Decentralized Autonomous Organizations: Concept, Model, and Applications

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***Abstract*— Decentralized autonomy is a long-standing research topic in information sciences and social sciences. The self-organization phenomenon in natural ecosystems, the Cyber Movement Organizations (CMOs) on the Internet, and the Distributed Artificial Intelligence (DAI), and so on, can all be regarded as its early manifestations. In recent years, the rapid development of blockchain technology has spawned the emergence of the so-called Decentralized Autonomous Organization [DAO, sometimes labeled as Decentralized Autonomous Corporation (DAC)], which is a new organization form that the management and operational rules are typically encoded on blockchain in the form of smart contracts, and can autonomously operate without centralized control or third-party intervention. DAO is expected to overturn the traditional hierarchical management model and significantly reduce organizations' costs on communication, management, and collaboration. However, DAO still faces many challenges, such as security and privacy issue, unclear legal status, and so on. In this article, we strive to present a systematic introduction of DAO, including its concept and characteristics, research framework, typical implementations, challenges, and future trends. Especially, a novel reference model for DAO which employs a five-layer architecture is proposed. This article is aimed at providing helpful guidance and reference for future research efforts.**

***Index Terms*— Blockchain, consensus mechanism, decentralized autonomous organizations (DAO), smart contracts.**

I. Introduction

With the popularization and development of blockchain technology [1], [2], the Decentralized Autonomous Organization (DAO) is emerging and attracting intensive attention in recent years. In an ideal DAO, there is no central authority or management hierarchy. All management and operational rules of the organization depend on collaboration and group decision-making and are encoded on tamper-resistant blockchains. Some implementations of DAO, such as the DAO and Steemit,[1] have made people gradually recognize the potential of this new organization form. In fact, decentralized autonomy is not a new concept. The self-organization phenomenon in natural ecosystems, the Cyber Movement Organizations (CMOs) on the Web, and the Distributed Artificial Intelligence (DAI) can all be considered as the embryonic form of DAO and lay the foundation for its emergence.

In natural ecosystems, many animal populations are self-organized [3]. Taking the ant colony as an example, although the behavior of a single ant is simple and limited, the ant colony can complete complex behaviors, such as foraging, feeding, nesting, and defense. The core is that individuals in ant colony can coordinate according to the division of labor and adjust actions based on environmental changes [4], [5]. In addition to ants, fishes, bees, and flocks also exhibit similar self-organization behaviors [6]. These animal populations are all characterized by the absence of centralized control and hierarchical structures, and the behavior of group will not be affected by abnormalities in individuals. This phenomenon is also widely known as *Swarm Intelligence* [7], [8].

At the Internet level, the popularization of the Internet, especially the mobile Internet, provides a carrier for rapid and large-scale aggregation of online netizens behavior, which has led to the emergence of CMOs [9]. The CMOs refer to social movement organizations or groups induced or strengthened through cyberspace, that is, netizens who quickly gather together in a short period of time to participate in, discuss, and jointly implement certain social behaviors for a specific topic or event. Human Flesh Search (HFS) [10], Internet Water Army [11], and Crowdsourcing [12], [13] are typical online CMOs. They are organized via various social media platforms such as bulletin board system (BBS), forums, blogs, Weibo, etc. to publish thematic information and then quickly infect and widely spread the behavior or movement of netizens. CMOs are usually characterized by dynamic, real-time, self-organized, and virtual–real interactions.

From the perspective of artificial intelligence (AI), DAI [14] represents the future development trend. DAI mainly studies how intelligent systems that are logically or physically dispersed solve complex problems in parallel and in collaboration. DAI systems often contain many distributed autonomous nodes (i.e., agents), which not only have capabilities of tasks selection, prioritization, and goal-directed behaviors [also called belief-desire-intention (BDI) [15]], but

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[1] Steemit. https://steemulant.com/

also have sociability through communication, cooperation, and negotiation. In a DAI system, there is neither centralized control nor global data storage, therefore, it is more open and flexible than centralized systems. Due to high redundancy, it has strong fault tolerance ability.

In addition, many researches have been conducted on decentralized governance. For example, the 2009 Nobel economics laureate Elinor Ostrom proposed the Polycentric Governance and Self-Governance theory [16], [17]. She believes that the multicenter self-governing structure formed by the spontaneous order of the community organization has the characteristics of decentralized and overlapping jurisdiction, which can restrain the opportunism and free-riding behavior to the greatest extent and realize the sustainable development of public interest. Empirical studies have shown that common resource sharers can conduct self-governance through crowdfunding and independent contracts, thus avoiding the dilemma of public affairs management such as the *Tragedy of the Commons*. Sociologist Walter W. Powell also pointed out that self-organizing is the third governance mechanism independent of hierarchy and market, as it is based on trust and negotiation [18]. Through self-governance and effective incentives [19], information acquisition costs, management costs, coordination costs, and supervision costs within the organization would be greatly reduced and ultimately achieve long-term survival and effective governance of the community.

However, the real implementation of DAO benefits from the emergence of blockchain technology [20]. Blockchain integrates distributed data storage, timestamp, consensus algorithm [21], asymmetric encryption, has the characteristics of decentralization, immutability, and auditability, and thus can realize information transmission and value transfer safely and effectively [22]. In 2015, Ethereum[2] has become the first public blockchain platform that supports smart contracts [23] with the help of Turing-complete virtual machine called Ethereum Virtual Machine (EVM). With smart contracts, users can design various decentralized applications (DApps) on blockchain. Inspired by this, people envisage that the organizations' management and operational rules could be also encoded on blockchain in the form of smart contracts, so that the organization will operate autonomously according to predefined business logic without third-party intervention. In 2016, the world's first DAO—The DAO was launched and raised Ether (ETH) worthy of 150 million dollars in a short period of time, making it the world's largest crowdfunding project at that time. Since then, a series of DAOs have been proposed, e.g., DigixDAO,[3] Aragon,[4] Steemit, etc.

