Web3-Based Decentralized Autonomous Organizations and Operations: Architectures, Models, and Mechanisms

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***Abstract*—Empowered by blockchain and Web3 technologies, decentralized autonomous organizations (DAOs) are able to redefine resources, production relations, and organizational structures in a revolutionary manner. This article aims to reanalyze DAOs from the perspectives of organization and operation, and provide a more precise definition of DAOs as decentralized autonomous organizations and operations. Based on this, the fundamental principles and requirements of DAOs are explained, while the infrastructure based on cyber–physical–social system (CPSS) and parallel intelligence, as well as the supporting technologies, such as digital twins, metaverse, and Web3, are discussed. Besides, a five-layer intelligent architecture is presented, and the closed-loop equation and new function-oriented intelligent algorithms are also proposed. Moreover, the governance mechanisms from the individual, organizational and social perspectives are discussed, and the incentive mechanisms for the human, robot, and digital human are analyzed. This article can be regarded as a stepping stone for further research and developments of DAOs.**

***Index Terms*—Blockchain, decentralized autonomous organization (DAO) and operation, intelligent algorithms, mechanism design, metaverse, smart contracts, Web3.**

I. Introduction

DECENTRALIZED autonomous organizations (DAOs) were formally defined by Vitalik Buterin in the Ethereum white paper in 2013. He believes that DAOs are a software-defined capitalized organizations with automation as its prominent feature, which realizes the interactive automation between human behaviors, and decentralization and autonomy are two crucial characteristics of DAOs. As the core element and innovative organizational paradigm of Web3, DAOs can run automatically through smart contracts without external intervention. The data of DAO members are controlled by themselves, which can sufficiently protect the privacy and security of user data and effectively avoid the abuse of user privacy data by centralized organizations [1]. By using the token economic system and value creation methods, DAOs can gather groups with consistent values and goals for Web3, and provide an essential means for Web3's autonomy, self-operation and self-evolution by virtue of the smart-contract-driven value automatic distribution method. DAOs help to maintain the fairness and justice of Web3 participants, protects their privacy and security, and facilitates them to maximize their value. Therefore, DAOs play a vital role in realizing Web3's key goals of building an open and prosperous novel value Internet.

However, the development of DAOs is still in their early stages, and there are great limitations in the cognition and research of DAOs. First, the existing works mainly focused on the underlying technologies, engineering implementation, and application technologies of DAOs. Due to the variety of types of DAOs, there are huge differences between different types of DAOs in terms of operation mechanisms and governance mechanisms [2]. At present, there is no unified framework applicable to the research and applications of all these types of DAOs. Second, there are few research on the model and algorithms of DAOs, which play an essential role in the realization of its distributed and decentralized, automatic, and autonomous characteristics. Third, the core of DAOs is the governance mechanisms and incentive mechanisms [3], [4]. Nevertheless, there are few relevant theoretical studies, most of which implement smart contracts at the code level. Since smart contracts have significant limitations and can only implement simple deterministic rules, they are prone to code loopholes and thus are not intelligent enough to meet the requirements of complex governance and incentive mechanisms.

Therefore, this article aims to propose a universal intelligent framework for DAOs and introduce new principles, subjects, models, and algorithms to innovate the elemental theories and application research of DAOs, so as to improve the scientific,

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normative, and sustainable development for the research and applications of DAOs.

The remainder is organized as follows. Section II discusses the principle and intelligent technologies. Section III proposes a new intelligent architecture. Section IV establishes a DAO model and analyzes the intelligent algorithms. Section V studies the core mechanisms. Section VI concludes this article.

II. Principle and Emerging Intelligent Technologies

DAOs are widely regarded as the decentralized autonomous organizations encoded on blockchain [5], [6], [7] and driven by smart contracts [8], [9]. This understanding treats the distributed automated operation as the default composition or natural result of DAOs and neglects their differences. However, DAOs cover the implications from the dimensions of both organization and operation by nature [10]. In view of this, we define DAOs from a more broad and precise angle as decentralized autonomous organizations and operations in this article.

A. Key Principles

According to the new definition, the key principles of DAOs can be summarized as distributed and decentralized (*D*), autonomous and automated (*A*), and organizational and operational (*O*).

1) D: "Distributed" means that DAOs do not rely on intermediaries and cannot be controlled by the third parties from the perspective of external coordination. By means of smart contracts, the incentive-driven coordination mechanism plays a crucial role in the trustless environment. Decentralized refers to that DAOs do not have a hierarchical structure and absolute power center from the perspective of internal autonomy. Based on decentralized heterogeneous ownership, the collaborative mechanism with disobedience is formulated.

