RESEARCH

An Intelligent Framework for the Management of Fractional Ownership of Digital Assets through Decentralised Autonomous Organisations (DAO)

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Abstract
With blockchain technology, digital asset ownership and governance paradigms have undergone profound changes. Decentralised Autonomous Organisations (DAOs) and fractional non-fungible tokens (F-NFTs) have emerged as pivotal mechanisms for managing shared digital assets that are secure, transparent, and participatory. In many existing F-NFT implementations, initial fractionalisation and trading are emphasised. However, subsequent lifecycle governance, including metadata evolution, share redistribution, and retirement, is handled off-chain or via ad-hoc arrangements, which creates operational and accountability gaps. Therefore, a governance framework based on DAO is proposed for F-NFT management in this paper. A fractionalized asset is governed by rules, quorum thresholds, and life-cycle transitions embedded in smart contracts on the blockchain. These contracts automatically execute token-weighted, proposal-driven outcomes without human intervention. In this paper, 'intelligence' refers to rule-based automation and verifiable state transitions encoded in smart contracts, rather than machine-learning-based decision-making. Digital assets are managed through a proposal-driven governance mechanism that decentralises authority, automates decision-making, and maintains transparency. There are three primary categories of proposals embedded in the system: (i) updating metadata to adapt to the underlying digital assets, (ii) redistributing fractional ownership in accordance with evolving stakeholder agreements, and (iii) retiring assets to dissolve ownership and legally distribute value. The DAO enforces ownership rules securely and verifiably through smart contracts and token-based governance, mitigating centralisation and fraud. The study provides empirical insights into the viability of the framework for co-owned digital asset ecosystems by evaluating its operational performance and scalability and discussing the implications for governance effectiveness. Based on our findings, DAO-enabled F-NFTs present an innovative mechanism for collaborative ownership in a transparent, democratic, and tamper-proof blockchain environment. As a result of the paper, a contribution is made to the governance and management of F-NFTs in digital asset ecosystems through presenting the framework conceptually and practically.

Keywords Fractional Non-Fungible Tokens (F-NFTs) · Smart Contracts · DAO · NFT · Digital asset · Fractional ownership



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1 Introduction

Digital asset ownership has been transformed by blockchain technology, which has introduced novel models that disrupt conventional paradigms. There have been several innovations among these. However, Non-Fungible Tokens (NFTs) have emerged as a significant innovation in representing unique digital and physical assets on decentralised ledgers. Using NFTs, one can verify provenance, track ownership transparently, and transfer assets securely without centralised intermediaries [53]. The use of NFTs has subsequently expanded beyond digital art and collectibles to a variety of other fields. In addition to real estate, automotive assets, gaming ecosystems, and intellectual property management, these domains are also included.

Fractional non-fungible tokens (F-NFTs) represent a significant advancement in this trajectory, since they allow ownership to be subdivided into fungible units. As a result of this model, multiple stakeholders can hold proportional rights to a single asset. This lowers investment barriers, enhances liquidity in otherwise illiquid markets, and enables a wider range of asset classes to be accessed [57]. In spite of these advantages, F-NFTs present a number of governance and operational challenges. The key challenges include the coordination of decisions among distributed stakeholders, designing equitable mechanisms for buyouts and reconstitutions, ensuring the security of smart contracts, and navigating the evolving legal and regulatory landscapes [29].

Recent years have seen a substantial increase in the number of tokenised digital assets. The Grand View Research estimates that the global NFT market will exceed USD 200 billion by 2030, despite large swings in trading volumes and valuations [13]. In addition, it is predicted that the global market for tokenized representations of real-world assets will reach USD 16 trillion by 2030, primarily due to the adoption of tokenization in finance and capital markets by institutions [4]. Currently, DAOs control on-chain treasuries worth billions of dollars, demonstrating the importance of on-chain governance in the management of tokenised assets [41]. Due to the rapid growth of token value and the complexity of collective ownership arrangements, fractional NFT governance frameworks are becoming increasingly important.

Fractional NFT (F-NFT) is a technology that enables access to high-value NFTs, as well as real-world assets, by breaking an ERC-721 or ERC-1155 token into multiple fungible token shares [53]. Despite improving liquidity and lowering entry barriers, this creates challenging governance and risk management challenges [47]. These challenges include reconstitution complexity, information asymmetry between fractional owners, and the possibility of scams or governance failures on opaque or poorly regulated platforms. As a result, F-NFTs carry several risks, which is why a comprehensive approach to governance is necessary. This includes the management of proposals over their life cycles, the redistribution of ownership, and the retirement of assets under transparent and auditable guidelines.

There are currently several platforms for shared digital asset ownership. Existing platforms typically use multi-signature wallets, centralised custodians, or off-chain contractual arrangements [9]. A multi-signature scheme and a shared custody wallet enable several parties to co-sign transactions, but their expressiveness for complex governance rules is limited, and their decision processes are largely transparent on the blockchain. It may be possible to manage sales, revenue distribution, and buyouts with centralized fractionalization platforms; however, this reintroduces a trusted intermediary and reduces the ability to audit the platform. As a result of our work, the entire lifecycle of F-NFT governance, including routine updates, redistribution, and retirement, is encoded directly in a DAO-governed smart contract framework.

This study aims to address these limitations by integrating a Decentralised Autonomous Organisation (DAO) into F-NFT management. By using on-chain voting mechanisms linked to ownership stakes, DAOs facilitate automated, transparent, and participatory decision-making and ensure governance processes are proportionate, verifiable, and resistant to centralization [11]. As a result of incorporating DAO governance into the full lifecycle of a fractional ownership model, stakeholder trust is strengthened. In addition, operational efficiency is enhanced, and fractional ownership models are more resilient. Through this approach, the economic and governance potential of

fractionalized digital asset ownership in decentralised markets is fully realized. By using a DAO-governed smart contract framework, our work encapsulates the entire F-NFT governance lifecycle directly.

Therefore, a Decentralised Autonomous Organisation (DAO) is proposed as the mechanism for managing and governing such digital assets. The concept of intelligence in our context does not refer to machine-learning-based or predictive contracts. Instead, it refers to the systematic encoding of governance logic proposal types, quorum thresholds, and state transitions into smart contracts that automatically execute agreed decisions upon meeting certain voting conditions [50]. This DAO facilitates participatory governance by enabling co-owners to propose, vote on, and implement changes to assets, such as updating the metadata for the digital asset. Through smart contracts, decision-making processes can be democratised and encoded, ensuring transparency, accountability, and resistance to centralisation.

An early and prominent implementation of Decentralised Autonomous Organisations (DAOs) on the Ethereum blockchain is the DAO, which was launched in 2016 [43]. It was ultimately exploited by a critical smart contract vulnerability and generated over $150 million in Ether. An Ethereum hard fork was subsequently triggered as a result of this. The blockchain community is focused on strengthening security protocols and governance frameworks in the post-DAO era, leading to more resilient and structured DAO models. The advent of decentralised finance (DeFi) and non-fungible tokens (NFTs) in 2020 has significantly accelerated the adoption of DAOs, with many contemporary projects utilizing DAOs for decentralised governance, funding allocation, and stakeholder coordination [17]. In addition to finance, DAOs are increasingly gaining traction in fields such as digital art, gaming, and social innovation, where they facilitate resource management and decision-making. Due to the rapid growth and global relevance of DAOs, regulatory scrutiny has increased.

Through a proposal-based governance model, this paper introduces a set of intelligent mechanisms for managing the lifecycle of fractional non-fungible tokens (F-NFTs). Specifically, the framework supports three core categories of proposals: (i) updating the metadata for the digital asset, which enables modifications to the underlying digital asset; (ii) redistribution of ownership, which allows co-owners to adjust fractional allocations; and (iii) asset retirement, which enables the disposition of fractionalized NFTs. Through smart contracts, these mechanisms are embedded within a decentralised architecture that ensures transparency, consensus-driven decision-making, and secure execution.

As a result of the DAO-driven governance mechanism, co-owned digital assets are preserved, and a collaborative environment is fostered that enables innovation. A key advancement in digital asset management is the integration of F-NFTs with DAO frameworks. Three factors contribute to the advancement of the state of the art in this article. First, a proposal-driven governance structure is introduced that organises the F-NFT lifecycle into three functionally distinct proposal categories: metadata updates, fractional ownership redistribution, and retirement of digital assets. Second, it provides a complete smart-contract implementation that combines a token contract for fractional ownership with a DAO governance layer to capture the full asset-creation process, fractionalization, and eventual retirement. A third component of this paper is to empirically evaluate the performance of these proposal categories and their scalability. A statistical analysis of gas consumption and execution latency is provided under varying proposal loads. Therefore, our empirical analysis indicates that the proposed governance framework can process batches of proposals with predictable gas and latency overheads. It has been demonstrated in the study that Standard proposals are efficient enough to be used frequently, whereas Contract Break and Retirement proposals remain effective when dealing with infrequent structural changes or asset disposals, despite being more expensive. By addressing long-term, on-chain governance of co-owned digital assets, these contributions enhance prior studies on F-NFT architectures and digital asset ownership that focused on asset fractionalization and marketplace [3]

The following describes how the remainder of the paper is structured. In Sect. 2, we discuss related work on fractional NFTs, DAO-based governance, and blockchain-enabled digital asset management. Section 3 describes the design requirements and architecture of the proposed intelligent DAO-based framework for co-ownership of F-NFTs. Section 4 provides a detailed description of the smart-contract design and lifecycle for each category of proposal. In Sect. 5, gas consumption, execution time, and the scalability of all proposal types are empirically

evaluated. Section 6 summarises the study's key findings. Section 7 concludes by discussing the limitations and future directions.

2 Related Work

With the advent of Fractional Non-Fungible Tokens (F-NFTs), considerable interest has been generated among academics and industry participants as a means of enabling collective ownership of high-value digital and physical assets. It is evident from the literature that a wide range of technological and governance frameworks are available to alleviate the complexity associated with fractional ownership. These frameworks are available particularly in the areas of asset divisibility, secure exchange, interoperable governance, and reconstitution of assets.

In most cases, ERC-721 or ERC-1155 NFTs are fractionalized into fungible ERC-20 tokens to facilitate divisible ownership. As a result of this architecture, assets are able to trade on decentralised markets with enhanced liquidity and tradeability. According to empirical studies [5]and [6], ERC-20-based implementations exhibit improved gas efficiency and scalable transaction performance, making them suitable for high-frequency transactional ecosystems.

In response to fragmentation and security limitations of existing implementations, [15] developed a standardised framework for F-NFT that is focused on secure deployment and cross-platform compatibility. They emphasise the need for uniform smart contract protocols to protect F-NFT systems deployed on heterogeneous platforms from critical vulnerabilities.

There are a number of examples of co-ownership governance models, such as those proposed by JOINFT, that integrate smart contracts with provenance data and trust scoring systems off-chain [1]. The authors demonstrate the utility of tokenised fractional investment schemes in real estate applications, where collective control, transparency, and affordability are achieved through tokenised fractional investment schemes.

