# Unpacking How Decentralized Autonomous Organizations (DAOs) Work in Practice

***Abstract*—Decentralized Autonomous Organizations (DAOs) have emerged as a novel way to coordinate a group of (pseudonymous) entities toward a shared vision (e.g., promoting sustainability). In just a few years, over 4,000 DAOs have been launched in various domains, such as investment, education, health, and research. Despite such rapid growth and diversity, it is unclear how these DAOs actually work in practice. Given this, we aim to unpack how (well) DAOs work in practice. We conducted an in-depth analysis of a diverse set of 10 DAOs of various categories and smart contracts, leveraging on-chain data and interviewing DAO members. Specifically, we define metrics to characterize key aspects of DAOs, such as the degrees of decentralization and autonomy. We observed some DAOs having poor decentralization in voting, while decentralization has improved over time for one-person-one-vote DAOs. Lastly, we offer a set of design implications for future DAOs based on our findings.**

***Index Terms*—DAO, Decentralization, Autonomy, Empirical, Metrics**

## I. Introduction

As of 2023, there have been over 4,000 decentralized autonomous organizations (DAOs) created with the goal of democratizing the management structure for organizations and open-source projects [1] utilizing smart contracts (i.e., computer programs encoded with specific rules that can be self-executed on blockchains) to govern their operations [2]. Compared to related fields such as platform governance or civic technology, DAOs tend to be more economically sophisticated and often involve more advanced technologies such as decentralized systems, blockchains, smart contracts, and cryptography. One of the key functions of a DAO is group decision-making, which is often conducted via a series of proposals where members vote with the DAO's governance tokens [3] where the market value of such governance tokens typically signifies the relative influence of stakeholders within the DAO. Despite challenges faced by early DAOs, it offers advantages such as community-led consensus, rule execution consistency, and decision-making transparency [4, 5].

Yet, DAO governance remains a multifaceted subject; it is not yet clear to what degree they attain decentralization and autonomy, even though the name of DAO implies the two. Nevertheless, the rising significance of online organizational forms in global politics and economies is undeniable [6]. The potential decentralized and autonomous nature of DAOs makes them particularly unique and interesting to study. In fact, DAOs have been explored and experimented in the wild as a promising approach in tackling hard questions of organization and coordination. Specifically, the influence of community involvement, decision-making authority, and positioning of DAO members in proposals and voting mechanisms on the level of decentralization remains unclear [7]. Furthermore, the extent to which DAOs operate without undue external influence (from corporate competitors, regulators, or third parties in general) in practice has not yet been explored. In this paper, we aim to discover how concretely DAOs work in practice (focusing on decentralization and autonomy). We address the following research questions.

**RQ1: What are the current perceptions & practices of DAO participants in fulfilling DAOs' vision?** Interviews with 10 DAO participants and two focus groups revealed nuanced perceptions and practices. Participants mentioned that "being decentralized is not the sole purpose," and voting similarity often results from the influence of "whales" (those with significant governance tokens), trust in key opinion leaders, and peer pressure. Definitions of DAO autonomy varied, with some emphasizing "less human intervention, more tool use," while others focused on "without undue external influence."

**RQ2: How decentralized is a DAO?** Token holdings correlate positively with proposal success in KrauseHouse, CompoundDAO, and dxDAO. BitDAO, BanklessDAO, and AssangeDAO show no significant correlation, likely due to predefined authorship. CompoundDAO, AssangeDAO, Bankless, and Krausehouse display polarized voting patterns, indicating poor decentralization, whereas Proof of Humanity (PoH), Meta Gamma Delta, and Moloch exhibit more equitable distribution of voting power. Additionally, members with more governance tokens tend to vote more actively, eroding decentralization. Decentralization has worsened in CompoundDAO, BitDAO, and BanklessDAO, which use token-based governance but improved in PoH, which employs one-person-one-vote.

**RQ3: How autonomous is a DAO?** Our analysis revealed variations among DAOs to achieve arbitrary transaction execution, with on-chain proposal submission being the most autonomous via code modules. We also observed most DAOs require 3rd-party services to operate.

**Main contributions.** Our work makes the following contributions: (1) We offer novel insights into the perceptions and practices regarding the degree of decentralization and autonomy in fulfilling the visions of DAOs by interviewing DAO participants. (2) Our empirical analysis of on-chain and off-chain voting/proposal systems and examination of associated smart contracts illuminate DAO decentralization and autonomy using key metrics, some derived from participant interviews. (3) Our empirical findings inform discussions on DAO governance model design and the development of transparency tools for DAO proposals.

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## II. Related Work

### A. History of DAOs

The first DAO, *The DAO*, was originally designed as an investor-driven venture capital fund that relied on voting by investors to disburse funds to proposals submitted by contractors and vetted by curators [8]. It operates as a transparent and democratically structured virtual platform, without physical addresses or formal managerial roles. Despite its potential of launching one of the largest crowdfunded campaigns ever seen [9], it was immediately hacked and drained of $50 million in cryptocurrency [10], highlighting a mismatch between the system's openness and the potential for nefarious actions [9, 11, 12]. Yet, this should not conflate the broader category of smart contract-based similar technologies, such as Dash governance [13], Digix.io , Augur , Uniswap. Many of these focused on blockchain-based assets and digital variants of existing socioeconomic instruments such as insurance, exchange markets, and social media [12]. While some researchers argue that DAOs were initially limited to private capital allocation [14, 15], there is a growing trend to use DAOs in high-value data, and reputational-based systems [14, 16, 17]. Unlike traditional capitalist organizations with undemocratic decision-making processes, where power is concentrated among boards, management, and shareholders, according to Marxist theory [18], DAOs offer a decentralized alternative, allowing for democratic decision-making through consensus protocols [12] and enforces rules for interaction among the members [4].