2) A: "Autonomous" stems from the revolution of value distribution of DAOs. During the process of large-scale collaboration, DAOs gather members with common goals, who collaborate autonomously and gain value equal to their contributions. Consequently, community autonomy with the goals of co-ownership, co-governance, and co-construction can be realized. "Automated" is derived from using smart contracts in DAOs, which automatically run in a coded and programmatic way according to the rules triggered by predetermined conditions, to make DAOs eliminate human intervention.

3) O: "Organizational" captures the features that DAOs revolutionize the management mode by allocating ownership and decision-making power to all organization members. These features will further enable them to express their opinions on DAO management by virtue of their ownership, thereby contributing to the achievement of the overall goals. "Operational" means that DAOs utilize technological innovation to change traditional decision-making and implementation methods to enhance the automation and intelligence of DAO operation, which makes the group consensus be quickly reached, disseminated and implemented.

B. Basic Requirements

A true DAO should meet different requirements for *D* and *A*, e.g., the organizational form and allocation of rights and responsibilities from the perspective of organization, and the decision-making and implementation methods from the perspective of operation.

1) Organization (Requirements of "D"): The organizational forms of DAOs are distributed and decentralized, and their organizational structures are loosely coupled. There is neither a central node in the organization nor subordinate relationships between nodes. Each node can voluntarily participate in organizational affairs, and their roles will be dynamically set according to the changes in organizational affairs. The degrees of decentralization of DAOs are usually determined by their consensus mechanisms. With the consensus mechanism having the characteristics of random and equal probability, each node with voting rights can randomly become a voting node with equal probability, which can ensure that the voting results are fair to each node in the organization. The following indicators can be used to measure whether the "D" requirements of the organization are met: the cost of entering and exiting DAOs, the dispersion of voting rights, proposal rights, and decision-making rights, the scalability of the node network, etc.

Requirements of "A": The "A" requirements are more reflected in autonomy. The organizations of DAOs have strong stability and can resist substantial hacker attack risks using distributed storage, and the affairs in the organization are decided by the members through voting. The ownership of DAOs belongs to all their members, and all the members holding the organizational token have voting rights, but they can voluntarily choose whether to participate in the proposal and vote [11]. The economic balance of the organization is guaranteed and maintained by the circulation of tokens, and thus it can form an automatic and autonomous organization that can circulate well and develop stably without external intervention. The following indicators can be used to measure whether the A requirements of the organization are met: the distribution of decision-making power and its corresponding holder, the proportion of automatic collective decision-making, the range of interests represented by voting results, etc.

2) Operation (Requirements of D): The operation of DAOs depends on the joint decision of all their nodes, and the changes in the regulations and policies need to be determined by the consensus of multiple distributed nodes. A single node's decision-making power and influence are limited, and the cost of controlling the organization through bribery, cheating, and other means is enormous. As such, the decision-making results of DAOs can hardly be changed and controlled by the collusion of nodes. The following indicators can be used to measure whether the D requirement of the operation perspective is met: the number of active nodes of DAOs, the impact of a single node on organizational decision-making, the marginal cost of the nodes gaining the decision-making power, etc.

Requirements of A: The A requirement is more embodied in automation. Except that the initial governance framework

can be generated off-chain, all the on-chain activities and decisions should be automatically executed through smart contracts without human intervention. The upgrading and supplementing of smart contracts should also be realized by smart contracts. Meanwhile, all the operational data of DAOs are tampered with proof to ensure the traceability of the decision-making process. The following indicators can be used to measure whether A requirements of the operation perspective are met: the security of smart contracts, the efficiency of smart contracts, the portability of smart contracts, etc.

C. Infrastructures

DAOs can be regarded as multiagent systems with social and engineering complexity. Their consensuses are large-scale group coordination and collaboration in a multiagent social network with uncertain psychology and behavior, diverse consensus mechanisms and strategies, and complex agent competition and cooperative games [12], and their encrypted chained data structure integrates various technologies to achieve reliability, trustworthiness, autonomy, and orderliness.

As code-based, autonomous operation and human-in-the-loop systems, DAOs rely heavily on the underlying operating protocols that are collaboratively designed and maintained by the community members. Unpredictable vulnerabilities caused by incomplete logic and code, as well as malfunctioning mechanisms, are capable of causing catastrophic damage to an entire organization. Through empirical data analysis, mathematical derivation, or simulation, it is not easy to manage, supervise, and control the overall operation of complex DAO systems [13]. Consequently, a new approach to DAO governance is urgently needed.

Traditional cybernetic-based management drives organizations to operate in an auto-dynamical manner. It uses information and knowledge to replace power and money to steer, control, and regulate complexity management [14]. Even though cybernetics-based management is still the ideal control method, it cannot effectively deal with the uncertainty and social complexity caused by human interaction.