Currently, DAO still faces many challenges. The first is the security issue. The most notorious case is *The DAO Attack* in June 2016, which had resulted in the theft of more than 50 million dollars ETH. The second is the legal issue, and this is because DAO has conflicts with the current *Corporation Law* and *Securities Law*. Other challenges include performance, privacy [24], and flexibility issues.

[2]Ethereum. https://ethereum.org/

[3]DigixDAO. https://digix.global/dgd/

[4]Aragon. https://aragon.org/

In view of the trend of technology and industry innovation-driven development in the field of DAO and the lack of a unified technical and analysis framework, in this article, we devote to conducting a comprehensive overview of DAO. The rest of this article is organized as follows. In Section II, we define the concept and characteristics of DAO. Section III proposes a five-layer reference model for DAO and discusses the components and elements in each layer. In Section IV, several representative DAO implementations are introduced. Section V discusses the challenges and future trends. Section VI concludes this article.

II. Concept and Characteristics of DAO

Currently, the DAO has not been uniformly defined. In our opinion, DAO is a blockchain-powered organization that can run on its own without any central authority or management hierarchy. In a DAO, all the management and operational rules are recorded on blockchain in the form of smart contracts, and the distributed consensus protocols and Token Economy Incentive are utilized [25] to realize organizations' self-operation, self-governance, and self-evolution. We summarize its characteristics also as *DAO*.

A. Distributed and Decentralized

A traditional organization follows a top–down hierarchy with centralized authority. However, there is no central authority and hierarchical architecture in DAO [26], the DAO's mission is achieved through bottom–up interaction, coordination, and cooperation among distributed network nodes. Therefore, the relationships between nodes and nodes or nodes and organizations are no longer determined by administrative affiliation, but follow the principles of equality, voluntariness, reciprocity and mutual benefit, and driven by individual's resource endowment and complementary advantage, as shown in Fig. 1.

B. Autonomous and Automated

In an ideal DAO, *code is law*, organization is no longer pyramidal but distributed, power is no longer centralized but decentralized, and management is no longer based on a bureaucratic system but on community autonomy. In addition, as DAO usually runs under the regulation rules and collaboration patterns defined by all stakeholders, consensus and trust within a DAO are easier to achieve, and thus the trust costs, communication costs, and transaction costs would be minimized.

C. Organized and Ordered

Relying on smart contracts, DAO's operational rules, participants' responsibility and authority, and the rewards and penalties terms are open and transparent. Through a series of efficient governance rules, rights and interests of relevant participants are accurately differentiated and dimensioned, that is, individuals who pay, contribute, and assume responsibility would be matched with corresponding powers and benefits to promote the division of labor and the unification of power, responsibilities and interests, so as to make the operation of the organization more coordinated and orderly.

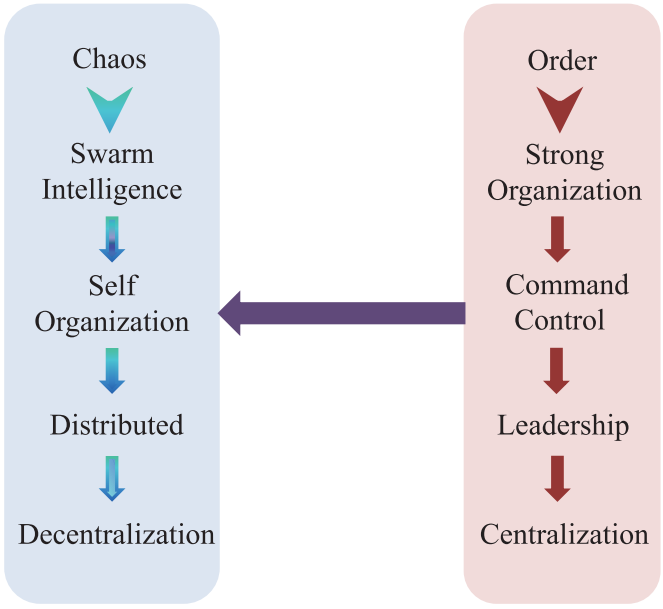

Fig. 1. From centralization to decentralization.

III. Reference Model for DAO

In this article, we propose a reference model for DAO. As shown in Fig. 2, the proposed model employs a five-layer architecture [27], namely, basic technology layer, governance operation layer, incentive mechanism layer, organization form layer, and manifestation layer from the bottom up. The details are as follows.

A. Basic Technology Layer

This layer encapsulates all the infrastructures that support DAO and its derivative applications, including Internet Protocol, Blockchain, Big Data, and Artificial Intelligence, and so on.

