Decentralized Autonomous Organization in Built Environments: Applications, Potential and Limitations

Abstract

The operations of built environment-related sectors are often run on centralized organizational structures. This centralized approach could lead to operational challenges that restrict efficiency, hinder transparency, and misalign with the community's interests. The emergence of decentralized autonomous organization (DAO) presents a promising avenue for addressing these issues by leveraging blockchain technology and decentralized governance models. This paper presents a review of DAO, examining its existing applications, limitations, and potential use cases in the built environment. Seven categories of DAO applications in the built environment were identified and discussed. The study also explores DAO's fundamentals, including its governance characteristics, operational mechanism, limitations and technical implementation, and corresponding challenges. Finally, this study highlights three potential areas in the built environment for future DAO use cases. This article serves as an essential reference for future academics, professionals, and policy regulators interested in learning more about the integrations of DAO in the built environment.

Keywords: blockchain; decentralized autonomous organization; smart contract; construction industry; built environment

1. Introduction

Blockchain technology has gained a rapid increase in adoption in built environment in recent years. Its applications extend to areas such as construction management, smart government, smart cities, transportation, smart homes, circular economy, smart energy, construction site environmental monitoring, and beyond (Li et al. 2019; Shojaei et al. 2021; Zhong et al. 2022). However, most existing blockchain applications in these domains primarily focus on secured payment processing, data security, and information management. There remains a notable gap in leveraging blockchain for decentralized governance within the built environment.

There are several underlying problems that stem from the traditional centralized approaches to decision-making and governance in the built environment domain, from design and construction to facility management and smart cities. For instance, in the design phase of built infrastructure projects, the traditional collaborative design processes within the Architecture, Engineering, and Construction (AEC) industry are often characterized by a lack of transparency and centralized control (Tao et al. 2022). Design decisions are typically made by a small group of people without the consensus of all stakeholders. This centralized decision-making process is typically incapable of incorporating diverse perspectives and can result in suboptimal designs and unsatisfactory outcomes for end-users. Similarly, in the construction phase, decision-making power is often concentrated among a few managers or executives (Senaratne and Samaraweera 2015). Consequently, decisions may prioritize the interests of a select few rather than the collective benefits of all involved stakeholders, leading to potential conflicts, delays, and inefficiencies in project execution. The issues associated with centralized governance extend to the operation and management of smart cities and their infrastructure. Most smart city systems heavily depend on centralized systems, which are prone to security risks and inefficiencies (Cui et al. 2018). Under such a centralized system, citizens also tend to have limited participation in decision-making processes that directly impact their lives and well-being (Oliveira et al. 2020). This centralized approach may fail to efficiently provide services and solutions to address the diverse needs of the community. Furthermore, in the realm of facility management, traditional building operations are operated on centralized organizational structures, where decision-making power typically resides among a few individuals such as building facility managers (Xu et al. 2020). This centralized approach can hinder transparency and misalign with the building occupant's interests. Previous studies have revealed dissatisfaction among building occupants due to the lack of participation in facility management-related decisions that could impact their living environment and experiences (Leaman and Bordass 2001). In addition, there is a growing recognition of the limitations of conventional, centralized facility management approaches and a need for community-based, participatory facility management models (Alexander and Brown 2006; Michell 2010; Adewunmi et al. 2023), that prioritize the inclusivity and diverse needs and perspectives of stakeholders. Therefore, it becomes increasingly necessary to explore alternative governance models with decentralized and community-driven structures that can address these inherent shortcomings of centralized decision-making and management models in the built environment.

Blockchain technology offers benefits such as secure and immutable record-keeping, smart contract automation, tokenization, and consensus mechanisms, however, these features on their own are not quite sufficient to provide effective decentralized governance and decision-making to address the aforementioned issue in built environments. These blockchain-inherited features primarily lay the important technological infrastructure for solving technical problems related to data integrity, transparency, security, and automation (Daneshgar et al. 2019). Blockchain governance, on the other hand, is defined as the collective decision-making processes and mechanisms adopted by public blockchain communities and key stakeholders, particularly concerning protocol changes (Finck 2018) . Blockchain governance involves distributing decision-making mechanisms and stakeholder coordination which requires additional decentralized coordination mechanisms in addition to the inherited features of blockchain.