Artificial systems, Computational experiments, Parallel execution (ACP) based parallel intelligence provides an effective research framework and practical methods for the organization and operation of DAO [15], [16]. In the parallel DAO system based on cyber–physical–social system (CPSS) and parallel intelligence, one or more artificial DAO systems corresponding to the real DAO system are constructed, allowing agents, software-defined robots, and digital humans to cooperate to complete various operations and service functions like human. Then, various computational experiments are designed to evaluate and validate the behaviors, mechanisms, and strategies of the DAO system. Finally, the decision can be optimized, and the DAO governance can be parallel-tuned through the parallel execution of the artificial and real DAO systems. The parallel DAO can effectively realize the learning and training, experiment and evaluation, and management and control of the DAO governance system. In addition, DAOs also provide new ideas for the realization of parallel intelligence: using the structure of blockchain and credit technology to improve the level of group intelligence, thereby reducing the requirements for the level of individual intelligence [17].

D. Supporting Technologies

In recent years, numerous DAOs with different goals, types, structures, and scales have continued to emerge. However, current DAOs are still in the early stage of development with the primary form, which is built for specific issues with a single goal and simple functions, and mainly comprises on-blockchain virtual identities controlled by humans. In the future, DAOs will further evolve to their advanced and ideal form. The advanced form refers to that DAOs can serve specific organizations with multiple goals and complex functions, with robots and digital humans assisting humans; the ideal form means DAOs can be used for society with ecological goals and functions, with robots and digital humans guiding humans. This development of DAOs is inseparable from the necessary support from various technologies, such as digital twins, metaverse, and Web3, and their maturity and application degree greatly determine the development stages of DAOs.

1) Digital Twin Is the Engineering Technology: Digital twin realizes the mapping from the physical system to the digital model by reproducing the organization and system in the virtual world, and they can interact with each other in real time [18]. It extracts complex laws and knowledge from large-scale multisource data via algorithms, such as machine learning, deep learning, etc., to generate global optimal strategies that surpass the local suboptimal decisions made by humans [19]. Consequently, digital twin can act on the digitalized modeling process of DAOs from the engineering perspective. As the mirror reflection of the physical system, digital twin is a dependent description system by nature. Besides, it rarely considers the social complexities due to diversified human behaviors and relationships in CPSS. However, the social factors produced by a group with a common goal must be included in DAOs. Meanwhile, an actual system that precisely corresponds to DAOs may not exist. As a result, DAOs also need scenario technologies [20] to build a trustworthy and interpretative organization and operation environment.

2) Metaverse Is the Scenario Technology: Metaverse builds a virtual world parallel to the real world that can realize the virtualization and digital extension of the real world [21], [22]. Essentially, Metaverse is one of the specific realizations of parallel systems. Based on digital twins, extended reality, augmented reality, blockchain, cloud computing, etc., Metaverse closely connects the virtual world with the real world through trust building, digital identity, economic autonomy, and virtual-real integrated applications, thereby reshaping the trust system and organization structure in the real world [23], [24]. Consequently, Metaverse can serve the social functional experimentation process of DAOs from the scenario perspective by constructing virtual application scenarios beyond reality and using distributed automatic methods driven by intelligent algorithms and computing power to promote the exponential increase of decision-making ability for DAOs. However, it is still essentially a systematic decision-making

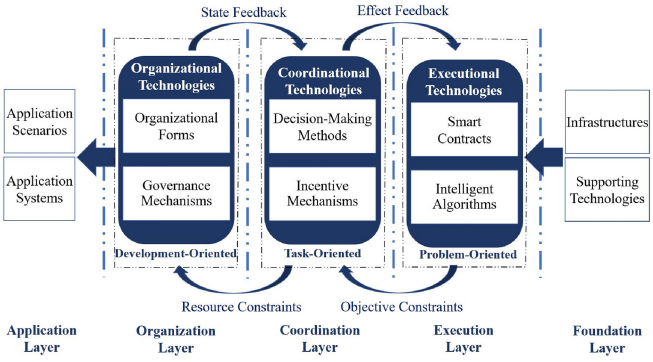

Fig. 1. New architecture of DAOs.

method that focuses on the DAOs themselves, and, hence, cannot well handle the increasing complexities due to the real-time interactions of DAOs and their environments. Therefore, the ecologically intelligent decision-making method for DAOs should be considered.

3) Web3 Is the Decision Technology: The innovation of Web3 lies in technologies and models. Its technological innovation is reflected by the integration of blockchain, artificial intelligence, big data, etc., while the model innovation refers to scarcity creation, the token economy formation, and the shared value network construction. Web3 transforms network ownership through a blockchain-based distributed collaboration mechanism with the cryptocurrency-based token economic system. It establishes a fairer production relationship and achieves a more balanced value distribution so as to pool collective wisdom better to fight for the goals of DAOs. Therefore, Web3 can work in the management and decision-making process of DAOs from the ecological perspective.