1) *Internet Protocol:* DAO is generally built on the peer-to-peer (P2P) network to encourage the participation of nodes distributed all over the world.
2) *Blockchain Technology:* The most notable feature of DAO is decentralization and open autonomy [2]. Blockchain technology is the key for DAO to realize its functions. The consensus mechanism of blockchain enables nodes in a decentralized system with highly dispersing decision-making power to effectively reach a consensus [1]. Smart contracts write operational rules of DAO into blockchain in the form of computer code, thus to realize the *code is law*-type of management [23]. Besides, asymmetric encryption and timestamp ensure the security requirements and ownership authentication of DAO.
3) *Artificial Intelligence:* With the rapid development of AI technology represented by deep learning [28], reinforcement learning, and generative adversarial network (GAN) [29], each individual node in a DAO will become an autonomous agent (also known as software agent/robot) [30]. Those agents are autonomous since they have capabilities of BDI. In the future, they are expected to replace human beings in perception, reasoning, decision-making, and other functions. Besides, smart contracts are no longer limited to automatic enforcement according to predefined *If-Then*-type statements, but also have *What-If*-type deduction, computation, and intelligent decision-making in unknown scenarios [23]. These will give DAO more intelligence.
4) *Big Data:* Big data technology [31] can collect the state data, intrachain transactions data, and system operation data of DAO nodes in real time and can help comprehend the evolution and development trend of DAO. It is worth noting that the blockchain itself is also a guarantee of data security and desensitization.
5) *Internet of Things:* The blockchain can be combined with Internet of Things (IoT) to form Blockchain of Things (BoT), which digitally transform and integrate smart devices and physical assets into DAO [32], [33]. As a dependable IoT service platform, DAO can monitor the full life cycle of smart devices in a secure and trusted manner, implement automated trading among equipment, and use smart contracts to achieve interoperability between smart devices.

B. Governance Operation Layer

This layer encodes consensus by smart contracts and can realize organization's self-governance and continuous iterative upgrades through on-chain and off-chain collaboration. Concretely, this layer includes consensus mechanism, smart contracts, digitalization, intelligent matching, and on/off-chain collaboration.

1) *Consensus Contractualization:* Organizations usually operate on the basis of consensus-based contracts. The purpose of establishing a contract is to guarantee the rights and interests of individuals, organizations and even the benign operation of society through the force of legal restraints. However, there are many problems in the actual implementations of contracts, such as the difficulty in judging the validity of contracts, the difficulty in realizing the rescission of the alteration, and the difficulty in investigating the liability for breach of contracts, etc. DAO is built on smart contracts that are deployed on and secured by the blockchain. Smart contracts generally encompass agreements made between contractors in the form of business logic and are automatically executable and enforceable [34]. Essentially, smart contracts program the complex relationships of network nodes, using protocols and interfaces to complete all procedures from negotiation to fulfillment. DAO enables nodes representing different interests (e.g., ordinary participants, technology developers, investors, etc.) to negotiate and clarify respective rights and obligations, determine and validate the contract terms, then program the contracts on blockchain for distribution, verification, and autoexecution.
2) *Digitalization as the Starting Point:* Smart contracts provide the trust guarantee for DAO governance, while the starting point of DAO governance is digitalization. The essence of digitalization is the collection and analysis

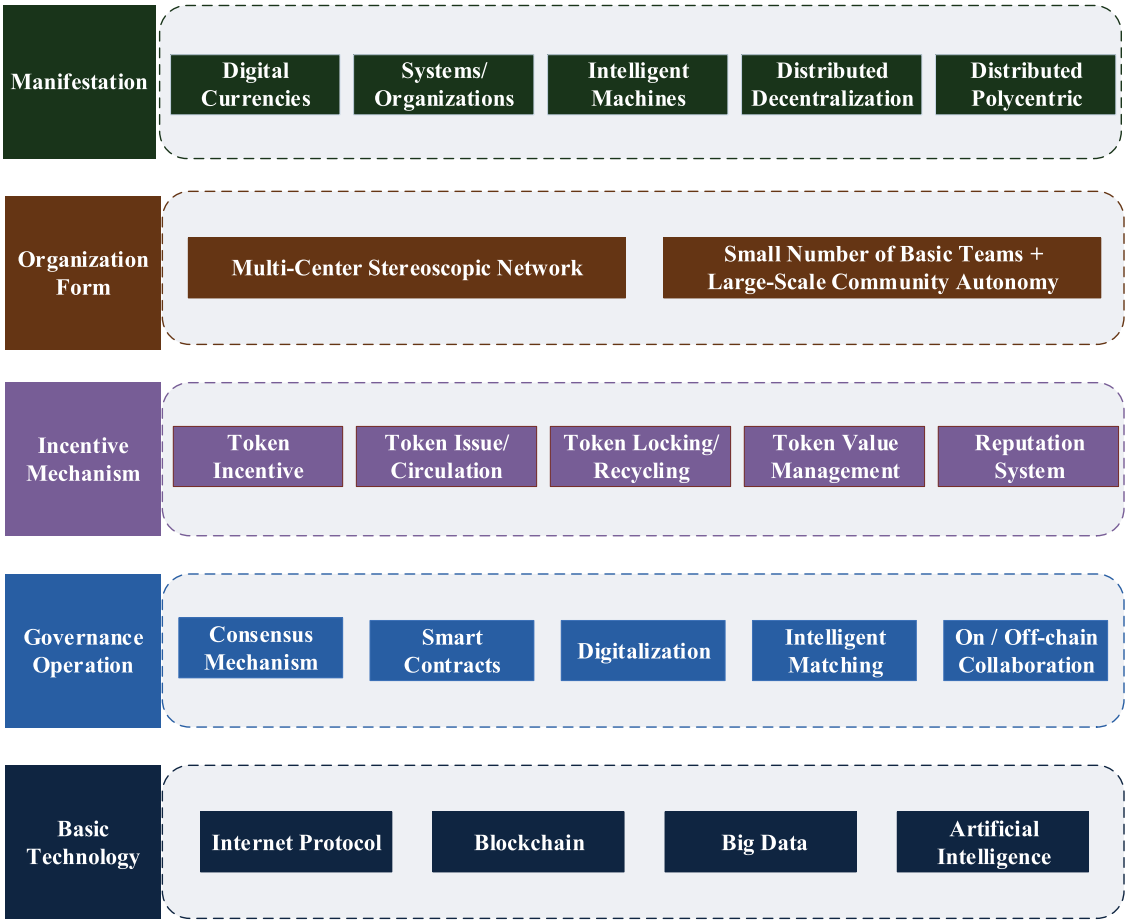

Fig. 2. Reference model for DAO.

of data, and then the data are applied for business model innovation, business ecosystem reconstruction, improvement of user experience, etc. Digitalization is not an end in itself, but a deep modeling and analysis of the organization, providing a basis for DAO to break its boundaries, and providing a tool for intelligent management [35] and decision-making.