Decentralized Autonomous Organizations (DAOs) present a promising solution by offering a decentralized governance framework that promotes transparency, democratic participation, and collective decision-making. A decentralized Autonomous Organization (DAO) is a blockchain-powered entity operating with full transparency and has its management rules and operational tasks programmed within sets of smart contracts (Wang et al. 2019a). The governance mechanisms within DAO are decentralized and are not controlled by any central governing body, top executive teams, or management hierarchy (Singh and Kim 2019). DAO aims to decentralize the management of any organization and entity by making all functional operations and activity records transparently accessible and encouraging the stakeholder or the token holder who share a common goal to make decisions and changes for the best interest of the entity (DuPont 2017). These unique characteristics of DAO are enabled by combining its two backbone components, distributed ledger technologies (DLT) and smart contracts. Distributed ledger technology is the digital framework and protocols running on a decentralized peer-to-peer network that simultaneously allows access, validation, and record updating of data across interconnected databases without requiring intervention from any centralized intermediary (Hunhevicz and Hall 2020). Smart contracts are computer-programmed agreements built on top of blockchain which launch when specific criteria are satisfied (Wang et al. 2018). DLT enables the authority of decision-making to be distributed among the DAO stakeholders and transparently records all the decisions and actions in an immutable way. Smart contracts allow DAOs to operate autonomously based on programmed rules.

DAO can provide an overlaying organizational layer on top of the blockchain architecture to address the mentioned governance-related challenges. As DAOs are built upon blockchain technology, they share certain characteristics with this underlying framework. The relationship between the technical properties of blockchain and DAOs, along with their associated concepts, is illustrated in Fig. 1. By leveraging blockchain's fundamental features and incorporating governance and incentive models, DAOs present new opportunities for creating autonomous, decentralized, and community-driven organizational structures. Voting mechanisms foster DAO member's participation in the organization's governance activities. Smart contracts allow DAOs to operate autonomously based on programmed rules. The combination of the technical foundation provided by blockchain and DLT and the governance mechanism offered by DAO is crucial in creating an efficient and comprehensive decentralized governance system. By implementing DAOs in the built environment, diverse stakeholders can actively participate in shaping the design, construction, operation, and management of built infrastructure, fostering better coordination and alignment with the collective interests and needs of the community.

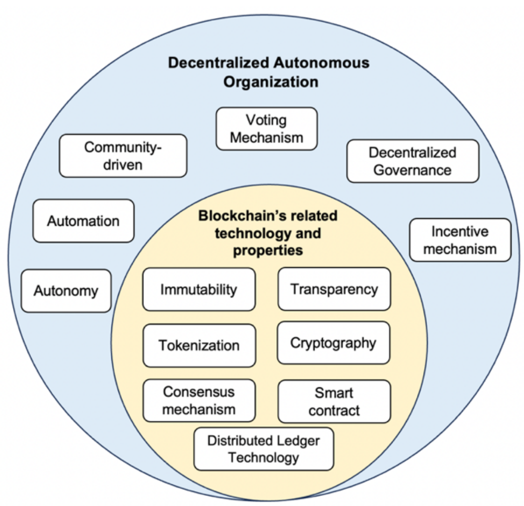

Fig. 1 The technical properties and concepts within a decentralized autonomous organization

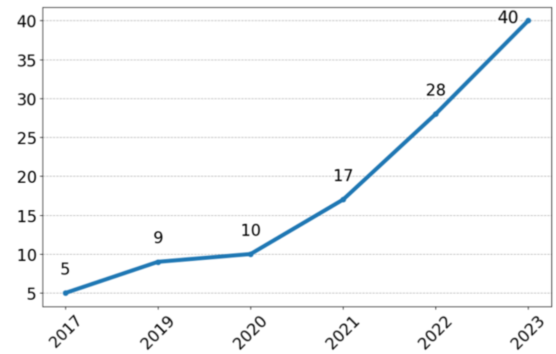

Fig. 2 Number of DAO-related publications by year (Source: Searching “decentralized autonomous organization*" OR dao*” in Scopus and limiting “Subject area” to “Engineering”, “Computer Science”, “Economics, Econometrics and Finance”, and “Business, Management and Accounting”, on 27th August 2023)