### B. Blurred Boundary of Autonomy in DAO: Human Involvement & External Influence

The concept of autonomy in DAOs has been a subject of ongoing discourse within technical, legal, and financial spheres [19, 19]. Specifically, DAOs are entities that operate autonomously for certain tasks using smart contracts but also rely on hiring individuals to perform specific tasks that the automaton itself cannot perform, interacting according to their protocols [20]. Themes that can be applied to DAOs include the degree of human supervision, decision-making roles, liability, and ethical considerations [21]. Of these dimensions, the notions of legal autonomy and financial autonomy would seem to be applicable in the context of DAOs. This is further complicated by regulatory proposals, such as the *"Responsible Financial Innovation Act,"* which classifies DAOs as business entities for tax purposes [22]. Additionally, the governance models of DAOs are evolving, with emerging forms such as CityDAO which proposes to adopt a mayor-council model, where an appointed Mayor holds administrative and budgetary authority, an appointed Council holds legislative authority, and Professional Managers hold administrative authority [23]. We aim to understand the degree to which DAO operates with less human intervention and without undue external influence, potentially from corporate competitors or regulators.

## III. Methodology

We adopt a mixed-methods approach, iteratively blending quantitative and qualitative analyses that involve multiple sources of data, including off-chain and on-chain data, and interviews with DAO experts.

| Smart Contract Data | DAO Proposal Data | Data Voting Data |
|---|---|---|
| | Proposal Author | |
| | Proposal Title | Voter Address |
| | Proposal description | Voter Organization |
| | Proposal Timestamp | Voter Token Weight |
| | Proposal start/end Block | Voter Average Token Weight |
| Compound Bravo | Author Token Wieght | Voter Name if available |
| DAOhaus | Proposal Signatures | Voting Pattern (1, -1, 0) |
| DAOstack | Proposal Outcome | Voting txHash |
| | Proposal State | Voting Gas Cost(ETH) |
| | Proposal Gas Cost | Voting Gas Cost(USDT) |
| | Execution Time delay | Voter Timestamp |
| | intendedExecutionTime | |

TABLE I: List of Metadata collected for off/on chain DAOs

### A. Empirical Analysis

We conduct in-depth quantitative analyses, investigating both on-chain and off-chain voting and proposal data. In particular, we use different methods of network analysis, economic and information theory (e.g., Gini, Nakamoto coefficient, Entropy) to investigate how different factors, such as voting power, participation, and token holdings, are assembled to identify the positionality of DAO holders within the network, and how this influences the decentralization. We also examined the underlying smart contract to assess to which capacity DAOs operate with less human intervention and without undue external influence, potentially from corporate competitors or regulators.

### B. Data Collection

We collected both off-chain data including DAO proposals, voting, token, and treasury smart contracts, as well as off/on-chain voting smart contract modules. For DAOs having readily available source code, we turned to Etherscan [24] which has become the de-facto source for Ethereum blockchain exploration. It offers a useful feature called *"verified"* contracts, where contract writers can publish source code associated with blockchain contracts. Etherscan then independently verifies that the compiled source code produces exactly the bytecode available at a given address. We scraped contracts as of March 2023. For MolochDAO, Meta Gamma Delta, and dxDAO, we aggregated factory contracts from DAOhaus and DAOstack. Table I lists three main forms of data including smart contracts, on/off-chain proposals, and on/off-chain voting. We collected the data in a comma-separated value.

### C. Formative Studies

Our formative study encompasses both individual and group sessions, comprising nine individual interviews and two group sessions with ten experts representing diverse DAO communities and governance (demographics details in Appendix **??**). The purpose of this study was to gain insights into the existing DAO governance practices to identify and establish a set of metrics to assess and quantify the effectiveness of governance, as viewed through the perspective of experts, who predominantly consisted of DAO founders and leaders.

## IV. Perceptions & Practices of DAO Experts

Here, we report the result of our formative study.

**Social & Technical measures of decentralization.** Our interviews revealed varying perceptions of decentralization at



2

different DAO development stages. As P8 suggested that early-stage DAOs often require a certain level of centralization, as *"at beginning to form it, it makes a lot of sense to be more centralized and move to a less centralized over time."*. Some DAO types, like DeFi protocol DAOs, require centralization for effective operation due to current contract limitations. Experts suggested exploring newer contracts for improved decentralization. They also highlighted the distinction between technical and social aspects as noted by P5–*"many facets of decentralization exist (perceptual, technical, legal) and that there are tensions between abstraction and practicality of [MelocV]3 contracts."* Voting methods and concepts like vote delegation were discussed in terms of their impact on collective decision quality and decentralization evaluation.

**Token-based economy lower decentralization.** Our experts compared core team/founder token holdings to grassroots members. P3, involved in projects like Aragon and Aave Hydra, highlighted the need to explore token distribution for effective decentralized governance, emphasizing the risk of discouraging contributions if the founding team holds too many tokens. P2, with experience in LexDAO, SporusDAO, CaliDAO, and onchain LLC, found token-based governance inefficient and questioned true decentralization when a few whales hold significant power among numerous token holders. Many experts stressed the importance of assessing token holder participation in voting/proposals and considering the proposer's affiliation with the core team. P6, formerly with MakerDAO and ConcenSys, mentioned that proposals often fail to reach quorum without whale voters, leading authors to lobby them for support. P8 noted that *"the reality is people don't like to participate in governance, [and] where you end up unfortunately, just speculating on the price value."* Our experts suggested that voting power should be proportional to one's contribution to DAOs.