3) *Intelligent Matching:* A DAO running on a decentralized processing-storage carrier often uses AI technology to automatically combine, match, and connects people/organizations/knowledge/events/products/services, etc., which is an important way for DAO to reduce communication costs and improve efficiency. For example, DAO can accomplish automatic matching of roles/tasks, through digitizing information and behavior data of individuals/organizations (such as users' click, search, and browse data), and match individuals' positions and roles in a DAO according to their contributions and abilities, then automatically complete task identification, recommendation [36], and matching. In this way, the human and knowledge capital can be mobilized quickly. In addition, DAO can perform multi-dimensional evaluation on the process and results of individual work. The evaluation results represent the individuals' level in the DAO honor system, and different levels will enjoy different rights and interests.

4) *On-Chain and Off-Chain Collaboration:* Different from traditional centralized management mode that the controlling shareholders' interests are paramount, DAO adopts an on-chain and off-chain collaborative governance mode. On-chain governance is mainly to determine, update, and maintain the consensus through smart contracts. The focus is to create a credible system in an environment of mutual distrust and ensure the benefits of all stakeholders. The consensus mechanism studies how nodes in a distributed system achieve data consistency and agree on a proposal in a complex, open, and untrusted Internet environment. Common consensus algorithms include Proof-of-Work (PoW), Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), and hybrid consensus, etc. [37]. Off-chain governance is a series of governance measures adopted to ensure the establishment, recognition, diffusion, and renewal of the consensus. Due to the limitations of current technology, DAO is more expressed as a small part of on-chain governance + most of the off-chain governance. However, as the technology matures, it will focus more on on-chain governance. In addition, forks that include soft fork and hard fork are also effective means to solve conflicts of DAO governance. Compared with the way in which public companies deal with disputes, the market

impact caused by forks is relatively low, which also reflects the advantages of DAO governance based on a consensus mechanism.

C. Incentive Mechanism Layer

Token incentive is the main motivator for DAO. Token is a kind of negotiable digital assets and the proof of rights and interests [38], [39]. Stocks, bonds, and options in the real world can be digitized in the form of token. Generally, it is believed that token at least integrates the attributes of equity (value-added, long-term income), property (representing the right to use, goods, or services) and currency (circulating within a certain range).

The sponsors, developers and other stakeholders of DAO share the property rights of the system, while the main economic incentives for other participants are tokens. The new economic model created by token is called *Token Economy* [25], which specifically refers to the use of the financial attributes of cryptodigital assets to map the commodities and services to token and then achieve low-cost or even zero-cost transactions. At present, the common types of token include payment token, functional token, and asset token.

Each DAO can issue its own token and set the circulation, lock-in period, distribution mode, and other elements of the token model [40], according to the project attributes. The key of token model design is the mechanism design. The goal is to promote the incentive compatibility of participants and achieve win–win situation. On the one hand, a good token model integrates the monetary capital, human capital, and other capitals together, changes the relationship between people and organization, reduces the operation costs, and meanwhile satisfies the fund demand in the early stage of the project. On the other hand, because token anchors the project itself, high-quality projects will make the market value of Token constantly increase, which can adversely better serve as economic incentives for participants.

D. Organization Form Layer

The organization form of DAO is multicenter stereoscopic network structure and small number of basic teams + large-scale community autonomy. Compared with traditional organizational form, DAO varies from the orderly to mixed, from the pursuit of stability and solidification to pursuit of dynamic balance, from relatively simple to diversified. Its characteristics can be summarized as follows.

1) *Flat:* The rank order in the organization is broken. The flexibility of individuals can be given full play, meanwhile the transparent and efficient management can be achieved.
2) *Open:* The internal and external boundaries of organizations have also been torn down. DAO can adjust at any time based on specific projects, requirements and tasks, and then disbands or perishes when its mission is completed.
3) *Parallel:* In a future DAO, every individual or organization in reality will have a virtual counterpart corresponding to it. Through their virtual–real interaction, closed-loop feedback and on-chain and off-chain collaboration, the decision-making optimization and parallel tuning of organizational governance could be realized [41].
4) *Human–Machine Integration:* With the advancement of technology, the DAO will further evolve into human–machine integration. The intelligent agents in a DAO will be authorized by humans to carry out various business activities. These agents will also perform competition, coordination, and cooperation just like human beings.

E. Manifestation Layer

DAO has a wide range of manifestations. Depending on the services provided, it can be either digital currencies such as Bitcoin or public development platforms/systems such as Ethereum or even interconnected IoT devices such as self-driving cars. Besides, depending on the degree of decentralization, DAO can be either fully decentralized such as public blockchain or partial decentralization such as the consortium blockchain (e.g., Hyperledger[5] and EOS).[6] Currently, DAO usually draws on the model of Nonprofit Foundation + Commissioned Companies + Various Manifestations. Generally, nonprofit foundation conducts fundraising [or Initial Coin Offering (ICO)], distribution, management, and supervision as the main body of the issuance of token. The commissioned companies are entrusted with technology development, marketing, and legal services. Then, DAO is often presented in the form of an open-source community to promote the on-chain and off-chain collaboration.