Over the past few years, DAO has garnered increasing research attention within academia across diverse scholarly disciplines. Fig. 2 demonstrates the increase in the frequency of academic publications on DAO-related topics, with the number of studies nearly tripling in the past four years. DAO has demonstrated great promise in different fields such as finance (Zichichi et al. 2019), healthcare (Mateus and Sarkar 2023), and education (L. Page and Elmessiry 2021). Despite the growing research interest in DAOs, comprehensive surveys on DAOs within the built environment context are still lacking. Although, there are discussions on the potential DAO use cases in the construction industry as well as a conceptual framework of DAO in the network design of the AEC industry (Sreckovic and Windsperger 2019; Dounas and Lombardi 2022), prior studies have yet to provide rigorous reviews on the current status and potential of DAO adoption in built environment-related areas. Therefore, this study aims to bridge this gap by providing a comprehensive literature review that synthesizes the existing body of knowledge on DAO applications in the built environment domain, by assessing the present state of DAO adoption in the built environment, drawing key insights from early DAO and blockchain use cases, and pointing out future research directions.

2. Goals and Objectives

This study seeks to provide a survey on the DAO technology, examine the existing technical challenges and limitations in DAO implementation, offer the latest reviews on DAO applications, and investigate its potential use cases in the built environment domain. The goals of this paper can be summarized in four main objectives: (1) to carry out an evaluative survey of DAO including its governance characteristics, technical implementation, operational mechanism, and voting models (2) to review and discuss existing applications of DAO in the built environment-related areas including smart cities, smart government, transportation and construction industry (3) to examine the potential challenges of DAO implementation and (4) to examine the potential opportunities for implementing DAO in the three key areas including construction management, facility management, and artificial intelligence integration.

The following is the structure of the remaining content of this manuscript. Section 3 outlines the methodology of the systematic literature review adopted in this study. This includes study identification, details on the inclusion criteria, and methods for the review and analysis. Section 4 addresses objective (1) and objective (2) by presenting the results of the DAO survey including its characteristics, voting mechanism, operation mechanism, and technical implementation as well as the review of the DAO use cases in the built environment domain. A discussion on the limitations of DAO is also provided to address the objective (3). Section 5 addresses objective (4) by discussing research trends and potential improvement strategies for future DAO research as well as providing insight and guidelines into its three potential use cases in the built environment. Finally, section 6 concludes the paper by providing a summary of the key contributions and limitations of this study, and recommendations for future research.

3. Research Method

3.1. Identification

The primary databases used for conducting literature searches in this study are Scopus and Web of Science (WoS).To comprehensively examine the existing and potential use cases of DAO in the built environment, an extensive search query was formulated to gather relevant literature. The search query used and the adopted methodology for the systematic literature review in this study are illustrated in Fig. 3. The search strings employed in this study were iteratively refined through multiple rounds of testing and carefully crafted to comprehensively capture a broad range of relevant publications, encompassing not only explicit mentions of DAOs but also related concepts, technologies, and potential application areas within the built environment. The primary search string consisted of two main components: the first part focused on identifying publications mentioning DAOs using keywords such as "decentralized autonomous organization*," "dao," and "daos," while the second part incorporated an array of terms related to the built environment, enabling technologies that are associated with the implementation of DAO or its potential use cases. These keywords included "built environment," "construction," "architecture engineering construction," "transportation," "smart city," "design," "artificial intelligence," "machine learning," "internet of things," "digital twin*," "blockchain," "distributed ledger," "smart contract*," "distributed network," "consensus mechanism," "governance," "autonomous organization*," "self-governing," "dao framework," and "dao platform." The inclusion of terms like "machine learning" accounted for the potential integration of AI with DAO systems, particularly in areas such as AI-enabled decision-making, automation, and decentralized intelligence (Singh and Chopra 2017; Cao 2022). Additionally, the term "smart city" was included in both singular and plural forms to ensure comprehensive coverage of the literature, as studies may refer to the concept in either form, such as "smart cities", when discussing multiple instances or examples. Conversely, the term "cryptocurrency" was retained only in its singular form, as it effectively represents the entire category of cryptocurrencies, aligning with the focus of this study which aims to discuss decentralized autonomous organizations (DAOs) with the concept of cryptocurrency or governance token in general, rather than any specific type of cryptocurrency. In addition, the term "architecture engineering construction" was initially included in the search string but was later removed after the initial round of search results revealed that its presence did not yield additional results beyond those already captured by the broader term "construction." However, the term "aec" is retained, as some papers may use this abbreviation without including either "construction" or "architecture engineering construction." Similarly, the term "BIM" was added in addition to the term "digital twin*" in the initial search string but later removed because it did not alter the search results, as relevant studies might be already captured by broader terms such as "construction" and "digital twin*".