Similarly, full ownership is reconstitutable from distributed fractional stakes, another core challenge addressed in the literature. In [42], a Bayesian Stackelberg game-theoretic model is presented to operationalise fair buyout protocols, enabling asset consolidation, while preserving fairness in a distributed system.

Nonetheless, the regulatory landscape remains underdeveloped. According to the legal scholarship, F-NFTs should be defined within the framework of securities and property law, with particular attention being paid to voting rights, investor protections, and revenue distributions [52]. As a result of an absence of legal clarity, mainstream adoption is hindered, and co-ownership agreements are limited.

Several different verticals have also explored the potential of F-NFT implementations. Fractional investment and streamlining of smart contracts have been successfully applied to the real estate sector [2] and automotive sector [51]. It is based on ERC-1155 standards, which support the issuance of multiple tokens and the automatic execution of ownership rights [34].

As well as the F-NFT-specific design, additional foundations for our framework are provided by the broader work on blockchain security and governance. The study by [30] developed a generative adversarial learning strategy that identifies smart-contract vulnerabilities automatically. Additionally, there are separate chapters devoted to examining attacks and defence mechanisms on blockchain systems in the Metaverse and Blockchain Use Cases and Applications [44]and [8]. Their research explores how distributed ledgers maintain privacy, data integrity, and accountability. For reliable and decentralised applications, the paper [27] discussed the interplay between distributed consensus and fault-tolerant mechanisms in blockchain networks. The implementation of blockchain-based electronic voting systems further illustrates how immutable audit trails, token-based voting, and end-to-end verifiability can be used in practice to assist with collective decision-making [50]. Additionally, domain-specific frameworks for addressing open-access copyright, detecting financial fraud with Hyperledger, and authenticating academic certificates demonstrate how blockchain provenance and smart contracts can be integrated into complex multi-party business processes [23, 33] and [7]. It is conceptually aligned with these

efforts; however, it emphasises the co-ownership decisions that govern the creation, redistribution, and retirement of fractionalised NFTs.

In addition to F-NFT-specific research, a growing body of research emphasises that to ensure secure and durable software systems, performance prediction, risk assessment, and usable security must all be taken into account [21, 38] and [25]. Previous studies demonstrating the benefits of statistical and soft-computing techniques for predicting software failures and guiding maintenance strategies have been carried out [37] and [39]. As a result, recent work on software durability, dependability, trustworthiness, usability, security, and human trust is integrated into a unified perspective. This emphasises the importance of a long-lived, maintainable software infrastructure. Furthermore, complementary studies have proposed hesitant-fuzzy, AHP, and TOPSIS-based decision models for evaluating and comparing security postures in software and web applications [24] and [26]. F-NFT governance frameworks are designed based on these insights, with robustness, maintainability, and human-centred security properties prioritised in conjunction with functional requirements.

Meanwhile, domain-specific studies have highlighted the importance of rigorous security architectures in environments with high stakes and high data volumes. Cybersecurity research has proposed strategies for combating deep fake-driven disinformation campaigns, highlighting the importance of robust threat models and integrity controls [20]. Decentralised finance frameworks that promote end-to-end security involve smart contracts, Oracles, and off-chain components [35]. Telemedicine poses similar concerns due to the need for reliable interoperability between heterogeneous systems to ensure patient data protection during real-time information exchange [36]. A recent study on the use of distributed-ledger technologies to secure communication protocols within military computing, as well as the use of blockchain to secure military systems, illustrates how these technologies can be used to safeguard mission-critical infrastructures by combining them with strong security governance [22] and [19]. In combination, these strands reinforce the need for frameworks of F-NFT governance based on DAOs that address issues such as integrity, accountability, and resilience to adversarial behaviour.

Although these developments have been made, a persistent challenge remains: how to facilitate decentralised, trustless coordination among fractional stakeholders in a scalable, secure, and transparent manner. As a result of this gap, dynamic governance, asset reconstruction, and profit-sharing scenarios are particularly salient.

2.1 Comparison with Deployed Fractionalisation Platforms

In addition to the academic and conceptual frameworks discussed above, several production-grade fractionalisation protocols have been developed in the past few years, such as Fractional.art and NFTX [12, 31, 45]. These platforms tend to prioritise fungible shares and liquidity mechanisms. In addition, they offer heterogeneous and often limited support for post-fractionalization governance, including metadata updates, ownership redistribution, and retirement. To clarify the specific governance scope addressed in this paper, we present a feature-level comparison that contrasts (i) lifecycle coverage across updates, redistributions, and retirement actions and (ii) the degree to which governance decisions and their execution are encoded entirely on the blockchain versus depending on off-chain coordination. The analysis exposes a persistent governance gap in the long-term management of co-owned assets and directly motivates the development of the DAO-governed lifecycle model.

Because deployed fractionalisation platforms are designed around different transaction workflows and objectives, it is important to note that comparing a direct head-to-head gas benchmark with Fractional's vault-based fractional ownership model governed by ERC-20 and NFTX's vault-based liquidity model using fungible vTokens would not be methodologically comparable. This Table 1 presents feature-level comparisons based on assumptions regarding governance and execution. While Sect. 5 presents our internal performance evaluation (gas consumption and execution latency) for our proposal-driven lifecycle operations.

This study addresses the limitations described above in F-NFT governance by integrating a Decentralised Autonomous Organisation (DAO) as a foundational layer for managing co-ownership structures. Using DAOs, decision-making processes are programmable, transparent, and verifiable through the encoding of governance rules within smart contracts as well as the allocation of voting rights proportionally among token holders [40].

Table 1 Feature-level comparison

Dimension	Our DAO lifecycle framework	Fractional.art [45]	NFTX [31]
Primary focus	Governance of full lifecycle (update, redistribution, retirement)	Fractionalisation + token governance over vault NFT(s)	NFT liquidity via vaults and fungible vTokens
Governance primitive	On-chain proposals + execution	Vault governance mechanisms over NFTs (protocol-level)	Vault mechanics; governance depends on protocol design
Lifecycle actions covered	Update, redistribute, retire	Emphasises fractional ownership + governance over held NFTs	Emphasises wrapping/redeeming/liquidity for NFT sets
Retirement/dissolution	Explicit retirement proposal + distribution	Buyout/auction style mechanisms (vault-oriented)	Exit via redeem/swap depending on vault rules
Evaluation in this paper	Gas + latency under proposal loads	(Qualitative comparison)	(Qualitative comparison)

There are several advantages to using a DAO-based model:

- Governance aligned with stakeholder interests: Token-weighted voting promotes accountability and participatory control by ensuring decision-making power reflects ownership proportions.
- Transparency on the blockchain: All proposals, votes, and governance actions are recorded immutably on the blockchain, providing greater auditability and stakeholder confidence.
- Elimination of intermediaries: DAO frameworks eliminate the need for centralised administrative bodies, which aligns with blockchain infrastructure decentralisation.

The DAO mechanism enables fractional owners to collaborate on managing shared assets, initiating buyout processes, and resolving disputes in a consensual and rule-bound manner [49]. As our DAO-based framework for fractionalized NFT governance aligns conceptually with these efforts, it focuses specifically on the ownership decisions that govern the creation, redistribution, and retirement of fractionalized NFTs. As a result of embedding DAO logic into the fractionalization process, the proposed governance mechanism addresses many of the critical research gaps identified in previous studies. In particular, these gaps relate to scalability, legal resilience, and operational transparency. The following sections discuss the architectural design, the implementation of smart contracts, and the empirical evaluation of the DAO-integrated F-NFT framework.

3 An Intelligent DAO Framework Based on F-NFT Management of Digital Assets

This paper presents a novel and intelligent method for fractional NFT management of digital assets using a Decentralized Autonomous Organization (DAO). The concept of the Decentralized Autonomous Organization(DAO) represents a new type of organization that operates without traditional management structures and uses blockchain technology [18]. To enable collective ownership and management of fractional non-fungible tokens (F-NFTs), the proposed method uses smart contracts as shown in Fig. 1. A DAO ensures transparency, security, and decentralized decision-making through blockchain technology. Through this approach, multiple F-NFT owners can participate in the governance and monetization of digital assets efficiently and equitably. Through the DAO, token holders can collaborate seamlessly, vote on key decisions, allocate resources, and share profits transparently. A further advantage of this method is that it eliminates intermediaries, thereby reducing costs and enhancing efficiency. An innovative framework such as this could revolutionize digital asset management within the rapidly evolving NFT ecosystem.

The following Fig. 2 illustrates the process of managing digital assets owned collectively by fractional NFTs (F-NFTs). This diagram illustrates a process by which collective owners of assets can make democratic decisions.