IV. Application Cases

In this section, we take Aragon as an example to analyze its elements according to the reference model proposed in Section III. Then, some representative DAO implementations are also introduced.

A. Aragon

Aragon network is a platform that provides infrastructures for users to create and manage various kinds of DAOs, such as corporations, nonprofits, and open source projects. Aragon empowers users to create global, bureaucracy-free organizations freely and collaborate without borders or intermediaries. Each Aragon organization exists as a set of smart contracts that define the organization's stakeholders and their associated rights and privileges. The smart contracts system on which Aragon is built is called *aragonOS*. aragonOS ensures that only authorized accounts and contracts (together referred to as *entities*) have permissions to perform specific actions, the rights, and obligations for an entity are also written in smart contracts. Each Aragon DAO has several Apps, the basis ones include Token Manager, Voting, and Finance App. Besides that, anyone can develop their own App and add it to their DAO. These Apps extend the functionality of

[5]Hyperledger. https://www.hyperledger.org/
[6]EOS. https://eos.io/

the organization. According to the reference model for DAO we proposed, its elements are as follows.

1) *Basic Technology:* Aragon DAOs are powered by Ethereum, a global blockchain for running unstoppable applications. In Ethereum, code and applications always run without any possibility of downtime or censorship.
2) *Governance Operation:* First, Aragon has an Aragon Governance Proposal (AGP). An AGP details a change to the management, allocation, or use of shared resources owned or directly influenced by the Aragon Network. All AGPs must be consistent with the goals and values of the community. The purpose of the AGP is to provide a structured process for making changes to the shared resources of the Aragon network. For these shared resources, governance processes are needed to grant or deny access and approve or reject proposed changes by DAO participants. Second, Aragon DAOs control in which addresses have access to perform actions on behalf of the organization in a permission registry called *Access Control List*. Addresses on the registry can be externally owned accounts or contracts. By chaining multiple smart contracts together, it can define complex criteria which constrain how actions can be performed within the organization. For example, if a DAO wants to transfer some treasury funds, it must be 1) proposed by a member of the organization; 2) approved by a majority of members; and 3) within a predetermined budget. Third, when a dispute is raised, Aragon has a Court Protocol to provide dispute resolution service. Specifically, when a dispute occurs, a jury is formed (users stake some tokens in order to become jurors and earn a portion of dispute resolution fees). The jurors are required to commit to a ruling on the dispute within a commitment period and then reveal their ruling after all drafted jurors have committed. The verdict is returned according to the opinions of majority of jurors [42].
3) *Token Incentive:* Token on the Aragon network is called *Aragon Network Token (ANT)*. ANT represents users' stake in their DAO. Members in a DAO can initiate proposals about the organization's rules and regulations, then token holders vote according to the token shares they hold (for the sake of security, the voting requires the holder's private key signature) to decide whether to accept the proposals or not. Proposers should also deposit a certain number of ANTs as collateral before their proposal can be forwarded to a voting. ANT was initially created and distributed as a result of a public token sale that took place on May, 2017, when ANT worthy of 275 000 ETH were sold. Added together with ANT sold in the presale, ANT granted to the Aragon Foundation, and ANT granted to founders and early contributors, the total initial supply of ANT after the token sale was 39,609,523.80952380954 ANT, as shown in Fig. 3.
4) *Organization Form:* Aragon network provides infrastructure and services (e.g., aragonOS) for users to create and manage decentralized organizations. The Aragon network will decentralize its governance by gradually handing over control of the project to its users. The ultimate goal is to make the Aragon network an autonomous organization itself, which is managed by members using it for communities' mutual prosperity. Therefore, Aragon network is a typical small number of basic teams + large-scale community autonomy.
5) *Manifestation:* Aragon network is a system/organization which acts as a public DAO development platform.

	Amount (ANT)	% of initial supply
Public sale + Pre-sale grant	27,726,666.666666666678 ANT	70%
Aragon Foundation grant	5,941,428.571428571431 ANT	15%
Early contributors and founders grant	5,941,428.571428571431 ANT	15%

Fig. 3. Initial supply of ANT.

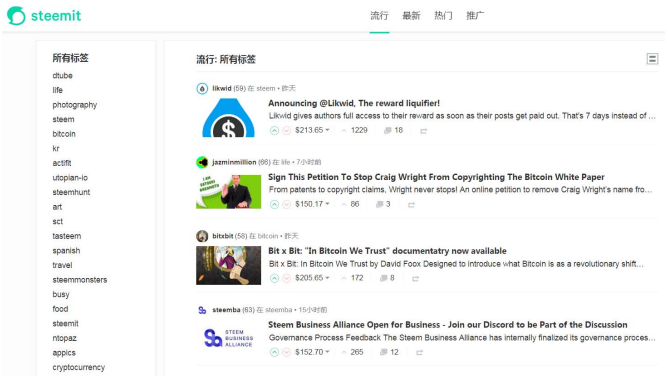

Fig. 4. Steemit.

B. Other Representative DAO Implementations

1) DAO: The DAO is the world's first DAO project which is created in 2016. The DAO is a decentralized investor-directed venture capital fund secured by Ethereum. The DAO is controlled entirely by program code (smart contracts), and has no conventional management structure or board of directors. The DAO is crowdfunded via ICO, and the funds it receives are locked in smart contracts. The ICO raises more than $150 million of ETH, which is the largest crowdfunding campaign at that time. Then, each participant gets corresponding DAO tokens according to how much they invest. The DAO token holders have the right to review investment projects and then vote. If an investment proposal is approved, the tokens are automatically transferred to that project, and the earnings will be returned to the token holder according to their shares. But soon after, the hacker exploited the recursive call vulnerability in the DAO smart contracts to siphon off one-third of the DAO's funds into a child DAO. Eventually, the Ethereum community decided to hardfork the Ethereum blockchain to restore virtually all funds to the original contract [43]. However, this hard fork is controversial because it violates the *code is law* principle in the spirit of DAO.