In addition, it is also important to note that the field of decentralized autonomous organizations is relatively nascent, and the academic literature on their applications is still emerging. As a result, some of the relevant literature, particularly those published as whitepapers, preprints, or reports by organizations and companies, may not yet be indexed in traditional scholarly databases like Web of Science and Scopus at the time of this study. To ensure a comprehensive review, the snowballing techniques (Wohlin 2014) were also used to identify relevant papers that hadn't been found through the traditional database search. This approach involved systematically reviewing the references cited in the initially identified articles (backward snowballing) and searching for articles that cited the relevant studies (forward snowballing). Google Scholar is chosen as the main tool for the snowballing process because of its extensive coverage of scholarly literature (journals and conference papers, whitepaper, etc.) and citation tracking capability.

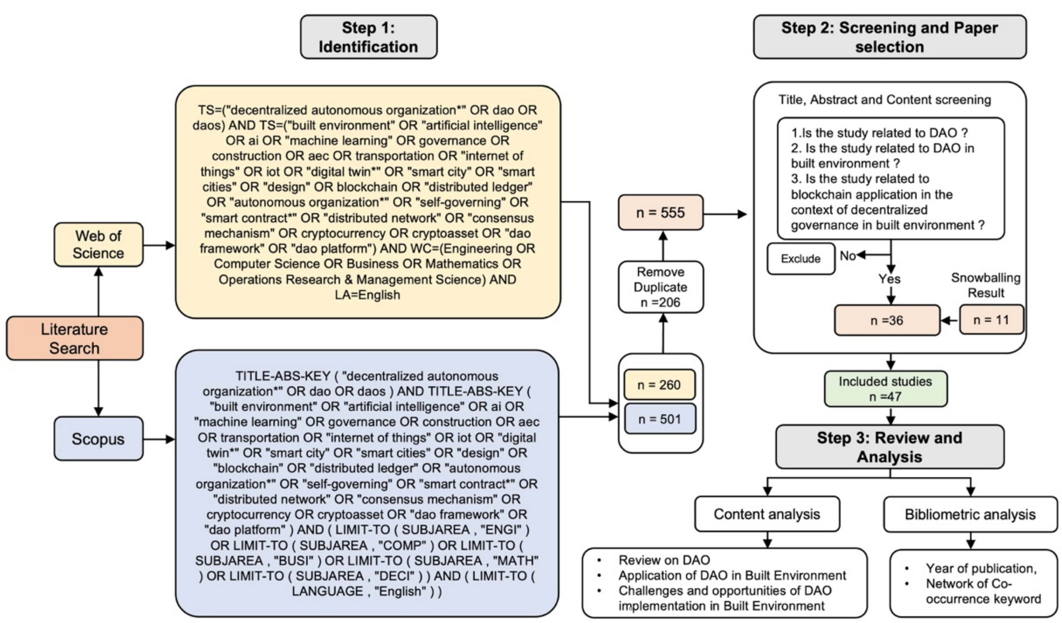

Fig. 3 Stages of the systematic literature review conducted in this study

3.2. Screening and paper selection

To ensure a comprehensive review of DAO and assist the exploration of its possible use cases in this field, this paper considers all available sources of the literature that are identified as long as the literature is relevant to the topics of DAO and related to the built environment. These include preprints, white papers, book chapters, conference papers, and journal articles. Also, there aren't any restrictions applied on the published date of the selected studies in this study. As of August 27, 2023, the literature search conducted on Scopus and WoS database returns a total of 761 publications. The title, keywords, and abstract of each paper are used for abstract screening to determine whether the article is eligible for inclusion. To select relevant papers for inclusion, studies were assessed based on three key criteria. First, the study must be related to DAO in some capacity by focusing on DAO characteristics, mechanisms, implementations, or potential applications. Second, the research must pertain to the built environment-related area. Finally, the study must examine blockchain or distributed ledger technology in the context of decentralized governance applications in the built environment. Papers that met one of these inclusion criteria were selected for further detailed review. The introductions, methodologies, results, discussion, and conclusion of each of the papers identified in the previous step are later closely reviewed and evaluated by the authors to determine their relevance to the scope of review and whether they address the objectives of this study. In addition, an article that does not directly center on DAO but has its content serves as an insight for proposing future implementations of DAO in the built environment was also selected for inclusion. After duplicate removal, the titles, abstracts, and full-text screening were conducted based on the mentioned inclusion filters, and the number of primary selected studies was narrowed down to 36. An additional 11 articles were included after the completion of the snowballing process on the primary selected studies.