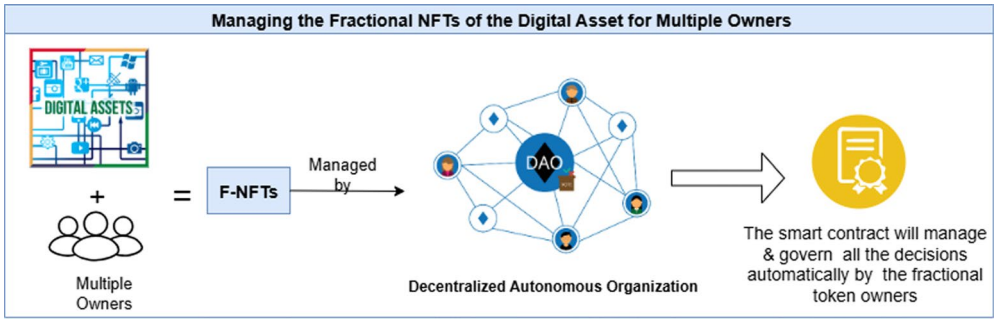


Fig. 1 The DAO-based F-NFT Management

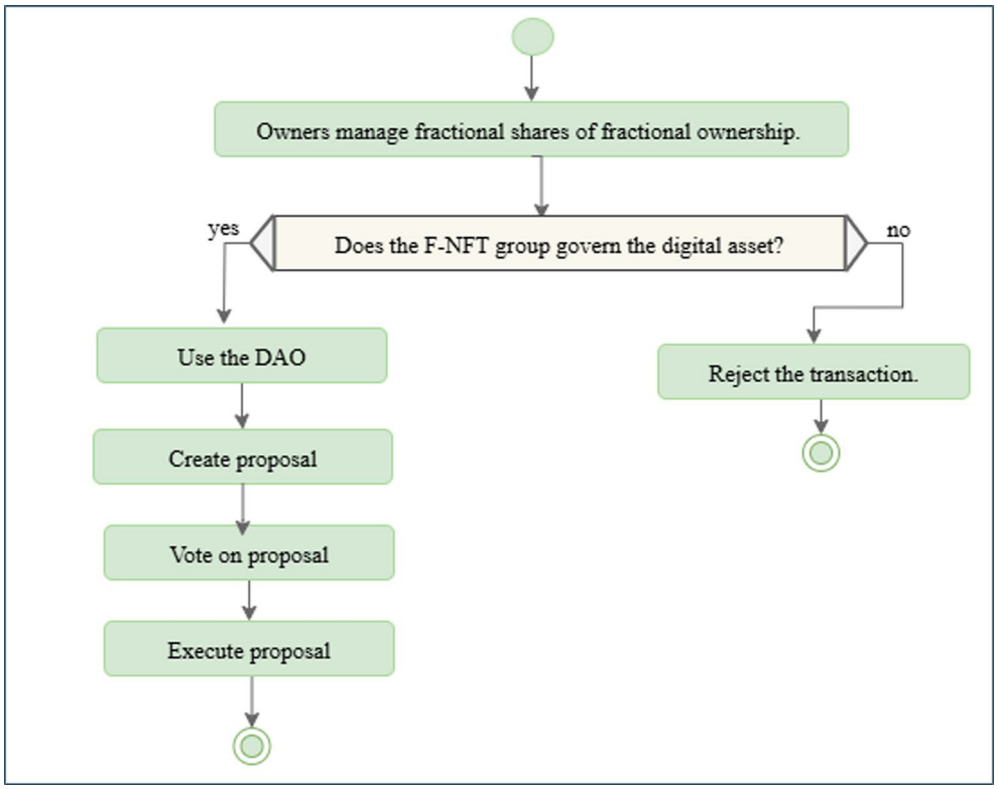


Fig. 2 The DAO Mechanism

Using a DAO, they can propose, vote on, and perform automatic actions related to the shared digital asset if they have the authority to do so.

To understand our DAO solution for managing the F-NFTs of token holders in the digital asset, we must first comprehend the operational resilience and conceptual sophistication of Decentralized Autonomous Organizations (DAOs).

- DAO Functionality: Technical Infrastructure DAOs are based on blockchain technology, which is a distributed ledger that records all transactions, procedures, and governance activities transparently. Using this cryptographic infrastructure, data is ensured to remain tamper-resistant, verifiable, and auditable, eliminating the need for centralised financial or legal intermediaries. In a DAO, smart contracts are embedded in the blockchain and serve as the autonomous execution layer. A self-executing protocol executes business logic, automating processes such as fund allocation, membership verification, and proposal ratification [16]. For example,

when a funding proposal is approved, token disbursement is automatically triggered, eliminating the need for human intervention. With smart contracts, all stakeholders can independently audit the logic underpinning the contract, thereby ensuring that trust and procedural integrity are maintained. Parallel to these activities, governance tokens serve as the primary means of engaging stakeholders in the process. Voting rights are conferred by these tokens as well as membership in the DAO, and they can indicate economic interest in the direction in which the DAO will take. Developing governance systems that reward long-term engagement while mitigating risks of disproportionate control is made possible with their programmable properties, such as fixed supply and stake incentives.

- Decentralisation of decision-making: Governance mechanisms The DAO governance mechanism is typically initiated through a proposal submission process, where qualified participants may submit proposals for consideration based on their token ownership status. A proposal can range from technical upgrades to strategic funding decisions and is usually formatted with standard templates to ensure clarity and facilitate structured decision-making. Through this bottom-up approach, community members can participate in organisational trajectory creation. Voting systems are used to govern the governance of a DAO. One of the most popular voting models is token-weighted voting, which distributes power proportionally to token holdings [48]. This alignment aligns voting power with financial stakes but also raises questions about equity and centralisation. Smart contract-enforced rules, such as quorum requirements or supermajority thresholds, often enhance outcomes' legitimacy. To ensure maximum transparency, voting may be conducted on the blockchain while reducing gas fees through platforms such as Snapshot. Final decisions will be recorded on the blockchain and verified later.

3.1 Framing Governance Proposals in DAOs for Managing Fractional Ownership:

In the governance framework of the proposed DAO, three distinct proposal types are illustrated in the accompanying Fig. 3, which represent the operational workflows through which fractional ownership holders collaborate on managing their digital assets. In this way, a transparent and systematic process is established for initiating, deliberating, and executing key decisions concerning shared ownership assets throughout the lifecycle.

As a result of a functional decomposition of the F-NFT lifecycle, three proposal types have been identified that reflect governance points relevant to the lifecycle. Type I (Standard) proposals represent routine, non-disruptive activities, such as metadata correction or recording of off-chain decisions on the blockchain. In Type II (Contract Break) proposals, ownership distribution is altered among token holders. In Type III (Retirement) proposals, terminal events within the life cycle of the underlying asset are considered, such as the sale or retirement of the asset. In these circumstances, ownership claims must be resolved and residual value distributed. A majority of existing F-NFT platforms provide mechanisms for Type I actions, but redistribution and retirement are usually handled off-chain or through ad hoc contracts, leading to legal and operational uncertainty [14]. A feature-level comparison of deployed platforms is provided in Sect. 2.1. This framework addresses the main governance challenges of F-NFT ecosystems by explicitly modelling all three categories: continuous adaptation of asset information, fair reallocation of ownership, and an orderly, consensus-driven exit. Figure 3 illustrates the process for submitting these proposals. Each of the three governance pathways is described in the sections below.

Proposal Type I: A Standard Proposal

DAO Standard Proposals serve as a foundational mechanism within the DAO to facilitate off-chain decision-making and gauge community consensus about strategic issues relating to digital asset management, especially in instances where smart contracts cannot be immediately implemented. A proposal type can be used to initiate discussions, signal intent, or approve actions taken off-chain, such as updating the metadata for the digital asset, since it is a digital asset and does not trigger automated responses on-chain. A DAO's primary function is to align community sentiment and establish consensus on issues that impact the organization's long-term direction.

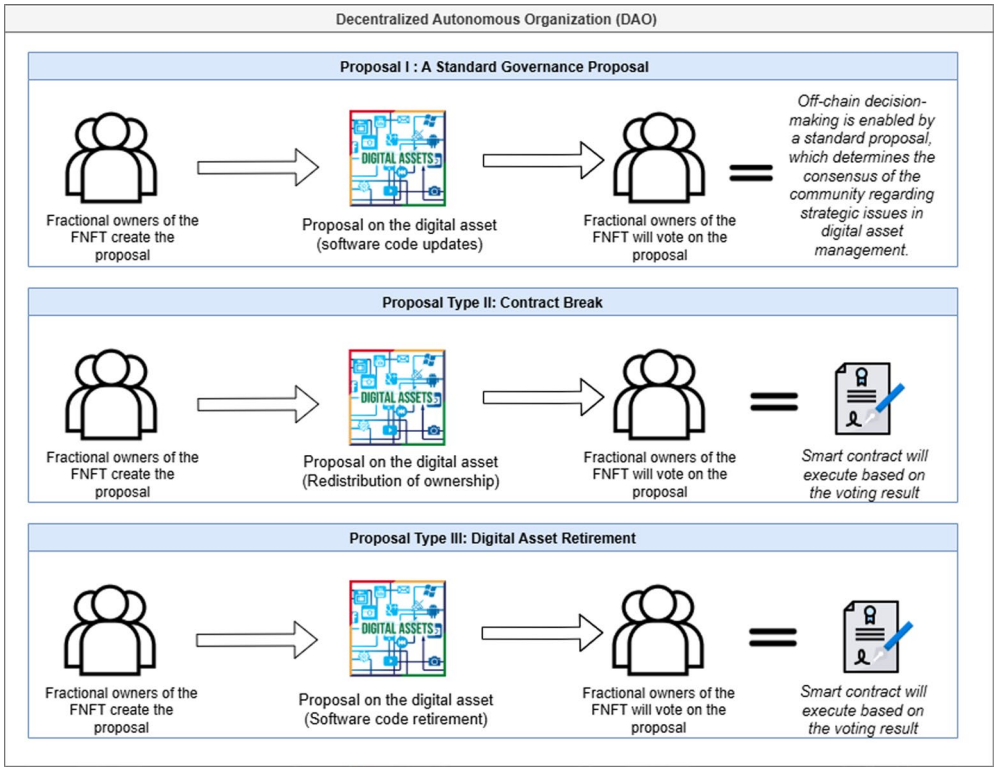


Fig. 3 Proposals for the DAO: Three Distinct Approaches

- Proposal initiation: Holders of governance tokens who possess F-NFTs are eligible to propose a standard proposal, exercising their participation rights in the DAO. For example, one might ask, "Is it necessary to update the metadata of the digital assets?" which would lead to an evaluation by the community.
- Voting mechanism: After a proposal has been submitted, it enters a defined voting period, which begins three days after it is created. Voting is only permitted during this period. It is during this period that fractional NFT holders may vote according to their ownership percentage of governance tokens. The token-weighted voting method is one of the most common voting methods. For a proposal to succeed, a majority rule must be followed. This requires that the weighted number of votes in support of the proposal exceed the number of votes in opposition. Proposals that do not reach this threshold will automatically revert and cannot be executed further.
- On-chain behavior: A standard proposal does not bind to code execution, unlike executable proposals, which contain smart contract logic. As a result of these transactions, no automatic action is taken on the blockchain. Their role is to facilitate off-chain activities through signalling, enabling community participation, and providing a formalised channel for endorsement.
- Execution off-chain after approval: Standard proposals are marked as executed on the chain when they pass. As a result, the `FractionalDAO` contract emits a dedicated event, but the event does not signal any changes to the asset itself. A maintenance wallet or designated operator is responsible for executing the off-chain action (such as updating an IPFS-hosted metadata file or Web2 service endpoint), and the on-chain event log serves as a verifiable record of community approval. It is common for deployed DAOs to use hybrid mechanisms that combine on-chain voting with off-chain actions [28]. Such mechanisms allow the framework to support decisions that are not fully automated by smart contracts.
- Transparency and accountability: An immutable record of each standard proposal's lifecycle is maintained on the blockchain. This is from the time it is created to the time it is voted on and to its outcome. Co-owners are

assured of a transparent and auditable governance process, which strengthens trust between them. The immutability of blockchain technology ensures that all stakeholders' actions will be subject to future scrutiny, creating a culture of accountability among decision-makers.

Proposal Type II: Contract Break

This proposal proposes a governance instrument that provides the DAO with the ability to interact with and possibly modify external smart contracts programmatically. This type of proposal is particularly useful in the context of decentralized architectures, as it enables system upgrades and fosters adaptability. We intend to invoke the `FractionalNFT` Contract in our implementation. Because of this, the redistribution of F-NFT ownership is conducted under this contract.