2) Steemit: As shown in Fig. 4, Steemit is a blockchain-based social media platform that everyone gets paid for creating and curating contents. Anyone who contributes their time

and attention to the contents (e.g., vote, give a thumb-up, comment) will receive pro-rata rewards. In order to produce a fairer and more inclusive environment for users involved, Steemit designed a sophisticated token incentive system. In Steemit, there are three kinds of tokens, namely, Steem (STEEM), Steem Power (SP), and Steem Dollars (SBD). STEEM is the fundamental token issued on the Steem blockchain; SP represents users' influence within the platform, users who own more SP will have more power on the distribution of rewards, and SP holders will be paid interests based on their SP balance; SBD is a stable cryptocurrency pegged to the U.S. dollar which designed as an attempt to bring stability to the cryptocurrency and to the individuals who use the Steemit network. Under this design, participants will have a financial incentive to contribute as it may maximize the long-term value of their tokens.

3) DigixDAO: DigixDAO comes from the DIGIX platform which aims at being the first digital gold trading platform. DIGIX ecosystem is powered by two native tokens: DGX and DGD. DGX serves as the asset-backed tokens on Ethereum (each token represents 1 g of gold from London Bullion Market Association-approved refiners). When physical gold is digitalized and confirmed by blockchain, it can be transacted and transferred with full visibility and auditability. Another token is DGD (also called *Governance Token*). Using Ethereum smart contracts, DGD holders can participate in the DigixDAO governance by pledging on proposals (pledging involves approving or rejecting proposals about platform development) in order to boost DGX adoption. Active participants will earn points redeemable for quarterly rewards and a portion of DGX transaction fees.

V. Challenges and Future Trends

DAO is now in its infancy stage and faces many challenges. In this section, we briefly outline the challenges and future development trends of DAO.

A. Challenges

1) Security Issue: Because of the tamper-resistant nature of blockchain, it is difficult to change a DAO, or the smart contracts underpinning it after it is deployed on the blockchain. Thus, attackers can take advantage of a loophole in the smart contract for a profit. As mentioned before, On June 2016, an anonymous hacker (or group of hackers) withdrew funds from the DAO into a childDAO, which resulted in 3.5 million ETH (which is about $50 million) stolen. Common security vulnerabilities also include recursive call, transaction-ordering dependence (TOD), timestamp dependence and mishandled exceptions, and so on. [44], [45]. These security issues have greatly restricted the development of DAO.

2) Unclear Legal Status: As DAO has the characteristics of decentralization, cross-border, and anonymity, once legal issues arise in actual operation, it will lead to difficulties in accountability and lack of ex-post remedy. At present, DAO has not been clearly defined at the legal level. Some people use a term *general partnership* for DAO and its investors. This puts every stakeholder or investor or someone who owns the tokens for particular DAO liable for any debts or legal actions that the DAO faces, while others think that DAO is more like investment contracts or securities. In the future, laws such as *Corporation Law*, *Contract Law*, *Securities Law*, and *Civil and Commercial Law* should make a definition of DAO in order to clearly define the scope of laws; therefore, DAO can assume corresponding responsibilities and fulfill relevant obligations.

3) Technical Limitations: Although DAO yearns for *code is law* or *Regulation by Code*, it is difficult to implement in practice. This is because there is a huge semantic gap between the legal rules (also known as *wet code*) and the rules written in smart contracts (also known as *dry code*). In order to achieve higher versatility, the former is usually drafted at a high level of abstraction using ambigious, inclusive, and flexible natural language. The latter, however, as a semantically explicit code, must accurately describe the rules using a strict and formal computer language [46]. It is inevitable that ambiguity and error would be introduced during the translation process. Also, many cases (e.g., some edge cases) are difficult or even impossible to be translated into code, which to some extent restricts the practicality and accessibility of DAO.

B. Future Trends

First, at the legal level, in view of the current lack of legal responsibility of DAO and the problems in law application and jurisdiction, it is necessary to strengthen the establishment of relevant legal and regulation systems, thus to confirm the rights, obligations, and responsibilities of DAO.

Second, in terms of security issue, the formal verification [47] and multi-party security audits of smart contracts, the establishment of smart contracts' terms conversion standards, and the regulatory sandboxes are effective ways to improve the DAO security and privacy protection.

Last but not the least, DAO can be regarded as a social system [48] composed of large-scale intelligent agents through social network connections, with uncertainty, diversity, and complexity (UCD) characteristics. In order to achieve effective management and control of DAO, the parallel blockchain approach [49] can be employed. Parallel blockchain is a combination of Artificial systems + Computational experiments + Parallel execution (ACP) approach [50] and blockchain technology. In parallel blockchain, the artificial systems (A) part is used to model one or more artificial blockchain systems corresponding to the real-world blockchain system in the code space of smart contracts. Based on the coevolving real-world and artificial blockchain systems, diversified computational experiments could be designed and conducted in the computational experiments (C) part to evaluate and verify specific behavior, mechanisms, and strategies involved in the blockchain systems; the optimal solution will emerge through these experiments and feedback to real-world blockchain systems in the parallel execution (P) part to realize the decision optimization and parallel tuning of the blockchain systems [49], [51].