**Unclear concept of autonomy.** Our interviews highlighted a common theme: the lack of clear autonomy metrics in DAOs. While some experts see autonomy as *"less human intervention, more tool use,"* others recognize that different types of DAOs may require varying levels of autonomy. To mitigate bias and excessive human involvement, some experts proposed creating separate "pods" within DAOs for different functions like marketing or legal. For example, P5 from Polywrap DAO, Llamadao, mentioned the desire to establish different pods to distribute governance power more evenly. Some experts argued that human intervention remains necessary due to a lack of suitable tools but stressed the importance of reducing reliance on external parties. Others defined autonomy in terms of the proposal and voting process, stating that if these activities occur within a machine, they can be considered autonomous.

**Autonomy in relation to quorum backlogs, and user experience.** Some of the limiting factors experts mentioned are execution time delays of DAO operations due to a lack of tooling, and proposals going into backlog due to quorum votes. P7, involved in pleasr DAO, NounsDAO added that limitations around token holding and lack of interest in participating in governance often cause delays in the proposal process since there are specific vote requirements to move the proposal forward. In his words —*"Token distribution among a few means a single point of failure, causing proposal delay."*

**Factors making whales vote in a similar way.** We identified several factors contributing to similar voting patterns among whale voters. Some interviewees noted that most whales are part of the managerial team, leading to aligned voting. P5 mentioned that these whales initially started with a centralized team, becoming the largest token holders. Additionally, P5 added—*"some of their communication happens through private channels like private discord, DMs or telegrams."*, which may contribute to the similar voting patterns observed. Another factor contributing to this trend is people's trust in the voting of earlier whales. P8 noted that—*"Honestly, for many proposals when earlier whales vote in a certain way, a lot of people just follow [..] they trust, whales know what they're doing."* Peer pressure during the voting process was also mentioned as a factor that may lead individuals to vote in a similar way to the whales. P8 noted—*"I didn't want to vote against the proposal, Just because, my reputation would be on the line or something."* Overall, *whales running governance* is identified as a major limitation in DAOs.

# V. Summary of 10 DAOs

We selected 10 DAOs, which were formed between 2019 and 2022, prioritizing diverse categories (e.g., investment, defi, video, social, etc.), popularity, and market capitalization. To add diversity to governance design, we, in particular, considered four DAOs, created with popular DAO factory contracts, including Governance Bravo DAOhaus, Kleros, and DAOStack, in the governance structure. Table II presents the key parameters of the 10 DAO projects.

# VI. RQ2: Decentralization of DAOs

In this section, we investigated the level of decentralization in the current DAOs with respect to voting and proposal.

## A. Voting Patterns Among DAO Holders

We analyze the voting patterns of large token holders (whales) to establish their positionalities and investigate whether their voting patterns align with the broader community. Given that greater token holdings represent the greater influence of holders in DAO voting systems, if voting patterns of whale addresses do not align with grassroots users or their voting patterns only have similarities among themselves, it implies that the grassroots users are marginalized, suggesting poor decentralization.

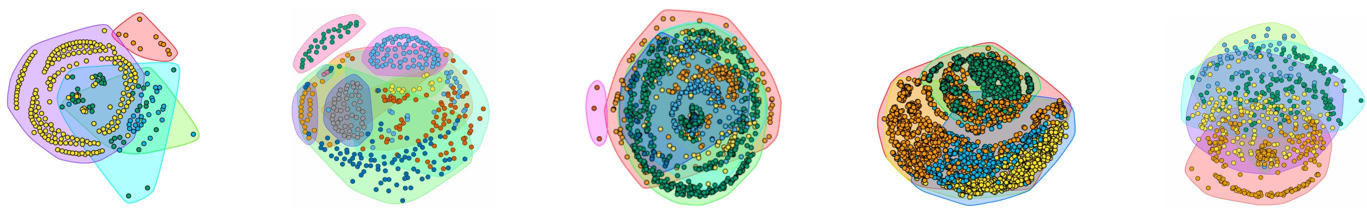
*1) Graph Model:* We developed network graphs to understand DAO holders' voting patterns across different proposals, considering their voting weights. In the graphs, each node $v_i (\in V)$ represents a unique Ethereum address, where $V$ indicates the full set of nodes. Nodes are connected via an edge if they voted the same way (e.g., voted yes) in the same proposal, and $E$ denotes a set of edges $\{(v_i, v_j) | v_i, v_j \in V\}$, where $(v_i, v_j)$ indicates an edge between $v_i$ and $v_j$. The graph structures of DAOs (Figures 1 and 2) are derived using the walktrap algorithm, commonly used to identify communities in networks via random walks [25]. We calculated the optimal similarities and differences of voting behaviors of DAO