3.3. Data analysis

Among the 47 selected articles, 14 of them are research and review papers on DAO. The data extracted from this set of literature were analyzed and classified into different groups, including characteristics, operational and voting mechanisms, technical implementation, and limitations of DAO. In addition, 16 out of the 47 articles focus on the existing DAO application in the built environment. The existing built environment-related DAO applications are summarized in Table 1. The key seven themes are design, construction management, smart cities, smart government, transportation, self-governing entities, and business and organizational structure. Finally, the remaining 17 papers selected in this study are not directly related to DAO application, but to some extent serve as the source of inspiration for future DAO use cases and the three key potential areas including construction management, facility management, and artificial intelligence integration. VOSviewer (Van Eck and Waltman 2010) was also used for conducting a bibliometric analysis of the included literature.

Table 1 Categorization of current DAO applications in the built environment

Research area	Number of studies	Reference
Design	2	(Dounas et al. 2022b) (Dounas and Lombardi 2019)
Construction management	1	(Darabseh and Poças Martins 2023)
Smart cities	3	(Mendoza and Behrens 2020) (Rawat et al. 2022) (Bernovskis et al. 2023)
Transportation	3	(Zhao et al. 2022a) (Hou et al. 2021) (Copel and Ater 2017)
Smart government	3	(Guidi and Michienzi 2022) (Diallo et al. 2018) (CityDAO 2021)
Business and organizational structure	3	(Wang et al. 2023) (Li et al. 2023) (Monteiro and Correia 2023)
Self-governing entities	2	(Hunhevicz et al. 2021) (Seidler et al. 2016)

4. Results and Discussion

4.1. Research trend: bibliometrics analysis

A network visualization analysis was conducted using a visual mapping application, VOSviewer. A collection of 34 research papers from the included studies consist of 333 keywords with 45 keywords appearing in at least two papers. The keywords unrelated to the scope of this study were manually filtered out, leaving only 38 relevant terms for the analysis. A network of co-occurring keywords from the included studies is shown in Fig. 4. The size of the individual node in the visualization demonstrates the rates of occurrence of the keyword and signifies its importance in the network. The larger the node indicates the higher frequency and greater importance in the literature. The distance between keywords represents their relatedness or similarity. The keywords with shorter distances are more closely related and vice versa. The keywords that are clustered together are strongly interconnected. The color of the node indicates the cluster that it belongs to. In network visualizations, categories that have a large number of connections to other nodes tend to be positioned toward the center. The centrally positioned clusters indicate that its core concepts are relevant and have linkage across the knowledge domain.

Based on the retrieved network visualization, the central blue cluster includes DAO-related concepts like decentralization, governance, and distributed ledgers which demonstrates its strong connections and relevance in any DAO applications. The terms “decentralized autonomous organization” and “blockchain” also possess strong interconnections, indicating that they are closely linked concepts. The proximity of the term “decision making” to both “blockchain” and “decentralized autonomous organization” also highlights the critical importance of governance and decisions within DAO frameworks. The connection between the term “decentralized” to these core topics also underscores the distributed and non-hierarchical nature of DAO as its main underlying principles. The red cluster contains keywords that directly relate to construction and built environment such as architectural design, building information modeling, construction, and project management which reflect the outcome of this research on the DAO’s use cases in the collaborative design and construction management domain. Additionally, green clusters comprise emerging technologies such as web3, metaverse, and NFTs which reveal the promise for DAO to create novel forms of digital engagement, assets, and organizations. In the purple cluster, artificial intelligence and human-machine collaboration highlight the potential for integrating AI with DAO. These terms indicate the possible synergy between automation and intelligence in augmenting DAO functionality and decision-making. The term “Internet of Things” and “distributed computer systems” describes the connected and technologically advanced nature of smart cities, another key area of the identified use cases of DAO in the built environment. For the yellow cluster, technical concepts like parallel intelligence and parallel governance indicate applications of these technical capabilities for organizing and managing built environment-related activities such as smart cities and transportation operations.