- Proposal initiation: Contract Break proposals may be initiated by any eligible F-NFT holder who has governance rights. It is essential that the submission explicitly designates the target contract address and meets a predefined set of verification requirements. This is to ensure the contract's legitimacy and compatibility.
- Voting Process: As with the standard proposal type, governance token holders vote in support of or against the proposal. A token-weighted voting system is implemented.
- Smart Contract Execution: If a supermajority quorum threshold is achieved (75% of the total token supply), the proposal will be approved after the designated voting period expires. In this case, a smart contract can autonomously execute the specified function at the target contract address. This will affect the proposed changes without human intervention. The 75% supermajority threshold for Contract Break proposals has been deliberately adopted. This is because they may fundamentally alter the terms of the fractionalization contract or ownership distribution. As a result of the higher bar, safety and protection against hostile takeovers are prioritized over liquidity. In many deployed DAOs, changes to the constitution or treasury level require a supermajority of votes for critical decisions that affect core mechanisms or significant assets because malicious behaviour or hasty modifications are usually prohibited [54] As a result of this emphasis on securing a supermajority, the fractionalized NFT ecosystem is made extremely difficult to change without the support of the entire community.
- Redistribution mechanism: Our implementation of the Contract Break proposal includes both the target contract address and the updated allocation of fractional holdings as part of its payload. The `FractionalDAO` contract invokes its dedicated redistribution function on the `FractionalNFT` contract upon successful approval. It passes the allocated addresses (as well as the corresponding token amounts) to the FractionalNFT contract according to the agreement. As part of the `FractionalNFT` contract, existing fractions are burned or transferred to the newly allocated fractions and the updated balance is assigned according to the proposal. As a result, the DAO redistribution will occur entirely on-chain, without the involvement of any off-chain parties.
- Transparency and accountability: All upgrade-related activities, including metadata associated with proposals, vote tally, and execution outcomes, are recorded on the blockchain. It ensures the integrity of procedures and builds trust among stakeholders by providing a verifiable audit trail.

Proposal Type III: Digital Asset Retirement

Using the Digital Asset Retirement proposal, DAO's association with the underlying NFT will be deliberately dissolved as part of a terminal governance mechanism. Through the sale of fractionalized NFTs to a predefined recipient, it is intended to initiate a formal exit process. A specified amount of ether is exchanged for this service. DAOs that have been successfully executed transition into a retired state, rendering them inactive and immutable.

- Proposal initiation: F-NFT holders may initiate the retirement process by submitting a formal request via the proposed retirement function. As a result of this action, the closure protocol of the DAO has been initiated.
- Voting Process: The decision-making process is governed by token-weighted voting. The votes of F-NFT holders are cast proportionally to their ownership stakes, and, when the voting window closes, the results are tallied to determine the viability of the proposal.

- Smart contract execution: If the proposal reaches the necessary approval, a quorum threshold (75% of the total token supply), and the NFT payment is verified, the retirement sequence is activated. Similar to Contract Break proposals, this 75% threshold denotes retirement's irreversible nature. It is designed to ensure that asset disposals only occur when fractional owners agree, even at the risk of governance gridlock. As a result, the following are undertaken.

  – A transfer of ownership of the original NFT to the designated recipient is required.
  – The distribution of ether reserves from the DAO to F-NFT holders is directlyproportionate to their equity holdings.
  – It is imperative to note that by activating the isRetired flag, the DAO governancesystem is effectively locked out of future activity.

- Transparency and Finality: Transparent processes are implemented and documented throughout the chain. This ensures that all participants know the rationale for asset retirement and its implications. As a result of this transparency, stakeholder consensus is secured and the legitimacy of the closure is preserved.

With these tiered and deterministic governance protocols, the DAO demonstrates its ability to autonomously manage the lifecycle of digital assets, from their initial creation to their final retirement. In this model, smart contracts are deployed for procedural enforcement, while token-based voting is used for stakeholder alignment, eliminating centralised oversight while maintaining decentralisation, adaptability, and community engagement. The use of supermajority thresholds in settings with little participation increases governance gridlock. However, they could be appropriate in situations with high stakes, where the cost of an error is much higher than the cost of delay.

3.2 Threat Model and Governance-security Considerations

Furthermore, the proposed DAO governance model explicitly assumes rational, yet potentially adversarial, participants who may attempt to steer proposal outcomes to their advantage, in addition to the inherent safety-liveability tradeoff introduced by supermajority thresholds for high-impact actions. Among the three classes of risk associated with proposal-driven lifecycle management are (i) proposal manipulation, including flooding the system with low-quality proposals, strategically timing submissions around voting windows, or crafting parameter choices that minority holders cannot realistically contest; (ii) vote collusion and bribery, where actors cooperate or effectively purchase votes to pass self-interested proposals; and (iii) Sybil-style behavior in environments with weak identity guarantees in which influence is fragmented across multiple addresses or temporarily amplified through short-term acquisition of voting power [10, 46, 55]. Despite the framework's requirement for a supermajority vote on Contract Break and Retirement proposals, these risks justify the introduction of additional safeguards, depending on the context of deployment. In order to prevent spam, practical mitigation measures include proposal deposits or bonds and minimum proposal thresholds. Additionally, they include execution timelocks to establish a buffer between approval and irreversible execution [32]. Further, they include mechanisms for delegating power to reduce voter apathy and strengthen informed participation [56]. A strong Sybil resistance may be achieved by incorporating identity- or attestation-based participation constraints that take into account the trade-offs between permissionlessness and user experience.

4 The Intelligent Implementation of the DAO-based F-NFT Management for Multiple Owners of the Digital Asset

This study implements a Decentralized Autonomous Organization (DAO) architec- ture on the Ethereum blockchain to operationalise autonomous governance and life- cycle management for fractionalized digital assets. As part of this implementation, smart contracts written in Solidity are used to ensure automation, transparency, and trustless coordination. F-NFT tokens can be managed equitably using the DAO frame- work, which combines programmable logic with token-based governance.

4.1 Smart Contracts Implementation for DAO-Based F-NFT Management

In our DAO framework, we utilise the Hardhat development environment, which is specifically configured for building decentralised applications (DApps) on the Ethereum blockchain. With Hardhat, Ethereum-based software can be compiled, deployed, tested, and debugged throughout its lifecycle. With its comprehensive ecosystem, it emulates the Ethereum network, featuring pre-funded accounts, robust debugging capabilities, and modular plug-ins. By combining all these features, it has established itself as the preferred platform for developing smart contracts. This system is based on Solidity, which is the most widely used contract-oriented programming language for building smart contracts on Ethereum and other blockchain platforms that support EVM. As a result of its high-level syntax and blockchain-specific features, it has become the dominant standard for deploying secure and deterministic contracts.

As part of the development of the fractional digital asset ownership framework, we developed three core smart contracts: `TestNFT, FractionalNFT, and FractionalDAO`. This research focuses on the deployment of non-fungible tokens (NFTs), their fractionalization, and the governance of shared ownership through a Decentralized Autonomous Organization (DAO).

1. **The First Smart Contract** As the first contract in our DAO-enabled infrastructure, `TestNFT` provides the foundation for a secure digital asset representation that is standardized and auditable. An NFT contract serves as the first step in a multi-layered process to enable the decentralization of ownership and governance of NFTs. Solidity implementation is compliant with the ERC-721 NFT standard. A significant amount of testing and community trust has been placed on the Open-Zeppelin library. This contract ensures it meets all standards for interoperability, security, and functionality. Therefore, this contract inherits the functionality provided by the Open-Zeppelin ERC721 standard, which enables the creation of Non-Fungible Tokens (NFTs). Each tokenId represents a unique digital asset created through the contract.

The Intelligent Algorithm for the Minting Process is as Follows:

Persistent State:
tokenCounter ← An integer counter for token IDs, initialized to 0.

function MINT
    ▷ This function is called by a user (msg.sender).
    tokenCounter ← tokenCounter + 1 ▷ Increment the global token counter.
    newTokenId ← tokenCounter ▷ Assign the new counter value as the token ID.
    _MINT(*msg.sender*, *newTokenId*) ▷ Create the token and assign ownership.
    return *newTokenId* ▷ Return the ID of the newly created token.
end function

Algorithm 1 NFT Minting

2. **The Second Smart Contract** The `FractionalNFT` contract is an implementation of the ERC-20 standard based on Solidity. It is designed to facilitate the fractionalization of ownership of a single non- fungible token

(NFT) under the ERC-721 standard. As a result of this mechanism, a set of fungible tokens (standard ERC20) is issued that collectively indicates the total value and ownership of the underlying NFT. Digital assets are represented by tokens, which represent a proportionate share of those assets. With this approach, a novel method of collective ownership is introduced. Enhanced liquidity is achieved, and access to high-value NFTs is democratized, with the financial threshold significantly reduced. Contract functionality is based on the wrapping of an ERC-721 NFT, which is kept in secure custody by the contract. ERC-20 tokens are minted in exchange for a pre- determined supply of fractional ownership units. It is possible to distribute, hold, or trade these tokens between participants, enabling participants to manage digital assets in a flexible and decentralised manner

The Intelligent Algorithms for Fractionization Process:

Algorithm 1: Initialisation (Constructor)

Called only once upon contract deployment. It sets the deployer as the contract owner.

function CONSTRUCTOR
  owner ← msg.sender ▷ Assign the deployer's address as the owner.
end function

Algorithm 2: NFT Fractionalization Setup

The `initialise` function is a one-time setup called by the owner to link the contract to a specific NFT and mint the initial supply of fractional shares to themselves.

Inputs: NFT contract address $\mathcal{A}_{NFT}$, Token ID $\mathcal{I}_{NFT}$, Initial Supply $\mathcal{S}$, Initial Price $\mathcal{P}$.
Caller: Must be the contract owner.
Require: Contract is not already initialized. $\mathcal{S} > 0$ and $\mathcal{P} > 0$.

function INITIALIZE($\mathcal{A}_{NFT}$, $\mathcal{I}_{NFT}$, $\mathcal{S}$, $\mathcal{P}$)
  Set state variable `nft` ← $\mathcal{A}_{NFT}$
  Set state variable `tokenId` ← $\mathcal{I}_{NFT}$
  Set state variable `initialSupply` ← $\mathcal{S}$
  Set state variable `tokenPrice` ← $\mathcal{P}$
  Set state variable `initialized` ← **true**
  _MINT(*owner*, $\mathcal{S}$) ▷ Create $\mathcal{S}$ ERC20 tokens for the owner.
  _ADDSHAREHOLDER(*owner*) ▷ Add owner to the on-chain shareholder list.
end function

Algorithm 2 NFT Fractionalization Setup

Algorithm 3: Adding a Shareholder (Internal)

A private utility function to add an account to the on-chain list, ensuring no duplicates are added.