III. New Architecture

The new architecture of DAOs mainly includes five layers, as shown in Fig. 1. The foundation layer mainly covers infrastructures and supporting technologies, and the application layer mainly concerns application systems and application scenarios. The following emphasis will be put on the other three strongly connected layers. The development-oriented strategic goals and principles in the organization layer will finally be refined into the problem-oriented practical work and methods in the execution layer, which must rely on the task-oriented coordination layer to bridge them. The coordination layer converts the goals and information into specific work by generating subtasks and sending them to the executive body, and equipment [25], [26], [27], [28]. The problem solution in the execution layer will be feedback to the coordination layer and affect the cost-benefit of the tasks, and the task response in the coordination layer will be further feedback to the organization layer and influence the development of DAOs. As follows, we will discuss the main components and techniques in the organization, coordination, and execution layers.

A. Organization Layer

The organization layer emphasizes the use of organizational technologies to fulfill the overall goals of the organization at the macro level. It aims to build an organizational structure that adapts to the development strategy of DAOs. The organizational structure is the foundation of DAOs, essentially the collaboration system under specific strategic goals with personnel as the inherent elements. One of the primary problems of organizational management is labor division, that is, assigning labor to different tasks. DAOs realize the labor division, the definition of power and responsibilities, and the allocation of resources in a distributed and decentralized way to build an organizational structure of community ownership. The organization layer under the proposed architecture mainly involves the organizational form and the governance mechanism.

1) Organizational Form: According to the degree of decentralization and distribution, the organizational form of DAOs can be divided into three types, including distributed multiple centers, distributed whole centers, and unequal centers. In the type of distributed multiple centers, the power of the traditional center node is distributed to multiple small center nodes, forming a balanced state of the coexistence of multiple small centers. Each node has a particular influence in its small center, and each small center will enhance its strength through competition and cooperation with other small centers, which can effectively improve the overall vitality and innovation of the organization. In the type of distributed whole center, the power of the traditional center node is evenly distributed to each node in the organization so that all the nodes become center nodes with equal rights, and they will participate in the decision making of the organization together. In the type of inequality centers, the power of the traditional center node is distributed to each node in the organization in an unequal way so that each node has different organizational rights, and the nodes with higher organizational rights will have more decision-making rights in the organization.

2) Governance Mechanism: DAOs usually adopt three governance mechanisms, including off-blockchain proposal, on-blockchain proposal, and the combination of off-blockchain and on-blockchain proposal. Off-blockchain proposals are put forward in the forum organized by DAOs and then voted off the blockchain, and on-chain proposals are put forward and voted on the blockchain. The combination of off-blockchain and on-blockchain proposals are put forward proposals in the forum organized by DAOs first, and then the proposals that have a critical impact on the development of DAOs organization will be selected and published by the decision-making committee organized by DAOs to the blockchain, and voted by the members of DAOs on the blockchain.

B. Coordination Layer

The coordination layer concerns the coordinational technology supporting task management at the meso level [29]. The nature of management lies in design, and its primary goal is to regulate and adjust the coordination mechanism under a specific labor division [30]. DAOs adopt the design of project-based tasks through the distributed network, motivate the construction of an autonomous and automated dynamic coordination mechanism by incentives, and realize the management and control of the organizational decision-making

process employing collective decision making in the trustless environment. The coordination layer of DAOs is mainly comprised of the decision-making method [31], [32] and the incentive mechanism [33].

1) Decision-Making Method: The important decisions related to the development of DAOs, such as agreement upgrading, parameter adjustment, fund control, strategic planning, etc., need to be voted on the blockchain by all the DAO members, while the daily affairs management and operation of DAOs are usually the responsibility of the committee elected by DAO members to avoid unnecessary and endless voting. When using protocols, decentralized applications (DApps), or DAO infrastructure, if there are any disagreements, disputes, and conflicts among DAO members, decentralized courts or ragequitting mechanisms are usually adopted to resolve them. Take the decentralized court Kleros as an example. Both parties need to pledge a certain number of tokens when submitting their dispute, and then submit their evidence to the court within the specified time. After that, the decentralized court will randomly select a certain number of members with governance power as jurors, and encourage them to vote within the specified time by means of economic incentives [33].

2) Incentive Mechanism: In order to fully encourage DAO members to actively participate in the DAO governance, to improve its safety and reliability, a variety of incentive mechanisms have been designed, including the generation and distribution of various incentives, such as token, reputation, and governance power. By combining different incentive means and adopting various incentive mechanisms, the external and internal incentive needs of different DAO members can be satisfied, which can motivate them to achieve organizational goals through coordination.

C. Execution Layer

The execution layer covers the executional technologies targeted to the management problems at the micro level. Its mission is to handle practical problems faced by organizational management and operation, which relies on executional technologies to generate optimal decisions in a trustworthy manner. DAOs utilize the automatic execution ability of smart contracts and the learning and optimization ability of intelligent algorithms to generate and implement consensus decisions in real time for specific problems in an unmanned way.