3

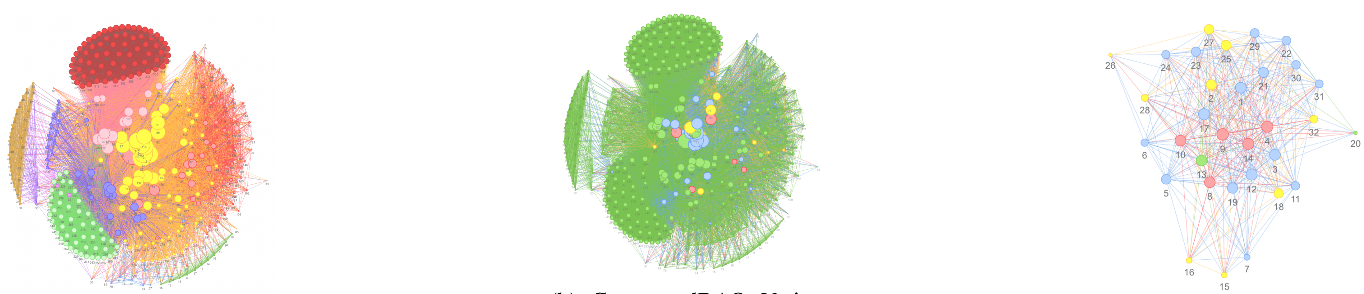
| DAO | Category | Treasury | #Holders | #Active | Avg votes | Participation % | # proposal | #votes | #Creator | Proposal Threshold | Quorum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CompoundDAO | Protocol | 90.7M | 205.9k | 4.1k | 78 | 1.80% | 137 | 12750 | 48 | 25000 COMP | 400,000 |
| BitDAO | Investment | 1.6B | 20.4k | 320 | 53 | 1.30% | 19 | 1347 | 14 | 200,000 BIT | 100,000,000 |
| AssangeDAO | Social | 242.9k | 6.3k | 1.1k | 298 | 12.30% | 11 | 3576 | 2 | 1,000 JUSTICE | 867,576,97 |
| Proof of Humanity | Social | 801.7k | 35.2k | 3.1k | 153 | 8.80% | 104 | 16557 | 25 | 0 VOTE | NA |
| Bankless DAO | Web3 fund | 1.6M | 5.9k | 3,375 | 344 | 43% | 51 | 18272 | 7 | 0 BANK | NA |
| KrauseHouse | Sports | 1.2M | 1.8k | 595 | 32 | 30% | 131 | 4,484 | 5 | 1,000 KRAUSE | 0 |
| LivePeer | Video | 0 | NA | NA | NA | NA | 7 | 600 | 7 | 0 LPT | 1/3*27,004,976 |
| MetaGammaDelta | Social | 29.7k | NA | 49 | 2 | 29.40% | 79 | 132 | 30 | 1 DAI | 0 |
| MolochDAO | Public Good | 0.1 | NA | 60 | 4 | 50.80% | 32 | 83 | 29 | 1 WETH | 0 |
| dxDAO | Protocol | 81M | 1.4k | 232 | 2 | 5.80% | 864 | 3161 | 160 | 0 rep | 0 if boosted else 50 % REP token supply |

TABLE II: DAO Projects Summary in terms of macro information



(a) BitDAO (b) CompoundDAO (c) AssangeDAO (d) BanklessDAO (e) KrauseHouse

Fig. 1: DAO holders' voting behavior for different proposals is displayed as community graphs. For example, figure (a) shows fewer overlapped clusters because the nodes from different clusters do not share much similar voting behavior. In contrast, figure (b) shows the cluster containing yellow nodes has an overlapped region with the cluster containing red nodes due to some voting similarity (at least one voting similarity between nodes/addresses).



(a) CompoundDAO Voting Pattern with a directed graph. Each edge means the two nodes voted the same way to a proposal.

(b) CompoundDAO Voting Pattern of different types of users. Blue: Industry. Yellow: nonprofit. Red: Educational Green: Indv users, big green: KOLs.

(c) CompoundDAO Whale address. Industry: blue, Non-Profit: green, Educational Institute: red, KOL: yellow

Fig. 2: CompoundDAO as an example to demonstrate the result of voting patterns among DAO holders. The size of the nodes is directly proportional to their input degree (i.e., the larger a node, the more tokens it has accumulated in the DAO). We found 32 addresses with a large threshold of Compound token holding. Figure 2c shows that whale addresses from industry, KOLs, and educational institutes tend to have similar voting behavior.

holders in a weighted graph $G(V, E)$. The colors represent clusters related to *"VoterType"* who vote in similar ways for different proposals. If two nodes have more than one same vote, they are more likely to be in the same cluster. To construct a voting network graph, we first created a matrix whose entity indicates a vote on a certain proposal done by an address. Entity values 1 and -1 imply a vote for and against a certain proposal, respectively. In the graph, an edge between Addresses and Votes indicates that an address has voted either against or for the proposals. Further, we present the community cluster with voting weight $w(v_i, v_j)$, which corresponds to the token amount each address delegated for themselves or others to perform the transaction (i.e., to vote for the proposal)(Figure 2).

*2) Patterns of Voting Networks:* In Figure 1, the clusters are colored based on the optimal similarity of voting behaviors



4

| DAOs | Freq of community | Vertics | Edge | Diameter | Mean Distance | Degree Transitivity | Degree Assortativity | Degree Centralization | Betweenness Centralization | Closeness Centralization |
|---|---|---|---|---|---|---|---|---|---|---|
| Bit | 4 | 283 | 26985 | 4 | 1.33 | 0.93 | 0.616 | 0.31 | 0.04 | 0.44 |
| Assange | 6 | 1065 | 380410 | 3 | 1.33 | 0.87 | 0.04 | 0.32 | 0.002 | 0.45 |
| PoH | 5 | 3084 | 1403628 | 4 | 1.7 | 0.66 | -0.2 | 0.68 | 0.008 | 0.77 |
| Bankless | 5 | 3139 | 1758001 | 3 | 1.64 | 0.59 | 0.09 | 0.64 | 0.004 | 0.24 |
| KrauseHouse | 4 | 587 | 63713 | 3 | 1.63 | 0.74 | 0.07 | 0.54 | 0.019 | 0.59 |
| Compound | 10 | 2482 | 378635 | 4 | 1.65 | 0.75 | 0.026 | 0.75 | 0.09 | 0.72 |
| LivePeer | 2 | 367 | 21802 | 2 | 1.68 | 0.68 | -0.2 | 0.67 | 0.04 | 0.79 |
| MGD | 2 | 15 | 56 | 5 | 1.49 | 0.66 | -0.2 | 0.32 | 0.09 | 0.42 |
| Moloch | 2 | 14 | 50 | 3 | 1.45 | 0.65 | -0.29 | 0.37 | 0.13 | 0.5 |
| dxDAO | 4 | 270 | 35520 | 2 | 1.02 | 0.99 | 0.60 | 0.32 | 0.01 | 0.03 |