Inputs: Account address $\mathcal{A}$.
function _ADDSHAREHOLDER($\mathcal{A}$)
  if shareholders[$\mathcal{A}$] is false **then**
    shareholders[$\mathcal{A}$] ← **true**
    Append $\mathcal{A}$ to `shareholderList` array.
  end if
end function

Algorithm 3 Add Shareholder

3. **The Third Smart Contract** The `FractionalDAO` smart contract developed in Solidity serves as the governance layer for managing the collective ownership of fractionalized non-fungible tokens (NFTs). With its decentralized governance principles, this contract is integrally linked to the `FractionalNFT` smart contract, which allows holders of ERC-20 fractional tokens to participate directly in the decision-making process. It is the proportional ownership of these tokens that determines governance rights, ensuring the alignment between

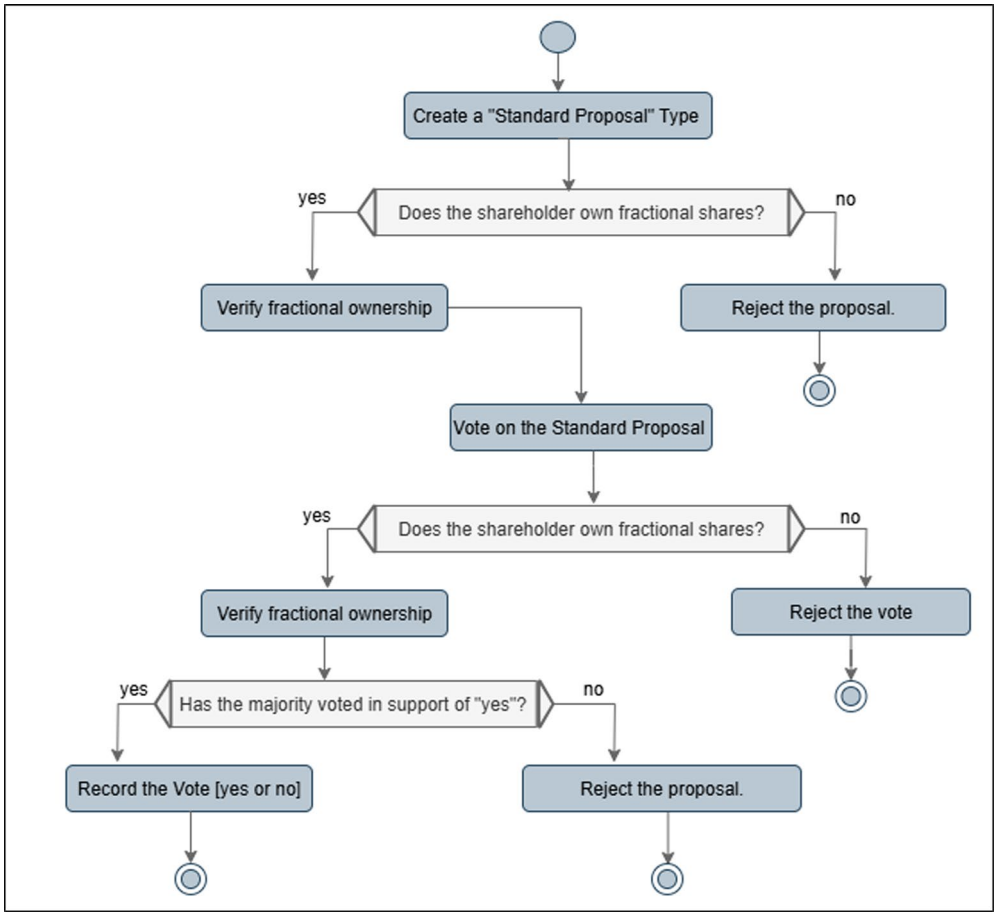


Fig. 4 The Standard Proposal Mechanism

voting influence and economic stakes through a representative model. `FractionalDAO` facilitates three primary governance actions at its core: (1) initiating standard proposals related to the digital asset, (2) enabling advanced proposals that execute an external smart contract address for an encoded function call, and (3) proposing and implementing the sale and retirement of the underlying NFT, which is of the utmost importance. Once this final action has been approved, the proceeds will be redistributed to shareholders according to their fractional shares of ownership. A transparent record of all governance actions is maintained on the blockchain, ensuring procedural integrity and minimising arbitration on the blockchain.

The Intelligent Algorithms for the Governance Process of the DAO:

In `FractionalDAO`, shareholders of fractionalized NFTs are provided with a governance system (which is managed by `FractionalNFT contracts`). In this way, shareholders can propose, vote on, and execute proposals regarding the underlying asset. Several types of proposals are supported by the contract, each with a different effect and logic for execution:

(a) Standard Proposal: A general proposal for expressing the views of the community. The following Figure 4 provides an overview of the lifecycle of a "Standard Proposal" in a fractional ownership or DAO system, which illustrates both the creation of the proposal and voting on it.

(b) Contract Break Proposal: A proposal for executing a low-level call on an external contract. This Figure 5 illustrates the process for a Contract Break Proposal. This type of proposal generally involves significant changes or interactions with another smart contract and thus has stricter rules than a standard proposal. It is for

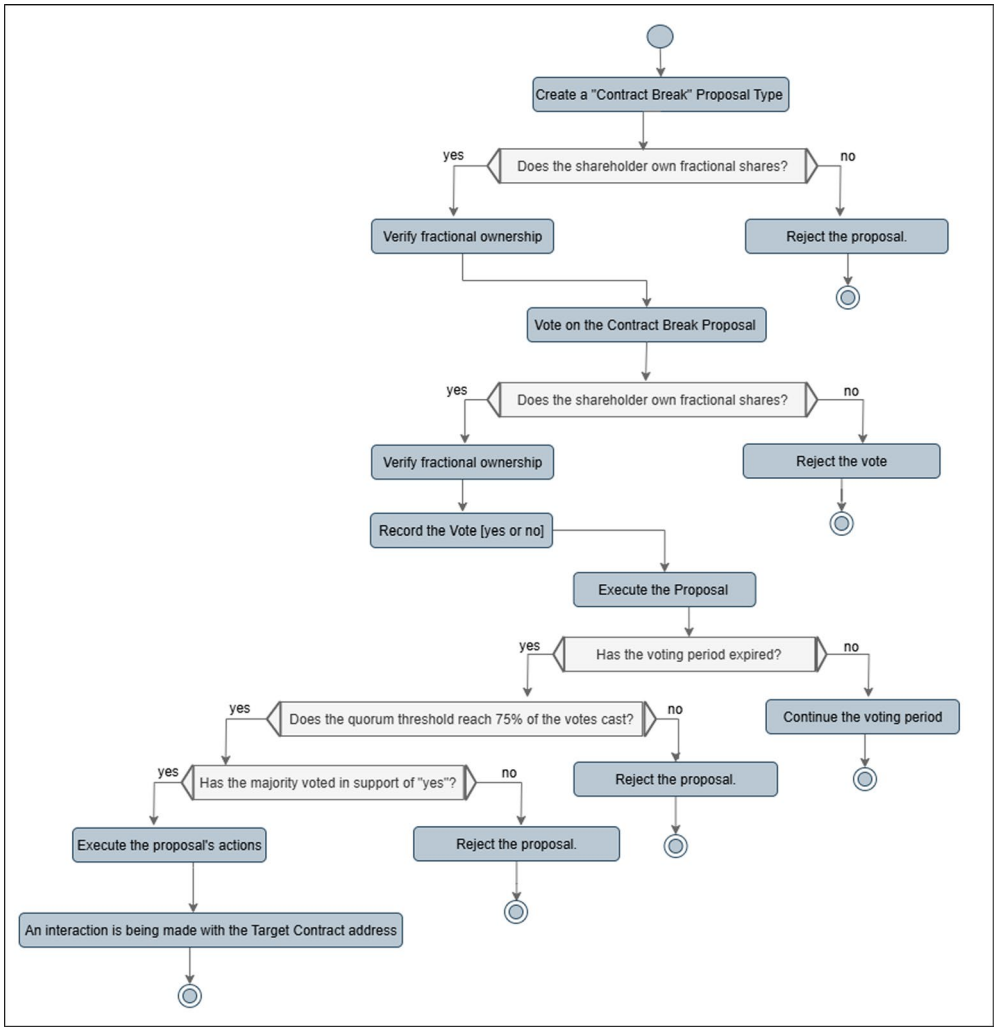


Fig. 5 The Contract Break Proposal Mechanism

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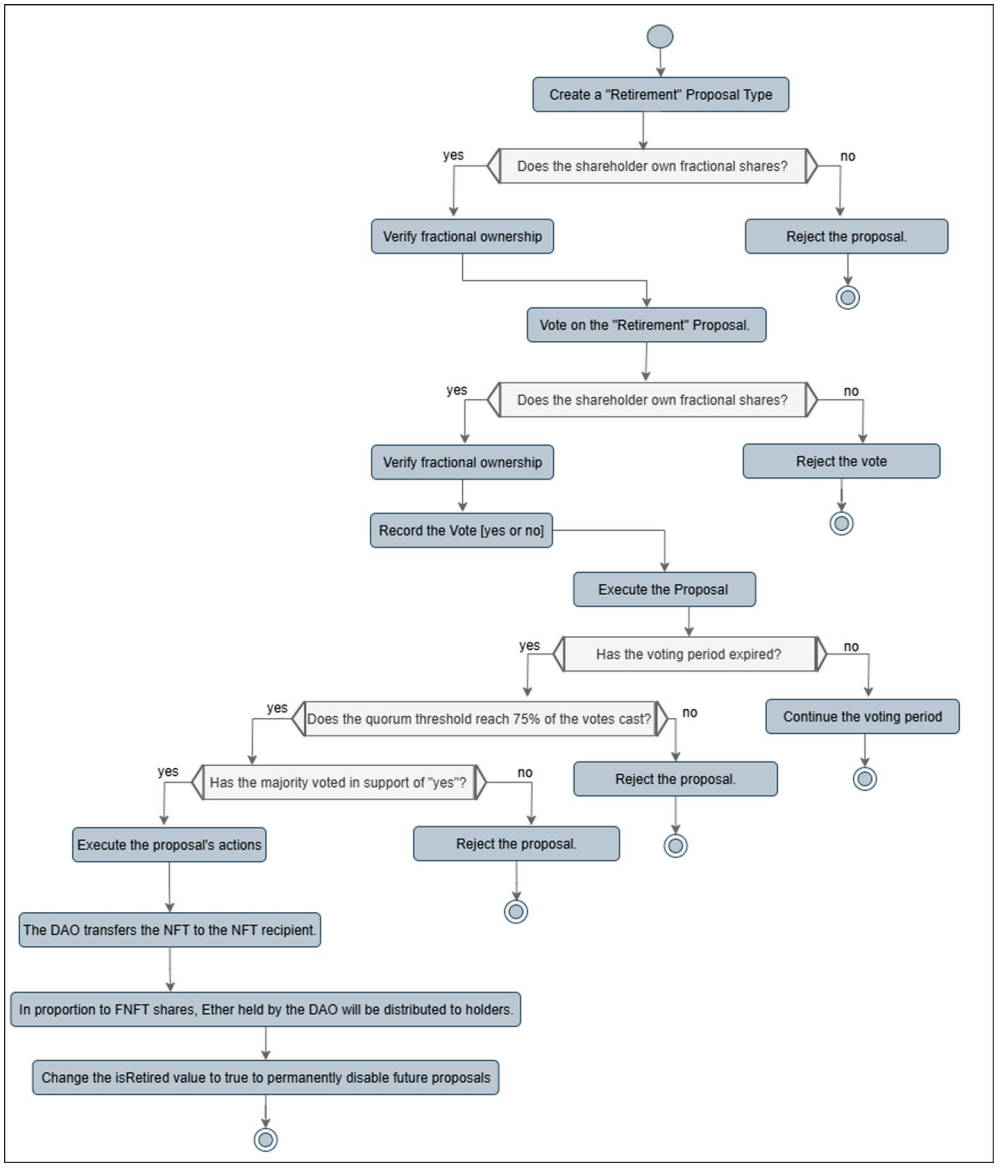


Fig. 6 The Retirement Proposal Mechanism

this reason that critical decisions are made with the broad consensus of the ownership group before interacting with another smart contract.