1) Smart Contracts: The rules and processes of the organization, coordination, and execution of DAOs that have reached a consensus will be written into the smart contract and deployed on the blockchain after verification. When the trigger conditions of the smart contract are met, it will be automatically executed and cannot be tampered with [34]. It has security, transparency, openness, and fairness, which can reduce costs and improve DAO governance and coordination efficiency without a trust foundation [35].

2) Intelligent Algorithms: Since smart contracts are only "If-Then" type situational coping rules, they do not have the abilities of learning, reasoning, and decision making, and cannot meet the intelligent requirements of DAO governance and coordination. Intelligent algorithms have powerful capabilities of data analysis, algorithm learning, and decision reasoning [36]. Therefore, by using intelligent algorithms, the functions and requirements of DAOs can be deeply analyzed, and the domain knowledge and rules for specific business scenarios can be encapsulated into smart contracts, which can effectively enhance the intelligence of DAO.

D. Applications

With the improvement of smart contract platforms, such as Ethereum and the maturity of decentralized governance tools, the application of DAOs is becoming increasingly diversified and shows a trend of integration with non-crypto industries. At present, DAOs have been applied in many fields, such as finance and venture capital, social network [37], [38], entertainment, science, etc., which led to the birth of decentralized finance (DeFi), such as Uniswap and MakerDAO, decentralized funding, such as VentureDAOs and GrantDAOs, decentralized social network, such as community DAOs and social DAOs, decentralized entertainment, such as CollectionDAOs and GameFi, and Decentralized science (DeSci) [39], [40], [41]. In addition, DAOs also have great potential in many fields, such as organization management, emergency command, and network governance.

IV. Models and Algorithms

A. Theoretical Models

As a new paradigm supported by the integrated innovations of technologies, models, and values, the sustainable development of DAOs cannot be separated from the guidance and support of the fundamental theoretical model. However, up to now, there are still few research efforts on the theoretical model. This section will analyze the main goals of DAOs under the proposed new architecture and then combine it with its basic requirements to build a theoretical model.

According to the D and A requirements of DAOs as discussed in Section II-B, we can denote

$$D = \begin{bmatrix} D^{\text{Org}} \\ D^{\text{Ope}} \end{bmatrix}, A = \begin{bmatrix} A^{\text{Org}} \\ A^{\text{Ope}} \end{bmatrix} \tag{1}$$

where D^{Org} and D^{Ope} represent the indicator vectors corresponding to the requirements of distribution and decentralization at the organizational and operational levels, i.e.,

$$\begin{aligned} D^{\text{Org}} &= \left(D_1^{\text{Org}}, \ldots, D_k^{\text{Org}}, \ldots, D_n^{\text{Org}}\right) \\ D^{\text{Ope}} &= \left(D_1^{\text{Ope}}, \ldots, D_k^{\text{Ope}}, \ldots, D_n^{\text{Ope}}\right) \end{aligned} \tag{2}$$

and A^{Org} and A^{Ope} represent the indicator vectors corresponding to the autonomy and automation requirements at the organizational and operational levels, i.e.,

$$\begin{aligned} A^{\text{Org}} &= \left(A_1^{\text{Org}}, \ldots, A_k^{\text{Org}}, \ldots, A_m^{\text{Org}}\right) \\ A^{\text{Ope}} &= \left(A_1^{\text{Ope}}, \ldots, A_k^{\text{Ope}}, \ldots, A_m^{\text{Ope}}\right). \end{aligned} \tag{3}$$

DAOs use new technologies and paradigms of complex intelligence to ensure that the right things will be done in the right way to achieve the goal of "TRUE," i.e., trustable

(T), reliable (R), usable (U), and effective and efficient (E), where T refers to the openness, transparency, and traceability of the process, content, and results of DAOs' organization and operation, so as to make the management decision results credible; R means that the construction technologies and mechanisms of DAOs can provide enough reliable security and robustness; U means that DAOs should be easy to build, maintain, modify and expand in specific applications; and E refers to the efficiency and effectiveness of DAOs in the intelligent decision of complex systems. Different types of DAOs will be built for different application scenarios using different technologies, mechanisms, and methods, which makes the measurement indicators of TRUE change accordingly, i.e.,

$$\text{TRUE} = (T, R, U, E). \tag{4}$$

Optimize the *TRUE* objective of DAOs on the premise that D and A requirements are met, and meanwhile, it is also necessary to measure the degree of realization of D and A requirements under the specific TRUE goal. Considering the relationship of mutual influence and entanglement among D, A, and *TRUE*, the following closed-loop equations of DAOs are established:

$$\begin{aligned} \dot{\text{TRUE}} &= f(T, R, U, E) \\ \dot{D} &= g(T, R, U, E) \\ \dot{A} &= h(T, R, U, E) \end{aligned} \tag{5}$$

where $f()$, $g()$, and $h()$ represent the transformation equations of *TRUE*, D, and A, respectively, which will not only be affected by the other two factors but also affected by themselves. In addition, the above equations are not static but change dynamically with the development stages of DAOs.