TABLE III: Network Graph connectivity and clustering statistics for each DAOs in terms of reciprocity, transitivity and assortativity, vertices, edges, diameter, mean distance

and the distance between the nodes (static properties are in Table III). The overlapped regions of colored polygons indicate that there is at least one voting similarity between the nodes in one cluster and the others. In BitDAO, nodes in specified clusters have very few similarities in voting with other clusters, which results in comparatively fewer overlapping regions in Figure 1a. On the other hand, the CompoundDAO network (Figure 1b) has a total of 10 clusters, where some nodes in clusters have at least one similar voting with nodes in other clusters. For AssangeDAO (Figure 1e), there are a total of six clusters, and most nodes have at least one voting similarity with other clusters. As such, one can see the significant difference in the network structures between DAO, which implies heterogeneous community voting behaviors. In contrast, we observed less cluster diversity in proof of humanity however, voters tend to have similar voting patterns Meta Gamma Delta, Moloch, Livepeer, dxDAO tend to follow the similar trend.

**Connectivity and clustering properties.** The assortativity coefficient [26] measures the homophyly level of the graph (i.e., how nodes are connected for a given property), and it ranges in $[-1, 1]$. More specifically, according to [26], a graph is said to be strongly assortative, weakly assortative, neutral, weakly disassortative, and strongly disassortative, if the assortativity coefficient falls into the ranges $[0.6, 1]$, $[0.2, 0.6)$,$(-0.2, 0.2)$,$(-0.6, -0.2]$, and $[-1, -0.6]$, respectively. Table III shows that majority of the DAO, including CompoundDAO, Krausehouse, Bankless and Assange, PoH to be neutrally assortative while BitDAO and dxDAO are strongly assortative indicating that the nodes tend to be connected to other nodes with similar properties. However, in the case of neutral assortativity, many DAO do not have the trend that members vote the same way as others with similar characteristics to them. We further illustrate this property in conjunction with degree centrality where we observed PoH, Bankless, Compound, Livepeer having degree centralization values above 0.6 indicating a significant concentration of node degrees. None of the DAO has a degree centralization value below 0.3. The transitivity coefficient (also known as a clustering coefficient) measures the probability for nodes connected via multiple edges to be adjacent; in other words, if there are two links $(v_i, v_j)$ and $(v_j, v_k)$, what the probability of there being a link $(v_i, v_k)$ is. Table III illustrates various levels of transitivity across DAOs and the value is quite high. dxDAO has the highest transitivity at 0.99, implying that similarity in voting behaviors between nodes connected to other addresses is 99%, BitDAO which in 93%, AssangeDAO(87%), CompoundDAO(75%), KrauseHouse(74%). PoH, Livepeer, MGD and Moloch have the probability for nodes connected via multiple edges 65-68%. We further provide a detailed examination of the voting network characteristics of various DAOs. Specifically, our analysis of the CompoundDAO protocol revealed high similarities in voting behaviors among grassroot users. Our analysis of the BitDAO also revealed similar voting patterns among nodes with higher token holdings, with less cluster distance and a tendency to vote in a similar manner. However, some higher token holders in these DAOs tend to be representative of grassroots compared to those in the CompoundDAO, although they remain polarized We also observed significant overlaps in voting behaviors among different token holders in dxDAO, AssangeDAO and BanklessDAO, with polarized voting behaviors among token holders. In contrast, our analysis revealed a more equitable distribution of voting patterns among different types of token holders for the Proof of Humanity DAO. It might be because a majority of the token holders ($> 99\%$) in this DAO are grassroot users. For Livepeer, we found two main different types of voting behaviors with small overlaps regardless of the token holdings of voters, implying better decentralization and less biased voting patterns dictating upon token holding status. Finally, Meta Gamma Delta (MGD) and MolochDAO, we can not say that their decentralization level is high due to the small number of voters, however, token holding didn't dictate the voting patterns.

*3) Positionality of Whale Addresses:* We utilize the Complementary Cumulative Distribution Function to detect whale addresses in various DAOs based on token holdings. In CompoundDAO, among 2,482 unique addresses, 32 are identified as whales (holding $100k-$10m COMP) in Figure 2c. Nodes are categorized by organization types: green for grassroots, blue for industry, red for educational institutes, and yellow for non-profits. Non-profits align with grassroots, while industry and educational institutes exhibit distinct voting patterns. Among green nodes, 90.6% hold less than 0.25 tokens, but some influential users with whale tokens are labeled as "Key Opinion Leaders." Graphs depict connectivity among significant whale addresses based on voting similarity, impacting



5

CompoundDAO proposal outcomes, with different colored edges representing voting behavior similarities. Identifying organization types in other DAOs is challenging due to the absence of user profiles.