VI. Conclusion

With the popularization and deepened applications of blockchain technology, the emerging DAO has become a hot topic. Because the management and operational rules of DAO are all encoded on blockchain in the form of smart contracts, it can autonomously operate without centralized control or third-party intervention. Therefore, DAO is seen as a subversion of the traditional hierarchical management

model. In this article, we present a comprehensive overview of DAO, including its concept and characteristics, composition and analysis framework, typical implementations, challenges, and future trends. Especially, we propose a reference model for DAO which employs a five-layer architecture. The focus of this article is to make a detailed introduction of DAO and provide helpful guidance and reference for its future research efforts and industrial applications.

REFERENCES

[1] Y. Yuan and F.-Y. Wang, "Blockchain and cryptocurrencies: Model, techniques, and applications," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 9, pp. 1421–1428, Sep. 2018.

[2] F.-Y. Wang, Y. Yuan, J. Zhang, R. Qin, and M. H. Smith,, "Blockchainized Internet of minds: A new opportunity for cyber–physical–social systems," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 4, pp. 897–906, Dec. 2018.

[3] R. Braakman, M. J. Follows, and S. W. Chisholm, "Metabolic evolution and the self-organization of ecosystems," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 15, pp. E3091–E3100, 2017.

[4] E. J. H. Robinson, O. Feinerman, and N. R. Franks, "Flexible task allocation and the organization of work in ants," *Proc. Roy. Soc. B, Biol. Sci.*, vol. 276, no. 1677, pp. 4373–4380, 2009.

[5] W. Wei, S. Liu, W. Li, and D. Du, "Fractal intelligent privacy protection in online social network using attribute-based encryption schemes," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 3, pp. 736–747, Sep. 2018.

[6] E. Bonabeau, M. Dorigo, and G. Theraulaz, "Inspiration for optimization from social insect behaviour," *Nature*, vol. 406, no. 6791, pp. 39–42, 2000.

[7] Y. Valle, G. K. Venayagamoorthy, S. Mohagheghi, J. C. Hernandez, and R. G. Harley, "Particle swarm optimization: Basic concepts, variants and applications in power systems," *IEEE Trans. Evol. Comput.*, vol. 12, no. 2, pp. 171–195, Apr. 2008.

[8] Y. Luo, G. Iyengar, and V. Venkatasubramanian, "Social influence makes self-interested crowds smarter: An optimal control perspective," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 1, pp. 200–209, Mar. 2018.

[9] P. Aragón, Y. Volkovich, D. Laniado, and A. Kaltenbrunner, "When a movement becomes a party: Computational assessment of new forms of political organization in social media," in *Proc. 10th Int. AAAI Conf. Web Social Media*, Mar. 2016, pp. 12–21.

[10] F.-Y. Wang *et al.*, "A study of the human flesh search engine: Crowd-powered expansion of online knowledge," *Computer*, vol. 43, no. 8, pp. 45–53, Aug. 2010.

[11] K. Zeng, X. Wang, Q. Zhang, X. Zhang, and F.-Y. Wang, "Behavior modeling of Internet water army in online forums," in *Proc. 19th World Congr. Int. Fed. Autom. Control*, Cape Town, South Africa, 2014, pp. 9858–9863.

[12] J. Howe, "The rise of crowdsourcing," *Wired Mag.*, vol. 14, no. 6, pp. 1–4, Jun. 2006.

[13] K. Zaamout and K. Barker, "Structure of crowdsourcing community networks," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 1, pp. 144–155, Mar. 2018.

[14] J. V. Rauff, *Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence*. Reading, MA, USA: Addison-Wesley, 1999.

[15] M. Georgeff, B. Pell, M. Pollack, M. Tambe, and M. Wooldridge, "The belief-desire-intention model of agency," in *Proc. Int. Workshop Agent Theories, Architectures, Lang.*, 1998, pp. 1–10.

[16] E. Ostrom, L. D. Schroeder, and S. G. Wynne, *Institutional Incentives and Sustainable Development: Infrastructure Policies in Perspective*. Boulder, CO, USA: Westview, 1993.

[17] E. Ostrom, "Beyond markets and states: Polycentric governance of complex economic systems," *Amer. Econ. Rev.*, vol. 100, no. 3, pp. 641–672, 2010.

[18] W. W. Powell, "Neither market nor hierarchy: Network forms of organization," *Res. Org. Behav.*, vol. 12, pp. 295–336, Jan. 1990.

[19] J. Li, Z. Cai, J. Wang, M. Han, and Y. Li, "Truthful incentive mechanisms for geographical position conflicting mobile crowdsensing systems," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 2, pp. 324–334, Jun. 2018.

[20] D. Larimer. *Overpaying for Security*. Accessed: Jun. 28, 2019. [Online]. Available: https://letstalkbitcoin.com/is-bitcoin-overpaying-for-false-security

[21] S. Basu, U. Maulik, and O. Chatterjee, "Stability of consensus node orderings under imperfect network data," *IEEE Trans. Comput. Social Syst.*, vol. 3, no. 3, pp. 120–131, Sep. 2016.

[22] M. Iansiti and K. R. Lakhani, "The truth about blockchain," *Harvard Bus. Rev.*, vol. 95, no. 1, pp. 118–127, 2017.

[23] S. Wang, L. Ouyang, Y. Yuan, X. Ni, X. Han, and F.-Y. Wang, "Blockchain-enabled smart contracts: Architecture, applications, and future trends," *IEEE Trans. Syst., Man, Cybern., Syst.*, to be published. doi: 10.1109/TSMC.2019.2895123.

[24] Y. Qu, S. Yu, L. Gao, W. Zhou, and S. Peng, "A hybrid privacy protection scheme in cyber-physical social networks," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 3, pp. 773–784, Sep. 2018.

