowski, 2018)

In this paper, the authors make a case for why ontologies can contribute to blockchain design. More specifically, ontologies that represent fundamental concepts in traceability can contribute domain knowledge to develop blockchain applications for supply chain provenance. To accomplish this, they outline and analyze the TOVE Traceability Ontology, and translate some of its representations to smart contracts that execute a provenance trace and enforce traceability constraints on the Ethereum blockchain platform.

Olivia Choudhury, Nolan Rudolph, Issa Sylla, Noor Fairoza, Amar Das, Auto-Generation of Smart Contracts from Domain-Specific Ontologies and Semantic Rules (Choudhury et al., 2018)

In this paper, the authors provide a novel framework for auto-generating smart contracts by enabling seamless translation of constraints encoded in a knowledge representation to blockchain requirements. To accomplish this, the authors have designed domain-specific ontologies and semantic rules to represent the underlying system and constraints, respectively. Once the concepts or entities of a domain are identified, they are defined as OWL classes. The relationships between classes are defined as object properties and those between class instances and literals are defined as data properties. Then, the corresponding semantic rules that specify the constraints are defined using the Semantic Web Rule Language (SWRL) (“SWRL: A Semantic Web Rule Language Combining OWL and RuleML,” 2004). Protégé, the popular ontology editor and knowledge-based framework, is used to build the ontologies.

Mengyi Li, Lirong Xiay, Oshani Seneviratne, Leveraging Standards Based Ontological Concepts in Distributed Ledgers: A Healthcare Smart Contract Example (Li et al., 2019)
In this paper, the authors present a preliminary work on capturing the semantics of the Healthcare Interoperability Resources (FHIR) standard in smart contracts. Their approach is applied by implementing an example from the healthcare domain that motivates the use of standards-based ontological concepts in DApps which enables interoperability in the healthcare system and allows each end of the transaction to understand the data more efficiently. In order to demonstrate their proposal, the authors present a smart contract that uses terminologies from a well-adopted standard, the relevance of these terminologies for features used in machine learning models, and a method for detecting data misuses both retroactively and proactively.

Leepakshi Bindra, Changyuan Lin, Eleni Stroulia, Omid Ardakanian, Decentralized Access Control for Smart Buildings Using Metadata and Smart Contracts (Bindra et al., 2019)

In this paper the authors propose a methodology based on blockchain smart contracts to describe, grant, and revoke fine-grained people’s permissions for commercial buildings in a decentralized fashion. Their approach supports access control using Resource Description Framework (RDF) graphs ("RDF - Semantic Web Standards," 2020) and implements two APIs for client applications. The proposal uses Brick, a schema for a semantic representation of the building sensors and systems, such as electrical, plumbing, Heating, Ventilation, and Air Conditioning (HVAC), and lighting, and their relationships in the context of the building space, but not related directly to smart contracts.

Wout J. Hofman, A Methodological Approach for Development and Deployment of Data Sharing in Complex Organizational Supply and Logistics Networks with Blockchain Technology (Hofman, 2019)

This paper proposes a methodology for the development and deployment of data sharing for supply and logistics with DLT, which is a data layer on top of the Internet. Business transactions are represented as concepts with properties and associations through the use of ontologies.

Alex Roehrs, Cristiano André da Costa, Rodrigo da Rosa Righi, Valter Ferreira da Silva, José Roberto Goldim, Douglas C. Schmidt, Analyzing the performance of a blockchain-based personal health record implementation (Roehrs et al., 2019)

This paper presents the prototype implementation and evaluation of the Personal Health Record (PHR) model that integrates distributed health records using blockchain technology, and the Electronic Health Record ontology, openEHR, as an interoperability standard. Their proposal enables the creation of a unified and interoperable view of health data. To achieve this, they implemented their own blockchain, which is based on
open APIs. The authors remark that their performance results indicated that data distributed via a blockchain could be recovered with low average response time and high availability in the scenarios they tested.


In this paper, the authors report ongoing work in modeling the conditions and requirements of parties involved in decentralized energy systems. They depart from previous work on models for economic transactions and discuss how these can be aligned with ontologies specific to energy systems, and with the emerging use cases of decentralized energy systems, and discuss a high-level model for local decisions of agents in that context. The author remarks that the use of ontologies, combined with rules or other procedural computation mechanisms as optimizers, allow for declarative specifications that can be matched in a distributed way oriented to decentralized energy systems. These when combined with blockchains and smart contracts for the automation of the commitments provide the required flexibility in expressing needs and constraints of any kind.

Manoharan Ramachandran, Niaz Chowdhury, Allan Third, John Domingue, Kevin Quick, Michelle Bachler, Towards Complete Decentralised Verification of Data with Confidentiality: Different ways to connect Solid Pods and Blockchain (Ramachandran et al., 2020)

In this paper the authors propose the methods of combining Solid Pods (“Solid,” 2020) and distributed ledger to facilitate the complete decentralization of data with total user-control, keeping the integrity of the stored information intact through Blockchain-based verification. Their approach is focused on the Web and mobile applications’ data storage that developers can benefit from while building Decentralized Applications (DApps) in a complete decentralized environment. In order to collect various data about users around wearable fitness devices their proposal uses a Fitness Ontology so that both machines and humans can read.