### B. DAO Holders' Proposal Pattern

*1) Factors Influencing Proposal Outcome:* We used logistic regression to analyze if proposers' token holdings influence proposal outcomes. Then, we conducted mixed-effect regression, considering token amount as a fixed effect and id as a mixed effect, and assessed its significance compared to a base model with only id. Additionally, we tested the influence of author addresses on proposal success by comparing models with and without id as a mixed effect. We find a significant positive correlation between the ***"token amount"*** and the proposal outcome (p-value¡0.05) in CompoundDAO, dxDAO and krauseHouse, in particular, for CompoundDAO, we find that token holdings have a significant effect ($p - value = 0.00676$) with an odd ratio of $95\%CI[1.244048, 1.000015]$. Further, the mix-effect analysis also confirms the token holding's significance to proposal success with the ANOVA test ($Pr(> X^2) :> 0.05$). For contextual information, from a total of 128 proposals, 90% were submitted by authors who held significant amounts of tokens. Overall, proposals submitted by organizations (e.g., Alameda Research) and KOLs (e.g., Arr0) had an aggregate success rate of 88.9%. In contrast, proposals submitted by "grassroots users" had a success rate of 50%. Similarly, dxDAO (p-value: $7.25e^{-07}$) and KrauseHouse (p-value: $0.00054$) also show a similar trend. In mixed-effect analysis, author addresses significantly impact proposal success for dxDAO ($Pr(> X^2) : 2.2e^{-16}$). Conversely, token holdings did not show significance for BitDAO, BanklessDAO, and AssangeDAO. However, contextual factors play a role; for example, BitDAO has predefined whitelisted addresses, while BanklessDAO and AssangeDAO have specific author selection criteria. Token holding homogeneity can limit model effectiveness. Notably, BitDAO also yielded a significant result ($Pr(> X^2) : 2.2e^{-16}$) for the "author address" as a mixed effect to enhance proposal success. In contrast, Proof of Humanity, Meta Gamma Delta, and MolochDAO, where anyone can propose, showed no significance for "token holding" concerning proposal success. Although people can delegate their votes, the total vote is $1 + \sqrt{delegatedvote}$ for PoH having an equal number of tokens to vote. For example, if 16 addresses delegate to an address, then the total vote for that address would be $1 + 4 = 5$. This means there is some level of homogeneity across token holding. However, for Proof of Humanity ($Pr(> X^2) : 2.2e^{-16}$) and Meta Gamma Delta ($Pr(> X^2) : 1.02e^{-10}$), we found a significance of *"author address"* to increase the possibility of proposal success.

### C. DAO Holders' Voting Power

*1) Evaluation of Decentralization Levels:* We initially analyzed the correlation between voters' token weight and participation rate to assess potential bias toward wealthy token holders. A positive correlation suggests richer voters' more active participation, potentially undermining decentralization, as summarized in Table IV for 10 DAOs.

Next, we evaluated the decentralization level of 10 DAOs in terms of voting power. To do this, we used three metrics: Entropy, the Gini, and Nakamoto coefficient. Entropy can be generally used to assess randomness and degrees of freedom for a given system. Mathematically, the metric for given a series of numbers $x(= x_i)$ is defined as follows:

$$Entropy(x) = \sum_i log_2 \left( \frac{x_i}{\sum_i x_i} \right) * \frac{x_i}{\sum_i x_i}.$$

If the value of entropy is high, it implies a DAO has a high degree of randomness and freedom, which is related to a high level of decentralization. The Gini coefficient used to measure wealth inequality traditionally can be applied to assess the voting power inequality among voters in our analysis. The metric for given a series of numbers x is defined as follows:

$$Gini(x) = \frac{\sum_{i,j} |x_i - x_j|}{2|x| \sum_i x_i},$$

where $|x|$ indicates the length of the number series. We computed Gini and Entropy metrics using voters' token weight and their participation rate, defined as "token weight multiplied by the number of proposals they participated in." A Gini coefficient of 0 signifies perfect equality, while 1 indicates full power concentration. The Nakamoto coefficient reflects the minimum entities required to subvert the system, highlighting the importance of avoiding significant power concentration for true DAO democracy. We calculated the Nakamoto coefficient based on voters' token weight. Table IV highlights widespread poor decentralization in most DAOs. Specifically, Compound, BitDAO, Krausehouse, LivePeer, Meta Gamma Delta, MolochDAO, and dxDAO exhibit significant decentralization issues, with Gini coefficients above 0.9 due to power inequality and/or low Entropy values stemming from limited voter participation. In contrast, Proof of Humanity demonstrates the highest decentralization, relying on a one-person-one-vote protocol instead of token-weighted voting. It's essential to note that this analysis doesn't conclusively favor one protocol over another; for instance, despite a similar protocol, Meta Gamma Delta faces challenges due to a low number of active voters.

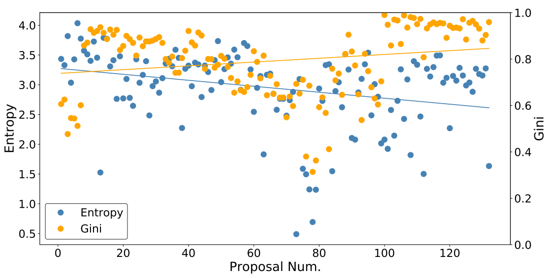
*2) Decentralization Dynamics Overtime:* We also present the decentralization dynamics over time. Table V summarizes the linear regression results of 10 DAOs, where we mark significantly negative and positive decentralization trends with red and blue, respectively. Overall, we can see that many DAOs (CompoundDAO, BitDAO, AssangeDAO, BanklessDAO, and KrauseHouse) show a significantly negative decentralization trend: the decreasing decentralization level over time (Figure 3a). On the other hand, Proof of Humanity and MGD have a significantly positive decentralization trend: the increasing decentralization level over time (Figure 3b). Note that, according to Table IV, in the Proof of Humanity system, a biased participation rate of voters is more a matter rather than a biased token weight distribution in terms of