(c) Retirement: The sale of the underlying NFT and distribution of the proceeds among shareholders results in the dissolution of the DAO. The following Figure 6 illustrates the process for a Retirement Proposal, which is intended to completely dissolve fractional ownership of an NFT and transfer it to a new owner. A Retirement Proposal is the final step in the process of a fractionalized NFT. The DAO is dissolved through a secure, consensus-based voting process. The digital asset is transferred to a new owner, the original shareholders are paid, and the governance system is permanently terminated.

Users are entitled to vote proportionately to the number of fractional shares they hold, which is known as a 'one share, one vote' policy. A contract can be divided into three main parts: the creation of a proposal, the voting process, and the implementation of the results.

Algorithm 1: Proposal Creation

Shareholders can create proposals. There are no differences in the logic for all three types; only the parameters required differ.

Inputs: Description $\mathcal{D}$, Proposal Type $\mathcal{T}$, and other type-specific parameters $\mathcal{P}_{extra}$.
Caller: A shareholder (*msg.sender*).
Require: DAO is not retired.
Require: Caller must own at least one fractional share.

```
1:
2: function CREATEPROPOSALBASE(D, T, P_extra)
3:     proposalId ← proposalCount + 1
4:     proposalCount ← proposalId
5:
6:     Access proposal storage: P ← proposals[proposalId]
7:     P.id ← proposalId
8:     P.proposer ← msg.sender
9:     P.description ← D
10:    P.deadline ← block.timestamp + votingPeriod
11:    P.proposalType ← T
12:
13:                                  ▷ Set type-specific fields based on T and P_extra
14:    if T is ContractBreak then
15:        P.targetContract ← P_extra.targetContract
16:        P.functionCall ← P_extra.functionCall
17:    else if T is Retirement then
18:        P.nftRecipient ← P_extra.nftRecipient
19:        P.nftSalePrice ← P_extra.salePrice
20:    end if
21:
22:    Emit relevant creation events.
23:    return proposalId
24: end function
```

Algorithm 4 Creating a Governance Proposal

Algorithm 2: Share-Weighted Voting

Shareholders vote on active proposals. The "weight" of their votes corresponds to the balance of their shares at the time they cast their votes.

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Inputs: Proposal ID $\mathcal{I}_p$, Vote choice (for/against) $\mathcal{B}_{support}$.
Caller: A shareholder (*msg.sender*).

function VOTE($\mathcal{I}_p$, $\mathcal{B}_{support}$)
    Access proposal storage: $P \leftarrow$ proposals[$\mathcal{I}_p$]
Require: Voting period for P is still active.
Require: Proposal P has not been executed.
Require: Caller has not already voted on P.

    weight $\leftarrow$ FNFT.BALANCEOF(*msg.sender*)
Require: weight > 0.

    Mark caller as having voted: P.hasVoted[msg.sender] $\leftarrow$ **true**.
    if $\mathcal{B}_{support}$ is true **then**
        P.forVotes $\leftarrow$ P.forVotes + weight
    else
        P.againstVotes $\leftarrow$ P.againstVotes + weight
    end if

    Emit `Voted` event.
end function

Algorithm 5 Voting on a Proposal

Algorithm 3: Proposal Execution

Any shareholder can execute a proposal after the voting period ends. The outcome depends on the number of votes cast and the type of proposal.

Inputs: Proposal ID $\mathcal{I}_p$.
Transaction Value (for Retirement only): Ether sent with the call, $\mathcal{V}_{ETH}$.

function executeProposal($\mathcal{I}_p$)
  Access proposal storage: $P \leftarrow$ proposals[$\mathcal{I}_p$]
Require: Proposal P has not been executed.
Require: Voting period for P has ended.

  totalVotes $\leftarrow$ P.forVotes + P.againstVotes
  if totalVotes == 0 **then**
    ▷ Handle division by zero, proposal fails.
    P.executed $\leftarrow$ **true**
    return
  end if
  forPercentage $\leftarrow$ (P.forVotes $\times$ 100)/totalVotes

  switch (P.proposalType)
    case ContractBreak:

Require: forPercentage $\geq$ BREAK_THRESHOLD
      (success, data) $\leftarrow$ P.targetContract.call()(P.functionCall)

Require: *success* is true.
      Emit `ContractBroken` event.
    case Retirement:

Require: forPercentage $\geq$ RETIREMENT_THRESHOLD

Require: $\mathcal{V}_{ETH} \geq P$.nftSalePrice ▷ Check payment from executor.
      Transfer NFT from `this` contract to P.nftRecipient.
      distributeFunds ▷ See sub-routine below.
      isRetired $\leftarrow$ **true**
      Emit `AssetRetired` event.
    case Standard:

Require: P.forVotes > P.againstVotes
      ▷ No on-chain action, proposal is simply marked as passed.

  P.executed $\leftarrow$ **true**
end function

Algorithm 6 Executing a Proposal

Fund Distribution Sub-routine for Retirement:

As a result of this logic, the Ether proceeds are distributed among all shareholders following the NFT sale.

```
function DISTRIBUTEFUNDS
    totalValue ← Ether balance of this contract.
    totalSupply ← FNFT.TOTALSUPPLY
    numShareholders ← FNFT.GETSHAREHOLDERCOUNT
    for i = 0 to numShareholders − 1 do
        shareholder ← FNFT.GETSHAREHOLDER(i)
        shares ← FNFT.BALANCEOF(shareholder)
        if shares > 0 then
            payout ← (totalValue × shares)/totalSupply
            if payout > 0 then
                Transfer payout amount of Ether to shareholder.
                Emit ValueDistributed event.
            end if
        end if
    end for
end function
```

The DAO becomes a self-governing ecosystem that allows collaborative oversight of digital assets that have been fractionalized through this contract. The `FractionalDAO` facilitates the management of the full lifecycle of shared digital assets by supporting flexible proposal types, such as general discussions, contract interactions, and asset disposals. By designing this framework, it provides a robust framework for decentralized asset management, allowing stakeholders to participate equally, to execute transparently, and to coordinate autonomously.

5 An Evaluation of DAO-Based Governance for Fractional NFT Management

This study offers critical insights into the operational performance, governance effectiveness, and scalability of the Decentralised Autonomous Organisation (DAO) framework that governs fractional non-fungible tokens (F-NFTs). Three types of proposals were evaluated: Standard, Contract Break, and Retirement. In order to conduct the evaluation, we deployed the TestNFT, FractionalNFT, and FractionalDAO contracts on an Ethereum-based test network based on the Hardhat framework. This evaluation does not serve as a head-to-head cross-protocol benchmark because deployed fractionalisation platforms like Fractional.art and NFTX differ significantly in objectives, contract architecture, and workload semantics. Rather, it provides an internal assessment of our proposal-driven lifecycle operations in terms of scalability and performance, in addition to a feature-level comparison in Sect. 2.1. The execution time and gas consumption for each proposal type were measured by generating synthetic workloads consisting of 1, 5, 10, 20, 50, and 100 proposals, respectively. Rather than providing exact estimates of mainnet-level costs, these measurements are intended to provide a relative comparison between proposal types and batch sizes. Each of these proposal types represents a distinct governance function within the DAO.

Several performance metrics were applied systematically in order to provide an assessment of the DAO's efficiency and responsiveness. Several metrics were evaluated, including average gas consumption, execution latency, and scalability in a scenario with increasing proposal volumes. Using these metrics, the DAO can be evaluated for its ability to maintain decentralized, transparent, and cost-effective governance on the Ethereum network.

Each proposal type was evaluated both for its computational resource requirements and its ability to support participatory governance while maintaining high performance. According to our analysis, each proposal mechanism exhibited a balance between on-chain efficiency and institutional decentralization, thus informing the broader utility of DAO structures in managing shared ownership of digital assets.

The purpose of this assessment is to gain a basic understanding of the DAO's capacity to facilitate stakeholder coordination and autonomous governance under varying operational loads. It provides a scalable model for managing complex ecosystems of digital co-ownership.

The following performance metrics were analyzed for the DAO:

Table 2 Execution Time Analysis (Seconds)

Proposal Count	Standard	Contract Break	Retirement
1	0.04	0.05	0.07
5	0.18	0.22	0.32
10	0.33	0.45	0.61
20	0.67	0.88	1.15
50	1.57	2.28	2.95
100	3.33	4.47	6.11

Table 3 Gas Consumption Analysis

Proposal Count	Standard	Contract Break	Retirement
1	290,498	564,773	633,849
5	1,384,090	2,755,465	3,169,245
10	2,751,092	5,493,842	6,338,490
20	5,485,192	10,970,692	12,676,980
50	13,687,492	27,401,242	31,692,450
100	27,358,004	54,785,504	63,384,900

FractionalDAO smart contract performance was assessed using quantitative metrics. As part of these metrics, execution time, gas consumption, and gas per proposal were considered. Each of these indicators was measured for each of the contract's three core proposal types: Standard, Contract Break, and Retirement. According to the results presented in tabular format, it is possible to assess the overall suitability and scalability of the DAO governance model for Ethereum-based environments based upon a comparison of the computational efficiency and cost-effectiveness of each proposal type, as shown in the following tables.