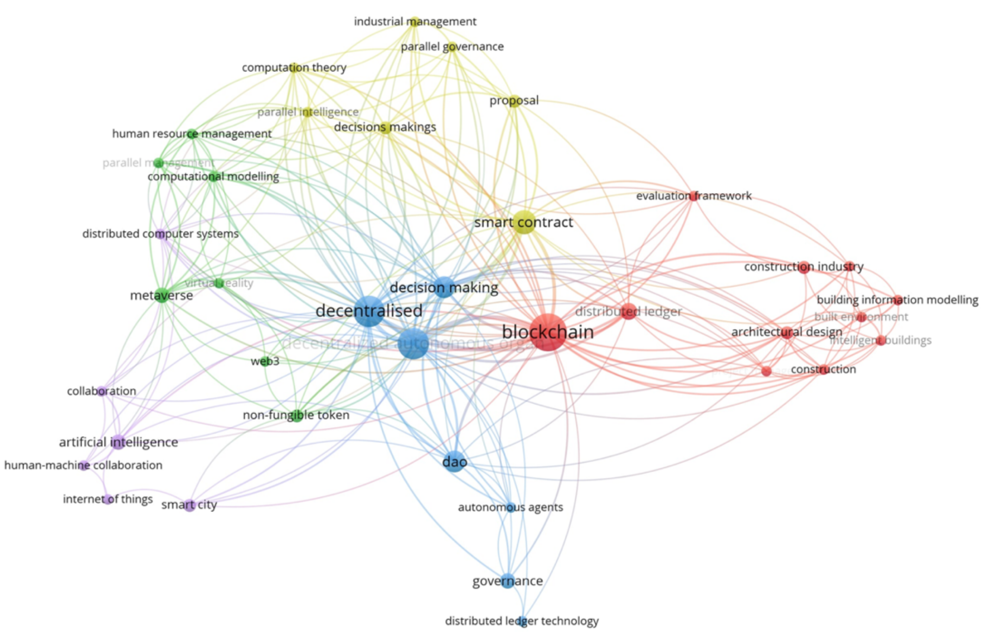

Fig. 4 A network of co-occurring keywords in the selected studies

The sources for the included studies include top journals in the field of blockchain technology and built environment such as IEEE Transactions on Systems, Man, and Cybernetics, IEEE Transactions on Computational Social Systems, IEEE Access IEEE Network, and Automation in Construction. The breakdown of different source types of the selected studies is shown in Table 2. The distribution of the publication years of the 47 articles included in this study is also depicted in Fig. 5(a). Among them, 28 articles either focus on DAO applications in built environment or provide valuable insights for future DAO use cases within this domain. The range of publication years for these 28 articles is also presented in Figure 5(b). This growth in publication volume indicates the increase in attention from both the academics and industry communities on DAO capabilities in the built environment which demonstrated the momentum of DAO in becoming a new disruptive technology in this research domain.

Table 2 Sources of included studies in the review

Publication	Number of Articles
Journal	15
Conference	19
Book chapters	3
White Paper	3
Preprint	7
Total	47