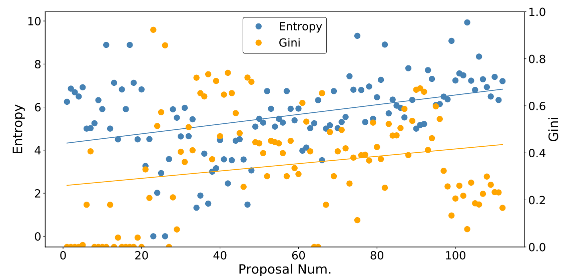
6

| Name | Corr. | P-value | Entropy (Token) | Entropy (Voting score) | Gini (Token) | Gini (Voting score) | Nakamoto | The num. of voters |
|---|---|---|---|---|---|---|---|---|
| CompoundDAO | 0.27 | 3.32E-44 | 5.86 | 5.17 | 0.98 | 0.99 | 15 | 2483 |
| BitDAO | 0.21 | 0.0005 | 3.9 | 3.35 | 0.96 | 0.97 | 6 | 284 |
| AssangeDAO | 0.24 | 4.69E-15 | 7.83 | 7.42 | 0.84 | 0.87 | 50 | 1066 |
| Proof of Humanity | 0.38 | 2.18E-108 | 11.46 | 8.85 | 0.05 | 0.73 | 1448 | 3086 |
| Bankless DAO | 0.05 | 0.003 | 9.95 | 9.13 | 0.7 | 0.84 | 268 | 3234 |
| KrauseHouse | 0.05 | 0.15 | 5.59 | 4.68 | 0.91 | 0.95 | 7 | 592 |
| LivePeer | 0.5 | 3.57E-27 | 5.36 | 4.63 | 0.91 | 0.95 | 9 | 368 |
| MetaGammaDelta | -0.89 | 1.99E-07 | 4.22 | 3.62 | 0.03 | 0.51 | 9 | 19 |
| MolochDAO | 0.18 | 0.51 | 2.37 | 1.823 | 0.73 | 0.81 | 2 | 15 |
| dxDAO | 0.03 | 0.57 | 6.21E-12 | 1.25E-11 | 0.99 | 0.99 | 1 | 278 |

TABLE IV: Evaluation of decentralization levels through correlation analysis and three metrics: Entropy, Gini coefficient, and Nakamoto.




(a) CompoundDAO Decentralization Level Overtime




(b) Proof of Humanity: Decentralization level over time

Fig. 3: Voting Power Evaluation of decentralization level by Entropy, Gini coefficient, and Nakamoto showed significantly poor decentralization for Compound, BitDAO, Krasehouse, MolochDAO, and dxDAO while the highest decentralization level for Proof of Humanity. The decentralization level of PoH is in increasing trend over time.

| Name | Entropy | Gini |
|---|---|---|
| CompoundDAO | -0.0050 (0.001) | 0.0008 (0.015) |
| BitDAO | -0.0275 (0.490) | 0.0341 (0.000) |
| AssangeDAO | -0.3010 (0.038) | 0.0005 (0.934) |
| Proof of Humanity | 0.0226 (0.000) | 0.0016 (0.020) |
| BanklessDAO | -0.0568 (0.000) | 0.0067 (0.000) |
| KrauseHouse | -0.0048 (0.014) | 0.0002 (0.507) |
| LivePeer | -0.0065 (0.903) | 0.0023 (0.571) |
| MGD | 0.0194 (0.000) | 0 |
| MolochDAO | 0.0125 (0.345) | 0.0063 (0.358) |
| dxDAO | 0.0050 (0.128) | 0.0002 (0.702) |

TABLE V: Decentralization Level Over time. Each value indicates a slope of a linear regression analysis, and the values in parentheses indicate the p-value.

a decentralization level; entropy and the Gini coefficient for voters' token weight are high and low, respectively. Therefore, we focus on the linear regression result for Entropy rather than that for the Gini coefficient. One can find that both DAOs, Proof of Humanity and MGD, are systems adopting the one-person-one-vote protocol. As a result, the level of decentralization has got better over time in the one-person-one-vote protocol.

## VII. RQ3: Autonomy of DAOs

For the DAO autonomy analysis, we explore (1) whether a DAO system can execute arbitrary transactions, (2) whether it relies on third parties after transaction execution, and (3) whether proposals have been canceled after being successful.

### *A. Capability of Arbitrary Transaction Execution*

Arbitrary transaction execution in a DAO enables it to fulfill various proposals without being restricted by specific requirements. We assessed 10 DAOs for their ability to execute arbitrary transactions via smart contracts, revealing varying autonomy levels . DAOs like CompoundDAO, Meta Gamma Delta, Moloch, and dxDAO, utilizing on-chain voting, demonstrate high autonomy with a comprehensive process for voting, consensus, and execution. Conversely, DAOs with off-chain voting, including AssangeDAO, BitDAO, Bankless, KrauseHouse, and LivePeer, rely on methods like multisig wallets, sacrificing decentralization and autonomy for simplicity in implementation and maintenance. Additionally, community members can refine on-chain transactions for approved proposals through a system involving monetary stakes, as exemplified by the Kleros Governor contract [27], adopted by Proof of Humanity. While more decentralized than multisig wallets, this approach introduces verification steps by multiple parties, potentially delaying execution. Proof of Humanity follows the Kleros Governor contract [27], which, while more decentralized than a multisig wallet, limits autonomy due to multiple parties needing to verify proposed transactions, potentially causing execution delays.