- Execution Time Analysis Table: This execution time Table 2 illustrates the cumulative runtimes required to process different quantities of proposals (1, 5, 10, 20, 50, and 100) in three different proposal categories: Standard, Contract Break, and Retirement. The execution time is reported in seconds and provides insight into the system's responsiveness as the number of proposals increases. According to this study, processing 100 Standard proposals requires approximately 3.33 seconds. In contrast, the same quantity of Retirement proposals resulted in a significantly higher latency of 6.11 seconds. As a result of these observations, it is possible to determine the performance and scalability of each proposal type under increasing transactional demands. Although the absolute execution times are in the order of a few seconds for batches up to 100 proposals, these transactions may still be subject to delay in block confirmation and congestion in the network. Due to this, the framework is more suited to governance actions of low to medium frequency (such as periodic metadata updates or asset sales) rather than difficult real-time scenarios, such as high-frequency trading or sub-second risk controls.
- Gas Consumption Analysis Table: This Table 3 provides a quantitative analysis of the amount of computational resources expended for executing multiple proposals in batch sizes ranging from 1 to 100. The amount of computational resources expended is measured in gas units. The execution of 50 Contract Break proposals results in a cumulative gas cost of 27,401,242 gas units. Based on the data, it appears that overall gas consumption scales linearly with the number of proposals submitted. Although the magnitude of consumption varies significantly between proposal types, it indicates that the level of computational complexity varies from proposal type to proposal type.
- Gas per Proposal Table: An additional method of refinement of the analysis is provided by the Gas Per Proposal Table 4, which presents the average gas costs per proposal. This is calculated by dividing the total gas consumption by the number of proposals that were executed in each batch. As a result of this metric, gas efficiency can be assessed on a more detailed level. In both Standard and Contract Break proposals, the average gas per proposal declines modestly with increasing batch size, suggesting optimisations were implemented. On the other hand, Retirement proposals demonstrate a constant gas cost per transaction, which indicates that

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Table 4 Gas Per Proposal

Proposal Count	Standard	Contract Break	Retirement
1	290,498	564,773	633,849
5	276,818	551,093	633,849
10	275,109.2	549,384.2	633,849
20	274,259.6	548,534.6	633,849
50	273,749.84	548,024.84	633,849
100	273,580.04	547,855.04	633,849

Table 5 Summary of the DAO Evaluation Results-Source: DAO prototype evaluation on Ethereum test network.

Proposal Type	Avg Gas per Proposal	Max Gas (100 proposals)	Avg Time per Proposal (s)
Standard	277,335.78	27,358,004	0.034
Contract Break	551,610.78	54,785,504	0.0457
Retirement	633,849.00	63,384,900	0.0612

[1]Gas values are averages over multiple runs; execution times represent mean wall-clock times

batching does not result in any measurable efficiency gains. As a result of their fixed computational footprint, this is likely to be the case. The following variables are defined to describe the calculation:

n: The Proposal Count.
$T_{\text{total}}(n)$: The Total Execution Time for *n* proposals, taken from the "Execution Time (seconds)" table.
$G_{\text{total}}(n)$: The Total Gas Consumption for *n* proposals, taken from the "Gas Consumption" table.
$G_{\text{per_proposal}}(n)$: The Gas per Proposal for a batch of *n* proposals, taken from the "Gas per Proposal" table.

This Table 4 calculates the average gas cost for a single proposal within a specified batch size. When a proposal count *n* is given, this value will be calculated by dividing the total amount of gas consumed by the number of proposals within that batch.

$$G_{\text{per_proposal}}(n) = \frac{G_{\text{total}}(n)}{n} \tag{1}$$

- Summary Evaluation Results Table: This Table 5 summarises key performance metrics for each proposal type based on 100 proposals. Based on the comparative analysis, retirement proposals require the most time and gas to execute, making them the least resource-efficient proposals. When it comes to cost and processing time, Contract Break proposals fall in an intermediate position. The Standard proposal, on the other hand, is rated as the most efficient option with the lowest average gas usage and execution time. As a result of this distinction, they are particularly suitable for frequent, low-cost governance activities within the framework of a DAO.

This Table 5 summarises the overall performance metrics. Its values are calculated as follows:

Average Gas per Proposal

This is the arithmetic mean of all "Gas per Proposal" values across the different batch sizes (where $n \in \{1, 5, 10, 20, 50, 100\}$).

$$\text{Avg Gas per Proposal} = \frac{\sum_{n\in\{1,5,10,20,50,100\}} G_{\text{per_proposal}}(n)}{6} \tag{2}$$

Max Gas (100 proposals)

This value is the total gas consumed when processing 100 proposals, taken directly from the "Gas Consumption" table where $n = 100$.

$$\text{Max Gas (100 proposals)} = G_{\text{total}}(100) \tag{3}$$

Average Time per Proposal (s)

This is the total execution time for 100 proposals, divided by 100.

$$\text{Avg Time per Proposal (s)} = \frac{T_{\text{total}}(100)}{100} \tag{4}$$

Gas and latency measurements make Standard proposals suitable for routine governance with high volume. In contrast, Contract Break and Retirement proposals require more resources. For the DAO to remain scalable over the long term, these decisions should only be used infrequently but be critical decisions. These decisions include renegotiating ownership or retiring assets.

To enhance the interpretation of the DAO's performance metrics, a series of visualisations is presented to complement the tabular data. These charts depict execution time, gas consumption, and relative efficiency across the three proposal types. They offer a comprehensive view of system behaviour under different operational loads.

The following Figures 7, Execution Time by Proposal Count and Gas Consumption by Proposal Count, highlight system scalability. Both charts exhibit a linear growth pattern, indicating a direct and proportional relationship between the number of proposals processed and the computational resources consumed. This linear trend suggests predictable cost progression within the evaluated range as DAO activity scales.

The following charts provide further insight into cost dynamics and performance differentials. The 'Relative Gas Consumption' Figures 8 normalise the gas consumption by benchmarking it against the Standard proposal type, which serves as a baseline. Based on this comparison, Contract Break proposals typically consume approximately twice as much gas as Standard Proposals. This reflects the higher computational complexity of Retirement Proposals, which require approximately 2.2 times more computation.

In the Time Efficiency Analysis Fig. 8, throughput is examined, indicating the DAO's processing capacity per second. A Standard Proposal averaged 30 proposals per second, followed by a Contract Break proposal at 22