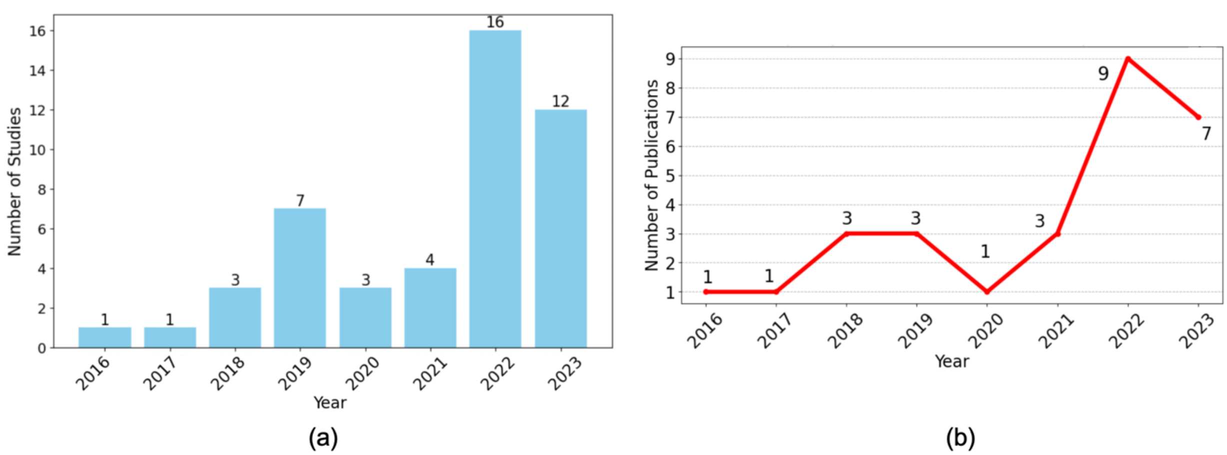

Fig. 5 (a) Year of publication of the 47 included studies (b) Range of publication years for the 28 articles that either discuss DAO applications in the built environment or offer insights for future DAO use cases within this domain.

4.2. Decentralized Autonomous Organization (DAO)

4.2.1. Governance characteristics

The fundamental pillars underlying DAO's organizational model are its three common distinctive features: decentralization, autonomy, and automation (Wang et al. 2019a). DAO's operational mechanism is based on a bottom-up interconnection and collaboration between different network nodes on the blockchain which is not controlled by any centralized governing hierarchy (Singh and Kim 2019). Fig. 6 illustrates the differences between the structure of DAO and traditional organization. In addition, DAO is designed to be a self-governing and autonomous organization through the participation of the decentralized peer-to-peer community and the utilization of a token-based incentivization (Santana and Albareda 2022). DAO's members can initiate and vote on proposals or changes to their organization. The smart contract's encoded rules and regulations facilitate DAO's autonomous operation and task execution without any centralized management. Also, DAO leverages automation capability through smart contracts, which execute transactions based on predefined rules (Dwivedi et al. 2021). With the immutable and transparent nature of blockchain, this automation can foster efficiency, cost reduction, and trust in the organization. Table 3 provides the comparison between the voting system in DAO and conventional centralized organization.

4.2.2. Implementation of DAO

This subsection outlines the key phases in DAO development including the planning, technical implementation, and the operation of DAO. Fig. 7 illustrates an overview of different components within the core phases of DAO development from DAO conceptualization to having a fully operational DAO. The first crucial step in launching a DAO is to conduct the necessary planning to determine the purpose and structure of the organization. These should include the goals and expectations of DAO, the target problems, and the governance structure such as voting systems and rights. Members also need to decide on token supply allocation, incentives mechanism, and voting-related settings (proposal velocity, voting period, voting models) (Liu et al. 2021). Next, DAO developers have two primary options for implementing the technical aspect of DAO. They can either choose to code the rules from scratch or leverage the existing DAO as a service platform (El Faqir et al. 2020).

A custom DAO can be built from scratch, using programming languages like Solidity (Wang et al. 2021) or Golang (Foschini et al. 2020) for Ethereum or Hyperledger-based DAOs, respectively. These options provide extensive customization flexibility, but the development demands higher specialized blockchain expertise. However, open-source libraries such as Openzeppelin can accelerate development by offering boilerplate codes and modules for creating smart contracts (Pierro and Tonelli 2021). Custom-built DAO provides granular control over different aspects of DAO's operation including membership, voting models, proposal settings, and tokenization. Alternatively, users can utilize DAO creation platforms including Aragon, DAOstack, Colony, and Moloch to access DAO templates and creation tools without programming knowledge (Rikken et al. 2023). These platform offers user-friendly interfaces and enable faster configuration and setup but provide less customization compared to full-stack custom development. Once the related smart contracts are deployed, the operational phase of DAO begins. Members can now start submitting proposals for votes. This proposal can be anything, from suggesting changes to the DAO's operations to funding initiatives.