B. Intelligent Algorithms

Although intelligent algorithms play a vital role in realizing various functions in the DAO ecosystem, such as data management, risk quantification, decision making, etc., they have not received enough attention, and the existing research rarely involve them. In general, a complete DAO system should be equipped with the functional modules of data, collaboration, decision, experimentation, development, and service, and each module is powered by the corresponding intelligent algorithms, as shown in Fig. 2.

1) Data: DAOs heavily rely on data to establish networks, run smart contracts, and maintain functions, including internal and external trusted data. The former is generated by the daily operation of DAOs, which are open, transparent, and traceable data stored on the blockchain; the latter is provided by a third party. The core goal of data governance in DAOs is to achieve efficient circulation, secure management, and sustainable application under the premise of data sovereignty protection, privacy preservation, and proper value allocation. Besides, the practical needs of different data functions from the perspective of DAO ecology must be taken into account. As such, DAOs need federated data algorithms and the corresponding data value creation and distribution algorithms to balance their security, stability, and efficiency goals.

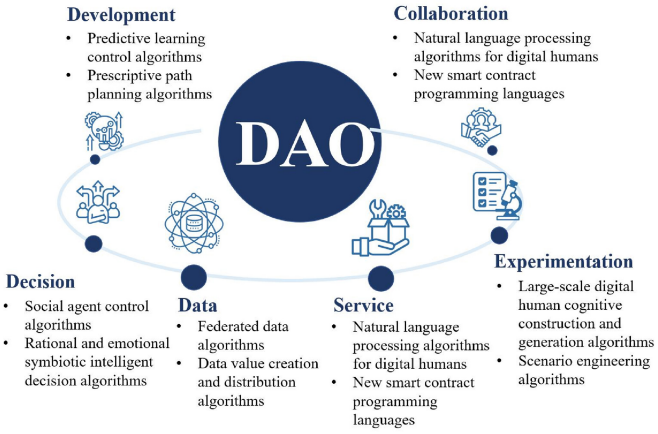

Fig. 2. Function-oriented intelligent algorithms of DAOs.

2) Collaboration: The core of DAO collaboration is to reach consistency in the distributed network. From the perspective of systems engineering, consistency means that all members agree with the organizational and operational results to ensure that the status presented by the system to the outside world is consistent, which strongly depends on the design of consensus algorithms. In this light, DAOs need consensus algorithms with provable security, high scalability, and efficiency to cope with dynamic complex collaborative networks. From the perspective of organizational management, consistency means that individual behaviors should meet the group goals, which mainly depends on the design of incentive mechanisms. As such, it is necessary to integrate the algorithms for constructing group-oriented knowledge graphs, skill graphs, and social graphs with the algorithms for analyzing individual emotions, characteristics, and behaviors. They will be further combined with tokenized, reputation-based, and knowledge-based precise incentives so as to form dynamic incentive algorithms that have the attributes of dual self-adaptation to both individuals and groups.

3) Decision: Although DAOs benefit from entrusting intelligent algorithms to manage its various functions due to the elimination of human biases and errors, complete mechanization and unmannedization will lead DAOs to lose management controllability and sustainable intelligence. Therefore, DAOs will inevitably develop toward the model of manned management in unmanned systems, and the starting point of this trend is to introduce digital humans into the management decision-making process of DAOs, which will develop the unmanned autonomous agent function of DAOs to manned social agent function. Digital humans have full consciousness, individual character, and personal emotions and can quickly and accurately identify helpful information, to make proper decisions and judgments. They can break through the limitations of human rationality but still keep human-like emotional needs. Given these, social agent control algorithms and rational and emotional symbiotic intelligent decision algorithms should be introduced into DAOs.

4) Experimentation: DAOs can support experiments on the organizational ownership and governance structure for scarce resources, such as data, trust, attention, etc. Currently,

the focus is on the design of incentive models and democratic governance forms, but the most fundamental experimental scenario design has been ignored. Because traditional experimentation methods usually have a deficiency in readability, interpretability, and traceability, they cannot match the features of openness and transparency of DAOs. Therefore, Web3-based DAOs rely on digitized and computational scenario design and construction technologies to promote the design, implementation, and evaluation of experiments, which are more trustworthy [42] and can promote the ability improvement and service development of DAOs. Accordingly, it is necessary to develop and apply cognitive construction and large-scale generation algorithms for digital humans and scenario engineering technologies and algorithms.