### *B. Third Party Dependency in Proposals*

The reliance on external entities to fulfill proposals after the voting period is commonly known as third-party dependencies. Analyzing the relationship between DAOs and third parties can not only aid in evaluating autonomy but also provide insight into how DAOs currently benefit from third-party services, minimizing risk exposure. Third-party dependent proposals involve external entities fulfilling parts of proposals post-voting, future service payments or decision delegation to a small group. We investigate this by analyzing



7

| Name | 1 (not reliance) | 0 (reliance) |
|---|---|---|
| AssangeDAO | 81.81% | 18.18% |
| CompoundDAO | 83.94% | 16.06% |
| BitDAO | 72.22% | 28.78% |
| Proof of Humanity | 86.54% | 13.46% |
| Bankless DAO | 70.59% | 29.41% |
| KrauseHouse | 25.19% | 74.81% |
| LivePeer | 85.71% | 14.29% |
| Meta Gamma Delta | 100% | 0% |
| MolochDAO | 84.84% | 15.15% |

TABLE VI: Percentage of proposals that relies on third-party services after execution. Rows are each DAOs where 0 means relying on a third party and 1 is not reliance

| DAOs | Binding | Total Prop | Total Prop Passed | Proposal Passed but Did Not Get Executed | Total Unknown Status |
|---|---|---|---|---|---|
| CompoundDAO | Proposer can cancel | 137 | 110 | 6 | 0 |
| dxDAO | Binding | 789 | 678 | 0 | 0 |
| LivePeer | Not binding | 7 | 7 | 0 | 0 |
| MolochDAO | Binding | 25 | 25 | 0 | 0 |
| MetaGammaDelta | Binding | 75 | 69 | 0 | 0 |
| AssangeDAO | Not binding | 11 | 10 | 0 | 0 |
| BitDAO | Not binding | 18 | 16 | 0 | 2 |
| BanklessDAO | Not binding | 51 | 48 | 0 | 2 |
| ProofOfHumanity | Not binding | 104 | 87 | 9 | 5 |
| KrauseHouse | Not binding | 131 | 113 | 14 | 44 |

TABLE VII: Proposal decisions in DAOs where are whether the consensus is binding through: smart contract timelock that cant be canceled, smart contract timelock that can be canceled by proposer, multisig, or single wallet.

proposal content and execution data, assessing whether post-execution actions deviate from the proposal's objectives, potentially undermining DAO effectiveness (Table VI ). Among the examined DAOs, only MetaGammaDelta DAO doesn't rely on third-party services post-execution, as its proposals typically involve membership requests or funding without return promises.KrauseHouse has the highest percentage of third-party dependent proposals at 74.81%, often involving funding requests from third parties with commitments of future returns in the form of work hours. While relying on third-party services can benefit DAOs, especially for off-chain objectives, mitigating associated risks is crucial. Our analysis identified strategies used by DAOs to reduce these risks, including (a) employing stream payments instead of upfront lump sums, (b) implementing milestone-based payments tied to completed tasks, and (c) appointing a committee with a multisig wallet to manage funds allocated for third-party services.

### C. Proposals Canceled after Voting Ends

We examined proposals that were accepted but not implemented, referred to as *"canceled proposals."* This measure assesses community consensus and DAO autonomy, examining on-chain DAOs' smart contracts and off-chain DAOs through Snapshot and Discourse. Some DAOs, like Meta Gamma Delta, MolochDAO, and dxDAO, have "binding" consensus, executing proposals via smart contracts without cancellation. CompoundDAO and Livepeer allow formal cancellation mechanisms. CompoundDAO permits the author or others to cancel if the author's token balance drops, mainly due to parameter issues or bug fixes (Table VII). LivePeer's multisig can still cancel proposals after consensus. Off-chain DAOs lack guaranteed on-chain consensus, making it challenging to calculate the percentage of canceled proposals accurately.

## VIII. Discussion

**Incentive mechanism: separation between voting power and monetary value.** Our research confirmed that biased voting power distribution and low participation rates in many DAOs stem from a lack of suitable incentive systems [28]. While the optimal incentive designs for decentralization remain unclear, DAO practitioners can consider several options to address this issue. They can opt for nontransferable/non-monetary vote tokens or explore social rewards like reputation-based and contribution-based voting, such as one person, one vote. Studies [29, 30] have shown that social rewards can effectively boost user engagement in the DAO context. Alternatively, DAOs with transferable voting tokens can adopt a quadratic voting scheme, making it increasingly expensive to purchase unit voting power as users acquire more tokens.

**AI-based intervention protocol with bubble-bursting fact-checks.** Fact-checking and moderation have been devised to encourage users to explore a wider range of viewpoints, transcend social media echo chambers, and ultimately decrease political and cultural polarization [31, 32]. In DAOs, whales often vote similarly due to limited technical knowledge, following trusted leaders. To address this, an intervention protocol, like an ML-based recommender system, can enhance information credibility, encouraging DAO participants to better understand proposals and make informed voting decisions. This benefits both whales and grassroots voters.

**Onchain proposal pipeline for autonomy & UX.** Off-chain tools like Snapshot provide gasless and verifiable voting but often hinder decentralization due to manual off-chain-to-on-chain translation by a small group. One solution is to move the entire proposal process on-chain, offering more transparency and autonomy, although it's harder to deploy and maintain. User-friendly tools for fully on-chain DAO systems can bridge this gap, featuring on-chain capabilities like stream payments and binding consensus, reducing reliance on third-party services. Fully on-chain DAOs allow any user to help execute proposals, addressing delays, and monetary incentives can further motivate prompt action.

**Fully automated tracking tools for proposal transparency.** Many third-party dependent proposals lack transparency during execution, leaving some with unknown status post-voting. Achieving consensus alone doesn't guarantee autonomy; DAO actions must be verifiable. While some tools like Notion are used to publicly post and interpret DAO actions, there's a lack of adoption for fully automated tools that track proposal status from start to finish. In DAOs heavily reliant on third parties, these tools are vital for informed decisions on compensation and future employment.

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8

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9