Hongman Wang, Yongbin Yuan, Fangchun Yang, A Personal Data Determination Method Based On Blockchain Technology and Smart Contract (Wang et al., 2020)

This paper proposes a personal data determination method based on blockchain and smart contracts, which are used to solve the problem that the current data transaction market relies heavily on system-center entities. Their approach uses certificates to generate identity certificates that establish ownership overcoming the disadvantages of blockchain anonymization, and it uses a hash algorithm to hash data. The authors formalize personal data in terms of an ontology, such as, on-line shopping data, travel information or knowledgeable document produced by the owner in a period of time.
This paper introduces a Distributed Ledger Technology (DLT)-based shared ledger solution in a formal way and compliant with Financial Reporting Standards. For this purpose, the authors have extended the REA Ontology (William E. McCarthy, 1982) for the essential layer to the core COFRIS accounting Ontology (Blums and Weigand, 2016) that is based on current Accounting and Financial Reporting Standards (IFRS) (“IFRS - Conceptual Framework for Financial Reporting,” 2018). The paper describes how their conceptual model can be implemented at the platform-independent (infological) level, by using smart contracts and the ECR20 token standard. The authors remark that smart contracts do not only have the advantage of automated execution (that is, delegated fulfillment of commitments), but also provide an aggregation level close to that of the economic exchange contract.

In this paper, the authors implement the Smart Contract-based agent marketplace on top of the Ethereum blockchain to address the problem of supplying a credible agent performance record in the J-Park Simulator (JPS) (Eibeck et al., 2019). The JPS is an example of a Knowledge Graph (KG) and serves as a research platform to explore how internet technologies can be used to achieve interoperability between different domains. According to the authors, a collection of the semantic concepts providing vocabularies to build KGs is called an ontology. Within the KGs, information such as the input/output (I/O) signatures and prices of agents are described on top of agent ontologies such as OntoAgent (Zhou et al., 2019).

### 4.3 Blockchain modeling

This paper presents a semantic index based on the BLONDiE Ontology (Ugarte, 2017) (Ugarte, 2019), a standard ontology to represent blockchain concepts, aimed at exposing distributed ledger data as Linked Data in order to support efficient access to data and smart contracts stored on Ethereum blockchains. This approach implementation answers questions such as “Who was the miner for each block?” and “How many transactions were included in each block?” Also, these data and smart contracts can be easily linked to other sources of information using Semantic Web approaches. For example, the authors remark they have been able to make
blockchain smart contract functions discoverable using Semantic Web Services tools such as iServe (Pedrinaci et al., 2010).

_Elena García-Barriocanal, Salvador Sánchez-Alonso, Miguel-Angel Sicilia, Deploying Metadata on Blockchain Technologies_ (García-Barriocanal et al., 2017)

In this paper, the authors propose an approach in which a blockchain combined with other related technologies can be arranged in a particular way to obtain a decentralized solution for metadata supporting key functions related to digital archival systems: decentralized identification, deferencing, proof of statement, and, separately, indexing. The authors remark that the interpretation of the metadata also requires that the schemas and ontologies or terminologies used by them are also deployed in immutable decentralized systems.

_Joost de Kruijff, Hans Weigand, Understanding the Blockchain Using Enterprise Ontology_ (de Kruijff and Weigand, 2017a)

This paper presents a theoretical contribution and guidance on what blockchain actually is by taking an ontological approach. They propose an initial blockchain ontology, _Enterprise Ontology_, which is implemented in order to make a clear distinction between the datalogical, infological and essential level of blockchain transactions and smart contracts. The authors remark that their approach could be used to support application development, as it suggests to specify the blockchain application on the business level first. Also, they highlight that in their view, it should be possible to generate the blockchain implementation automatically, with some design parameters to be set. For the specification of the business level, in terms of contract languages and graphical formats, it could be possible to draw on already proven modeling approaches. However, their proposed ontology has not been validated yet.

_Joost de Kruijff, Hans Weigand, Ontologies for Commitment-Based Smart Contracts_ (de Kruijff and Weigand, 2017b)

Related to other papers of the authors (de Kruijff and Weigand, 2017a) (Weigand et al., 2020), in this case, the authors present a conceptual approach focused on commitment-based smart contracts, in which a contract is viewed as a business exchange consisting of a set of reciprocal commitments. Therefore, in line with their proposed _Enterprise Ontology_ and the REA Ontology, the authors model smart contracts, via ontologies, as a bundle of interrelated commitments among those parties who have signed it. To do so, they design smart contract ontologies abstracted at the essential, infological and datalogical layer conforming to the principles of enterprise ontology. According to the authors, this proposal should help professionals involved in drafting and managing
contracts to functionally design a platform-independent commitment-based smart contract that eventually can be implemented on any blockchain platform.