5) Development: DAOs gather members and make them cooperate in a trustless environment to achieve common goals, so it is guided and driven by collective thinking rather than individual thinking. Usually, DAOs organize and operate on their own once getting run instead of being controlled by the creator. To maintain the characteristics of decentralization and distribution, it will be better if DAOs can rely on its own "soft" strength to solve the problem but not the external "hard" measures. As a result, besides the friendly self-learning ability that adapts to the environment, DAOs still need vigorous path planning and adjustment ability to accommodate even change the environment, develop new skills to guide themselves, and lead others on this basis. Therefore, the commonly used descriptive intelligent algorithms should be upgraded to predictive learning control algorithms and prescriptive path planning algorithms.

6) Service: As independent and open value networks, DAOs can be applied in finance, art, management, and other fields by providing various services, including project funding, social interaction, talent gathering, content creation, and asset management. The member composition of the DAO network is crucial to the realization of these service functions. Multiple identities that can be dynamically converted are helpful for the enrichment and improvement of DAO service, but this cannot be realized in the current DAOs because of the potential risks brought by the manipulation and abuse of virtual identities, such as the Sybil attack. If DAOs are built mainly by digital humans with independent personalities instead of virtual identities controlled by humans, then this dilemma may be overcome. For this purpose, natural language processing algorithms and new smart contract programming languages for digital humans are needed, especially, digital-human-oriented smart contract programming languages, automatic generation algorithms, and self-verification technologies.

V. Core Mechanisms

DAOs organize and operate in the form of democratic decision making by unifying the ownership and management rights and returning them to DAO members, which severely rely on the design of its core mechanisms including the governance mechanisms and the incentive mechanisms [43].

A. DAO Members

The first task of mechanism design is to analyze its functional objects, namely DAO members. At present, DAO members are mainly composed of virtual identities of humans, which makes the organization and operation of DAOs essentially controlled by them. Aiming to make DAOs more intelligent and powerful in decision making, robots and digital humans should be introduced into DAOs. They are both intelligent agents or avatars of humans, assisting or even replacing them to complete specific tasks. Accordingly, there are three types of DAO members: humans, robots, and digital humans. Among them, humans are active in DAOs with the help of virtual identities; robots exist as intelligent wares, and smart contracts are the simple form of intelligent wares; and digital humans are usually the codes or programs, which originated from humans but not the simple replica of humans.

B. Governance Mechanisms

This section takes matters and purposes, collaboration paradigms, decision-making techniques, etc., as the measurement dimensions and reorganizes the design of DAO's governance mechanism from the perspectives of individuals, groups, and societies in order to provide helpful guidance for DAO governance.

1) Individual Governance: DAOs are the typical human-in-the-loop complex systems involving multirole collaboration and governance. DAO members in three different roles cooperate to perform organizational tasks without trust through professional, human-machine, and virtual–real division of labor. Presently, individuals participating in the governance of DAOs are mainly carried out by humans and robots through democratic voting on and off-chain. Among them, based on experience and knowledge, humans form consensus and participate in organizational governance through democratic voting; robots automatically execute the rules and regulations formulated by humans. Commonly used voting governance mechanisms include: direct voting, delegated voting, quadratic voting [44], belief voting, and Futarchy mechanism [45]. In the future, robots and digital humans will play an increasingly important role in DAO governance, and the challenge that comes with it is how to allocate what form of voting and decision-making power to them, and how their governance powers both differentiate and interact with humans.

2) Group Governance: Organizational structure and internal coordination are the main ways for DAOs to achieve their governance goals. Generally, the organizational structure of DAOs can be divided into two types: a fully decentralized governance structure and a progressive decentralized governance structure. The former means that the underlying infrastructure of DAOs adopts a decentralized structure, while the formulation of incentives and governance mechanisms and the management of foundations are all operated by DAOs. The latter is an inevitable choice for most DAOs, and its underlying infrastructure still adopts a decentralized structure, but the formulation of incentive and governance mechanisms and the management of foundations are progressively decentralized. The decentralized governance structure

of DAOs promotes dynamic changes in its members, member roles, and power relations. In addition, the decentralized governance structure also promotes the design of DAO's internal control model to change from a strict division of responsibilities, authorization, and command to relying on a complete set of democratic governance processes. That is, utterly decentralized governance, or a mix of centralized and decentralized systems based on proposals, evaluation, voting, execution, dispute resolution, and arbitration. The internal control mechanism has changed from guaranteeing the organization's regular operation through a series of incomplete natural language contracts to guaranteeing the governance of the organization through explicit smart contracts, and parallel DAOs.