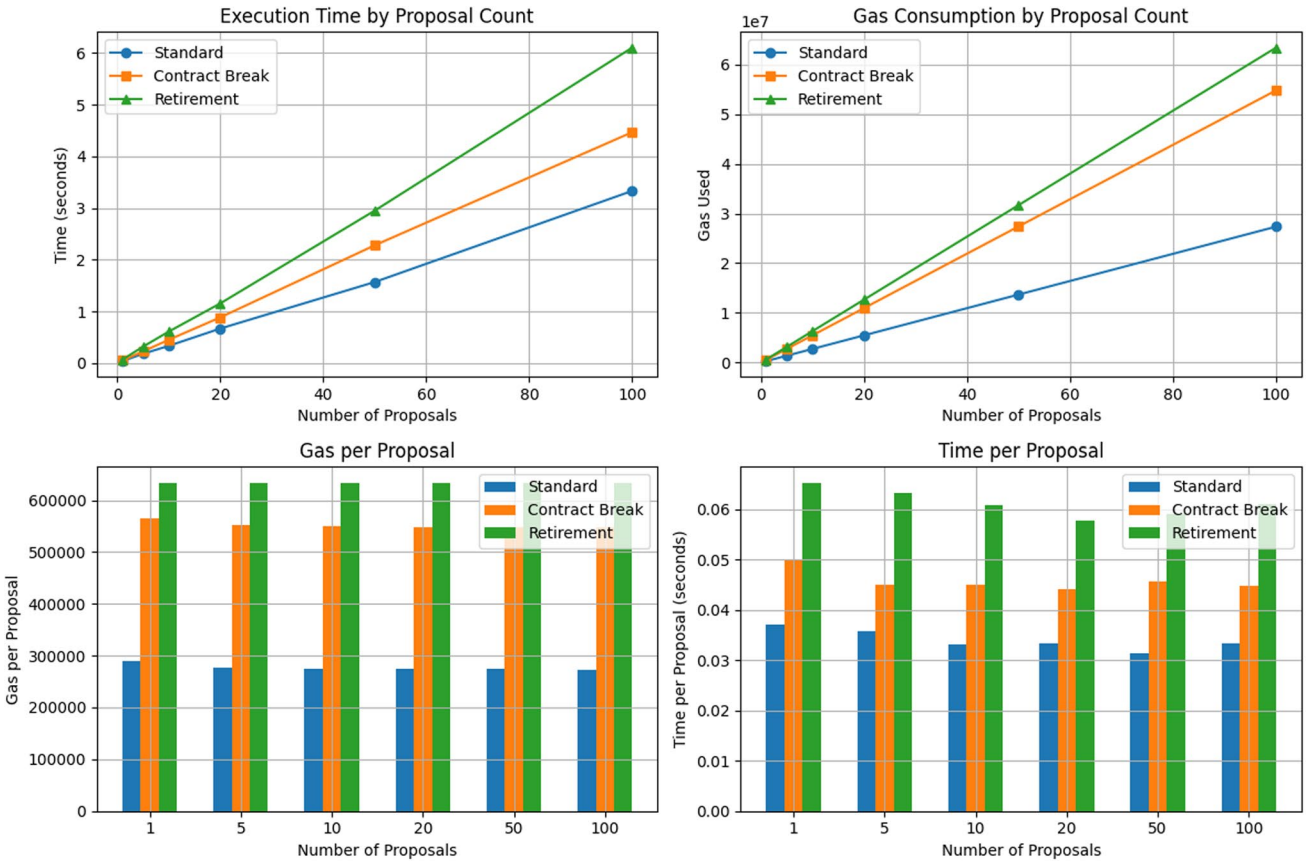


Fig. 7 The Analysis of the Time of Execution and the Consumption Charts

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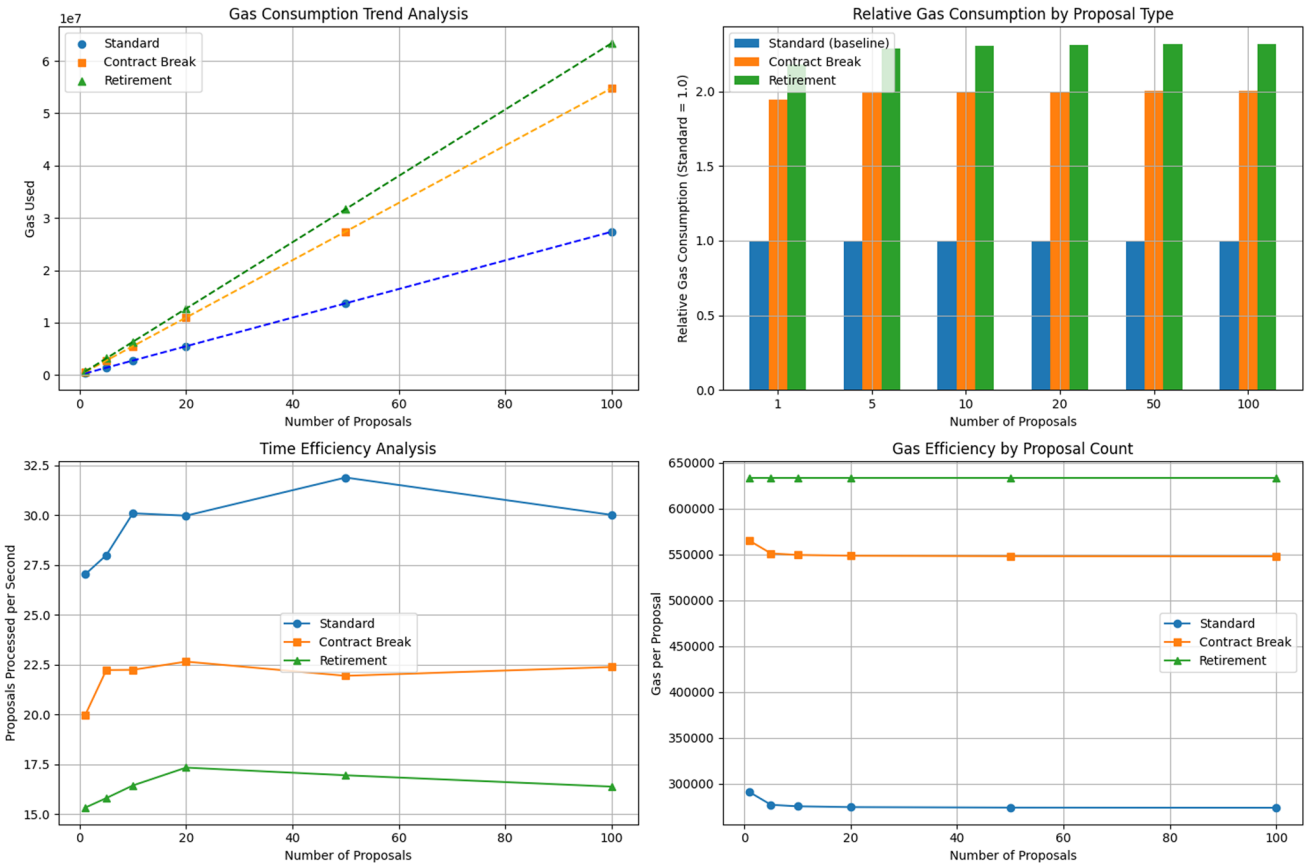


Fig. 8 The Analysis of Efficiency and Trends Charts

proposals per second. It was followed by a Retirement Proposal at 16 proposals per second. In this stratification, the time burden associated with each governance function is illustrated differently.

As a final consideration, the Gas Efficiency by Proposal Count Fig. 8 shows batch efficiency. For both Standard and Contract Break types, a slight decrease in gas usage per proposal indicates modest batching optimisations. On the other hand, the horizontal line for Retirement Proposals shows that gas costs are fixed per proposal. This indicates that batching does not increase efficiency. As a result of this immutable cost structure, the Retirement Proposal mechanism demonstrates unique operational characteristics.

Therefore, the key results of the DAO performance evaluation are as follows:

1. Cost and Execution Time Hierarchy Gas consumption and execution time are ranked across all proposal types. A standard proposal is the most efficient, followed by a contract break proposal, and retirement proposals are the most resource-intensive. The stratification of costs highlights the computational complexity of each proposal category.
2. Linear Scalability According to the performance analysis, the execution time and gas consumption scale linearly with the number of proposals, regardless of the type of proposal.In the evaluated batch sizes, this pattern is consistent with stable scaling behaviour; further evaluation on public networks is required to ensure robustness in adversarial and congested environments.
3. Stable Per-Proposal Costs In Standard and Contract Break proposals, gas costs per proposal decrease slightly with larger batches, but Retirement costs remain fairly constant; overall, per-proposal costs remain stable. By ensuring consistency in per-unit costs, performance degradation will be minimised, and resource planning will be more predictable.

4. Functional Complexity Versus Economic Cost There is a direct trade-off between the functional complexity of a proposal and its on-chain execution cost. It is critical to note that proposals involving asset retirement or termination of contracts require significant computational effort. Therefore, they require more gas. As a result of this insight, governance design can be aligned with economic sustainability.

As a result of the DAO implementation, stakeholders are able to make informed decisions based on predictable, efficient, and well-structured performance characteristics. Standard proposals provide a strategic advantage for routine governance due to their efficiency. As well, the cost differences between proposal types will assist members in balancing governance needs with resource expenditures.

5.1 Discussion

In this section, we compare three types of DAO proposals: Standard, Contract Break, and Retirement. We compare them based on execution time, gas consumption, and operational efficiency. This analysis is based on empirical data from a range of batch sizes to assess the scalability and cost-effectiveness of each proposal category.

1. Standard proposals The standard proposal type demonstrates the highest performance efficiency and the lowest computation cost.

   - Execution Time: The most efficient proposal processing rate is achieved with standard proposals. For a single proposal, the execution time ranges from 0.04 seconds to 3.33 seconds for a batch of 100 proposals. The average execution time per proposal was 0.034 seconds, demonstrating superior responsiveness.
   - Gas Consumption: The gas expenditures incurred by these proposals were the lowest, with an average of 277,335.78 gas units per proposal. Based on the cumulative gas consumption for 100 proposals, the cost-effectiveness of these proposals at a large scale can be demonstrated by their gas consumption of 27,358,004.
   - Efficiency Metrics: Based on the Time Efficiency Analysis, the DAO is capable of processing over 30 Standard proposals per second under optimal conditions (i.e., a batch size of 50 proposals). Additionally, the Gas Efficiency by Proposal Count visualisation indicates that gas consumption per proposal is decreasing and stabilising. This indicates higher batching efficiency and reduced marginal costs at scale.

2. Contract Break proposals A Contract Break proposal occupies a middle position in terms of resource consumption and processing speed.

   - Execution Time: The execution times for batches containing 1 to 100 proposals range from 0.05 to 4.47 seconds, with an average processing time of 0.0457 seconds.
   - Gas Consumption: Compared to Standard proposals, these proposals are more gas-intensive, averaging 551,610.78 gas units, resulting in 54,785,504 gas units for 100 proposals overall.
   - Efficiency Metrics: It is estimated that the DAO processes approximately 22.5 Contract Break proposals per second, demonstrating moderate throughput. Contract Break proposals consistently require significantly more gas than Standard proposals, as shown in the Figure 8 of Relative Gas Consumption. There is a significant resource gap.

3. Retirement proposals In the DAO ecosystem, retirement proposals are the most computationally intensive and cost-intensive governance actions.

   - Execution Time: The execution time for these proposals ranges from 0.07 seconds to 6.11 seconds, with an average of 0.0612 seconds. As a result of this reduction in processing speed, the overall performance of the system is affected.

- Gas Consumption: The Retirement proposals had the highest gas expenditure, with 633,849 gas units. For 100 proposals, this results in 63,384,900 gas units.
- Efficiency Metrics: In terms of time efficiency, the DAO only processes 16 Retirement proposals per second, which is the lowest among the three types. Based on the Gas Efficiency by Proposal Count chart and the Gas per Proposal table, the gas cost per Retirement proposal remains static regardless of batch size. As a result of this lack of batching efficiency, these proposals are highly resource-intensive.

In light of the analysis, Standard, Contract Break, and Retirement follow a clear hierarchy. Scalability, execution speed, and gas consumption are based on these criteria. As a result of these distinctions, DAO participants can make informed governance decisions by balancing functional complexity with economic cost.

According to these results, standard proposals are best suited to frequent signalling and daily coordination from a governance perspective. In contrast, Contract Break and Retirement proposals are associated with higher gas and time overheads, which may be acceptable for infrequent, high-stakes governance initiatives. Consequently, the economic cost of a proposal can be compared to its potential impact on the digital asset. It is one of the desirable characteristics of DAO-based governance frameworks.

6 Conclusion

In this paper, we introduce an intelligent and proposal-driven framework for governing fractional non-fungible tokens (F-NFTs) via a Decentralised Autonomous Organisation (DAO). By combining fractional ownership tokens with DAO governance layers, the framework organises governance actions into three categories: (i) Standard proposals that provide routine updates and parameter adjustments; (ii) Contract Break proposals that alter and redistribute fractional ownership tokens; and (iii) Retirement proposals that sell or retire the underlying digital assets and distribute the proceeds to the appropriate parties. As a result, co-ownership rules are transparent and more verifiable, and the governance logic specified in smart contracts is programmable and enforced on-chain.

Empirical evaluation shows that each of the three proposal categories exhibits a distinct performance profile. There is almost a linear relationship between the number of proposals and the gas consumption and latency of standard proposals. Therefore, they are suitable for frequent governance operations. Gas costs and execution times increase with Contract Break proposals because they alter ownership structures and update on-chain records, but they remain tractable for infrequent structural changes. Retirement is the most resource-intensive, since it involves terminating the asset's life cycle and distributing its residual value as a one-time event. Therefore, the framework supports governance workflows for exceptional events such as redistribution and retirement while maintaining a lower-cost process for routine governance actions. The findings in this paper are based on experiments performed on a local Ethereum test network with synthetic workloads; performance and latency characteristics may differ under conditions of a public network.

7 Limitations and Future Work

However, it is necessary to consider limitations. The first consideration is that the evaluation is conducted on a local Ethereum-compatible test network with synthetic proposal workloads. It does not consider user behaviour, network congestion, or the adversarial conditions associated with public chains. Furthermore, this study did not include a formal smart-contract security audit or formal verification, nor did it simulate governance attack scenarios such as vote-buying, collusion strategies, or adversarial token acquisition dynamics. As a result, future work will be required to validate the framework's security assurance and incentive compatibility. In addition, the framework implements token-weighted voting, which is known to be vulnerable to a number of well-known vulnerabilities, such as power concentration among large token holders, voter apathy, and collusion or vote-buying.

Additionally, governance processes can be exposed to Sybil-style behavior when identity verification is not used, where influence is split among multiple addresses or amplified by temporary tokens, as well as proposal manipulation strategies that degrade governance quality. Depending on the operational setting, these risks motivate future extensions such as proposal deposits, execution timelocks, and Sybil-resistant voting constraints. The present design assumes that governance decisions can be confirmed with confirmation times ranging from seconds to minutes. However, it has not been designed to support true real-time control in high-frequency DeFi strategies. Additionally, regulatory and legal uncertainty associated with fractional NFTs and DAOs may affect the enforceability of on-chain decisions.

In the future, there will be several approaches to addressing these limitations. One way to achieve this goal would be to integrate alternative voting schemes and incentive mechanisms, such as delegated, conviction, or quadratic voting. Consequently, token concentration risks will be mitigated while proportionality and accountability will be maintained. As a second approach, future work could develop risk- and reliability-focused metrics to assess F-NFT governance durability, based on research on software durability, usable security, and reliability prediction. Another direction is to validate the framework through extended case studies with real-world digital asset communities. This would include analysing how these categories are applied, how ownership changes, how assets retire, and how DAOs perform under realistic network conditions. In the tokenized asset market, which is growing in scale and regulatory importance, auditable, reliable co-ownership mechanisms will be essential.

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Declarations

Competing interests The authors declare no competing interests.

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