Zhengxin Chen, Understanding Granular Aspects of Ontology for Blockchain Databases (Chen, 2019)

In this paper, the author studies granular aspects of ontology for blockchain databases providing various kinds of granules at different levels in blockchain databases. According to the author, an ontological philosophy of blockchain would provide a concise definition of what the technology is, including its purpose, function, and dimensions. As a consequence, an examination on ontological philosophy of blockchain technology should benefit future research and practice of blockchain technology, and the examination from granular aspects should contribute to the exploration of the ontology of blockchains. However, the paper is not intended to be an introduction of blockchain technology or blockchain databases, nor a complete survey of blockchain technology.

Hamza Baqa, Nguyen B. Truong, Noel Crespi, Gyu Myoung Lee, Franck Le Gall, Semantic Smart Contracts for Blockchain-based Services in the Internet of Things (Baqa et al., 2019)

The paper proposes to use ontologies to develop semantic smart contracts which are deployed on the Ethereum network. To do so, the authors extend the OWL-S service ontology (Martin et al., 2005) by incorporating some domain-specific terminologies (i.e., semantic annotation), which are used in the development of the proposed semantic smart contracts. Their proposal extends the existing EthOn (“EthOn - An Ethereum Ontology,” 2020) (“EthOn: Ethereum Ontology,” 2020) (Loubet, 2017) with a service ontology to support Ethereum smart contracts by considering the smart contracts under the context of semantic web services. The authors use the open-source ontology editor Protégé to build the smart contract semantics ontology. As a result, semantic queries over smart contracts such as “finding a smart contract with the minimal gas payment” can be executed using their approach. However, the validation of their framework is still under investigation.

Wim Laurier, Blockchain Value Networks (Laurier, 2019)

The paper proposes a Model-Driven Architecture (MDA) approach (“Model Driven Architecture (MDA),” 2014) in which the REA Ontology (Laurier et al., 2018) could serve as a computation independent model (CIM) (Osis et al., 2007) aimed at contributing to formal verification of smart contracts and blockchains. The author believes that ontologically well-founded definitions of the concepts in smart contracts and blockchains could improve interoperability and understanding.

Seung-Min Lee, Soojin Park, Young B. Park, Formal Specification Technique in Smart Contract Verification (Lee et al., 2019)
In this paper, the authors analyze the constituent elements of smart contract and they expressed them for validation in terms of an ontology (i.e., the construction of a smart contract is represented by an ontology) where the process of negotiating the components is represented by each transaction. Also, they construct the component represented by the ontology as Extensible Markup Language (XML) (“Extensible Markup Language (XML),” 2020) by including the state information in the transaction. In this way, smart contracts are represented in a formal language that contains state information enabling the foundation for smart contracts that can be reused and verified.

Jan Ladleif, Mathias Weske, A Unifying Model of Legal Smart Contracts (Ladleif and Weske, 2019)
In this paper, the authors present a model-driven theoretical approach that encapsulates essential components of legal smart contracts. Their unifying model, which is specified in the form of a UML class diagram, may be used as a reference for language designers aiming at a holistic representation of legal smart contracts. In order to provide a common conceptual understanding of legal smart contracts, the author mention some approaches that include ontologies in their implementation. However the paper is not focused in the formalization of smart contracts in terms of ontologies.

5 Conclusions
Our research responds to an increasing interest and adoption of DAOs as a new approach for the implementation of blockchain-based decentralized software systems, where the establishment of a consensus and a common understanding is of major importance. In this paper, we have answered the research question presented in the section 2 by getting an insight into the recent research on the integration and use of ontologies into DAO development process in order to identify new research challenges to carry out. This systematic review provides up-to-date information on how ontologies can be used in the implementation of DAOs from a blockchain-based decentralized perspective.

The evaluation and analysis of the primary studies reveal that ontologies can be applied across several interrelated blockchain-based decentralized software systems knowledge areas that could be extrapolated to DAOs in a seamless manner.

Most of the studies are focused on the use of ontologies for governance modeling (i.e., business decision-making models). In this context, smart contracts are seen from a legal perspective, and ontologies may help to describe knowledge related to rights management and legal aspects. Also, other studies are focused on the
lifecycle of collaborative business processes and in the traceability and control in this type of collaborative governance.

Another line of research involves the use of ontologies for domain modeling. In this case, ontologies may help to describe knowledge related to complex and specific domains that could be reused to build similar or more complex ones. That is, authors use ontologies to define specific domains aimed at solving different problems and gaps related interoperability and data sharing in several business scenarios through a blockchain-based decentralized way. The proposals for domain modeling include personal and health data, supply and logistics information, and energy systems, among others.

Finally, other studies reveal that ontologies may be used for blockchain modeling in order to provide interoperability and a common knowledge and understanding aimed at defining in a formal, automated and flexible way, the requirements of the blockchain-based decentralized systems which could be used and extended to automate certain tasks associated to DAO development process. Ontologies define the conceptual elements necessary to integrate the blockchain technology and smart contracts in the implementation of DAOs.

All these results indicate that there is a growing interest in applying ontologies in different aspects of blockchain-based decentralized software systems. We have observed that ontologies can play an important role in the DAO development process and can help to improve the development of tools and frameworks that provide support to adopt this approach.

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