3) Social Governance: One of the most prominent advantages of DAOs is to solve the principal–agent relationship and the resulting trust dilemma faced by traditional organizational structures and social governance structures. DAOs also turn the trust and attention that are difficult to commercialize into new production factors, thus opening up a new economic space. Within a DAO, members must reach a consensus on a common goal, which represents the collective interest of the whole DAO community. Besides the collective interests, each DAO member also has his own goals for interest optimization. Outside a DAO, the circulation of production factors promotes information sharing, professional cooperation, and mutual assistance between multiple DAOs, thereby transforming the social cooperation model from a zero-sum game to a positive-sum game [46], [47]. Meanwhile, DAO is the basic unit of society, and it is inseparable from the decentralized autonomous societies (DASs) composed of multiple DAOs. Therefore, the social governance of DAOs should cover three respects: 1) the unity of collective interests and individual interests within a DAO; 2) the interests intermediation among multiple DAOs; and 3) the realization of social interests of DAS formed by DAOs. However, the current research on the social governance of DAO only captures the first respect, which relies on collaborative design of the governance and incentive mechanisms to realize the governance goals of a single DAO.

C. Incentive Mechanisms

DAOs entirely rely on the incentive mechanisms to unite benefit-sharing members in the blockchain-based trustless environment, and encourage them to effectively interact and collaborate around common goals according to their own information, resources, goals, and risk appetite.

The design and research of the incentive mechanisms of DAOs should consider the characteristics and needs of different types of members. From the perspective of the game theory [48], [49] and mechanism design, we first analyze their rationality. Humans face uncertainties from both the exogenous environment and endogenous behaviors, and their capabilities of information processing and decision making are limited. That is, humans usually have bounded rationality. Robots act according to the preset procedures and rules without personal emotions and human intervention, thereby being almost completely rational. Digital humans not only possess perception, calculation, reasoning, and learning capabilities like robots but also have the characteristics, emotional attributes, and thinking methods like humans. In addition, they have unique language systems and interaction methods. Different from humans and robots, digital humans do not have static rationality but have matching rationality that evolves and develops with changes in the internal and external environment of DAOs. This kind of rationality coincides with the ecological rationality proposed by Gigerenzer [50]. These three types of DAO members with different rationality build the harmonious DAO ecological network through professional, human-machine, and virtual–real division of labor so as to achieve various functions and goals, and also promote the development of DAOs [52].

In general, incentives in DAOs can be divided into transferable incentives and nontransferable incentives. Transferable incentives are dominated by economic incentives in the form of fungible tokens or non-fungible tokens (NFTs) [53], [54], including contribution rewards, profits, remuneration, bounties, etc. [51]. The incentive mechanisms of DAOs mainly stipulate their generation, distribution, and transfer. Nontransferable incentives mainly refer to noneconomic incentives, including reputation, belief, soul, knowledge, etc. [55]. The incentive mechanisms of DAOs mainly regulate their acquisition and use. The challenge is how to combine these incentives and design proper mechanisms to meet the specific needs of each type of member and also the common goal of DAOs.

Bounded rational humans participate in collective collaboration and contribute to the common goal of DAOs with the purpose of getting high personal rewards, which leads their decisions and behaviors to be self-interested. The effect of the incentive mechanisms dramatically depends on their individual needs and optimization goals, which are substantially different for everyone. Because of this, measurability and individualization are particularly important in designing proper incentive mechanisms for human members. Therefore, the mixed incentive mechanisms dominated by transferable incentives and supplemented by nontransferable incentives can be used for humans to quantify their contributions to DAOs and then allocate the reputation, certificates, tokens, and governance power accordingly.

Altogether rational robots have no emotional needs and no social activities, making nontransferable incentives approximately invalid. However, robots need to learn and upgrade, which is inseparable from the continuous supply of raw materials, such as data, models, and knowledge. Therefore, transferable incentives can be used for robots, allowing them to obtain tokenized incentives and automatically exchange them for the raw materials they require to improve their abilities in a programmed manner.

Ecologically rational digital humans Gigerenzer [50] can choose to participate in DAO tasks according to their personal preferences but cannot deviate from the missions of assisting, serving, and guiding humans under any circumstances. This requires them to behave and seek their own interests without sacrificing that of humans. Therefore, the mixed incentive

mechanisms, mainly based on nontransferable incentives and supplemented by transferable ones, can allocate reputation and knowledge matching their contributions, and endow them with specific governance power.

VI. Conclusion

With the Web3-powered new generation of Internet technologies gradually approaching, productivity and production relations are undergoing unprecedented changes in the closely connected and highly overlapped real and virtual worlds simultaneously. As a brand-new organizational and operational mode, DAOs are precisely one of the cores of this significant change. Compared with the blossoming development of industrial applications in recent years, the fundamental theoretical research of DAOs still severely lag, and many underlying scientific problems need urgent and deep exploration. Aiming at understanding and enriching DAOs from the perspective of scientific research more comprehensively and deeply, this article analyzed the principles and new intelligent technologies of DAOs, constructed a new architecture of DAOs, proposed their theoretical models, studies intelligent algorithms, and elaborated their core mechanisms. It is expected to provide a helpful reference and strong support for the research and applications of DAOs.

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