[25] F.-Y. Wang, J. J. Zhang, R. Qin, and Y. Yuan, "Social energy: Emerging token economy for energy production and consumption," *IEEE Trans. Comput. Social Syst.*, vol. 6, no. 3, pp. 388–393, Jun. 2019.

[26] *What Is a DAO*. Accessed: Jul. 2, 2019. [Online]. Available: https://blockchainhub.net/dao-decentralized-autonomous-organization/

[27] X. Xu *et al.*, "A taxonomy of blockchain-based systems for architecture design," in *Proc. IEEE Int. Conf. Softw. Archit. (ICSA)*, Apr. 2017, pp. 243–252.

[28] S. Madisetty and M. S. Desarkar, "A neural network-based ensemble approach for spam detection in Twitter," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 4, pp. 973–984, Dec. 2018.

[29] Z. Pan, W. Yu, X. Yi, A. Khan, F. Yuan, and Y. Zheng, "Recent progress on generative adversarial networks (GANs): A survey," *IEEE Access*, vol. 7, pp. 36322–36333, 2019.

[30] P. J. Ye, S. Wang, and F.-Y. Wang, "A general cognitive architecture for agent-based modeling in artificial societies," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 1, pp. 176–185, Mar. 2018.

[31] X. Wang, W. Wang, L. T. Yang, S. Liao, D. Yin, and M. J. Deen, "A distributed HOSVD method with its incremental computation for big data in cyber-physical-social systems," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 2, pp. 481–492, Jun. 2018.

[32] A. Dorri, S. S. Kanhere, and R. Jurdak, "Towards an optimized blockchain for IoT," in *Proc. ACM 2nd Int. Conf. Internet-Things Design Implement.*, 2017, pp. 173–178.

[33] B. Zhou *et al.*, "A 3-D security modeling platform for social IoT environments," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 4, pp. 1174–1188, Dec. 2018.

[34] I. Bashir, *Mastering Blockchain*, 2nd ed. Birmingham, U.K.: Packt, 2018.

[35] J. Aguilar and G. Garcia, "An adaptive intelligent management system of advertising for social networks: A case study of Facebook," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 1, pp. 20–32, Mar. 2018.

[36] T. Stepan, J. M. Morawski, S. Dick, and J. Miller, "Incorporating spatial, temporal, and social context in recommendations for location-based social networks," *IEEE Trans. Comput. Social Syst.*, vol. 3, no. 4, pp. 164–175, Dec. 2016.

[37] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *Proc. IEEE Int. Congr. Big Data*, Jun. 2017, pp. 557–564.

[38] J. Li, Y. Yuan, S. Wang, and F.-Y. Wang, "Transaction queuing game in bitcoin blockchain," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Changshu, China, Jun. 2018, pp. 114–119.

[39] R. Qin, Y. Yuan, and F.-Y. Wang, "Research on the selection strategies of blockchain mining pools," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 3, pp. 748–757, Sep. 2018.

[40] K. Saito, S. Hatta, and T. Hanada, "Digital currency design for sustainable active debris removal in space," *IEEE Trans. Comput. Social Syst.*, vol. 6, no. 1, pp. 127–134, Feb. 2019.

[41] S. Wang, X. Wang, P. Ye, Y. Yuan, S. Liu, and F.-Y. Wang, "Parallel crime scene analysis based on ACP approach," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 1, pp. 244–255, Mar. 2018.

[42] *Aragon Whitepaper*. Accessed: Jun. 19, 2019. [Online]. Available: https://github.com/aragon/whitepaper

[43] D. Siegel. *Understanding the DAO Attack*. Accessed: Mar. 19, 2019. [Online]. Available: https://www.coindesk.com/understanding-dao-hackjournalists/

[44] A. Dika, "Ethereum smart contracts: Security vulnerabilities and security tools," M.S. thesis, Dept. Comput. Sci., Norwegian Univ. Sci. Technol., Trondheim, Norway, 2017.

[45] K. Delmolino, M. Arnett, A. Kosba, A. Miller, and E. Shi, "Step by step towards creating a safe smart contract: Lessons and insights from a cryptocurrency lab," in *Proc. Int. Conf. Financial Cryptogr. Data Secur.*, 2016, pp. 79–94.

[46] P. De Filippi and H. Samer, "Blockchain technology as a regulatory technology: From code is law to law is code," 2018, *arXiv:1801.02507*. [Online]. Available: https://arxiv.org/abs/1801.02507

[47] K. Bhargavan *et al.*, "Formal verification of smart contracts: Short paper," in *Proc. ACM Workshop Program. Lang. Anal. Secur. (PLAS)*, Vienna, Austria, Oct. 2016, pp. 91–96.

[48] J. J. Zhang *et al.*, "Cyber-physical-social systems: The state of the art and perspectives," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 3, pp. 829–840, Sep. 2018.
[49] F.-Y. Wang, Y. Yuan, C. Rong, and J. J. Zhang, "Parallel blockchain: An architecture for CPSS-based smart societies," *IEEE Trans. Comput. Social Syst.*, vol. 5, no. 2, pp. 303–310, Jun. 2018.
[50] X. Wang, L. Li, Y. Yuan, P. Ye, and F.-Y. Wang, "ACP-based social computing and parallel intelligence: Societies 5.0 and beyond," *CAAI Trans. Intell. Technol.*, vol. 1, no. 4, pp. 377–393, 2016.
[51] F.-Y. Wang, Y. Yuan, X. Wang, and R. Qin, "Societies 5.0: A new paradigm for computational social systems research," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 1, pp. 2–8, Mar. 2018.

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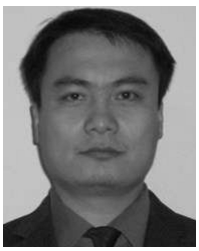

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