Table 3 Comparison between the voting in DAO and traditional voting method

	DAO Voting	Traditional Voting
Process	Automated through smart contracts	Require manual handling
Transparency	Transparent and auditable	Relies on the system's internal trust and transparency
Accessibility	Anyone with tokens can participate	Voting might not be available for everyone in the organization
Governance Structure	Decentralized and community-driven	Centralized authority
Security	Built on immutable blockchain technology	Relies on secure voting infrastructure, protocols, and centralized server security

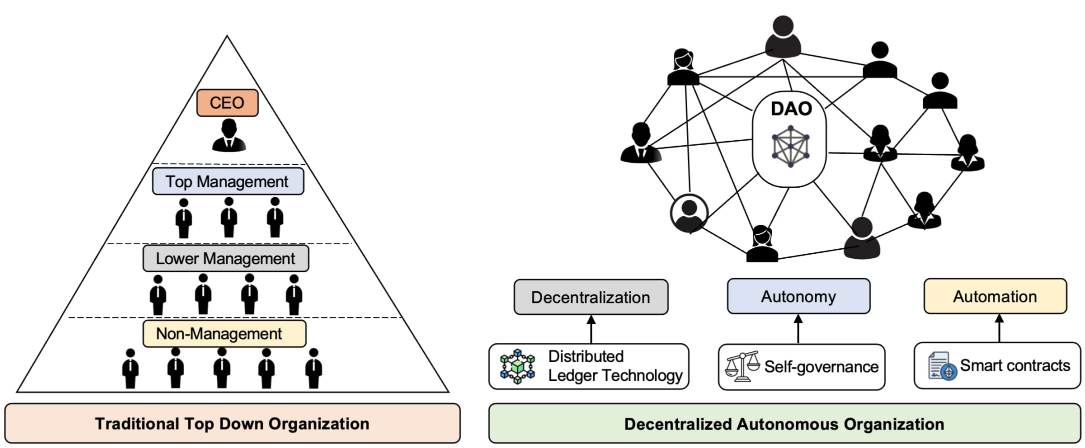

Fig. 6 The difference in structures between the traditional Organization and Decentralized Autonomous Organization

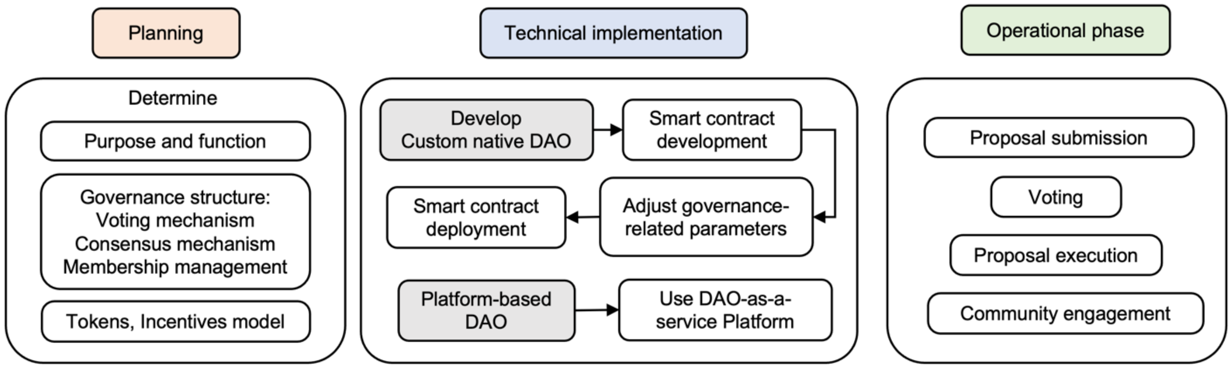

Fig. 7 Overview of key stages in DAO development

4.2.3. Operational mechanism

The majority of DAOs today are open to the public through a token-based membership whereas the possessed tokens can be regarded as DAO cryptocurrencies and voting rights. Incentive mechanisms are also essential in motivating member participation in DAO governance-related activities (e.g., voting) and aligning member interest with future DAO's objective (Qin et al. 2023). There are several common types of incentive design. Some DAOs use internal governance tokens to incentivize membership and reward contributions. These tokens determine the user's voting rights and power over the decision-making process. DAO also awards non-transferable reputation points or badges for contributions. Those who engage actively in the community will gain a greater reputation which in turn can be converted into increased voting power. (Saito and Rose 2023). DAO operates on blockchain networks, which require some sort of consensus model to be functional. The choice of consensus algorithms can also affect the governance mechanism of DAO. Certain consensus models might indirectly lead to problems of centralized governance (Wang et al. 2019a). For instance, the voting mechanism with proof-of-stake characteristics can be vulnerable to voting manipulation by large token holders.

In addition, voting processes are the core functionality of any DAO. Proposing a proposal, casting votes, and executions are the main aspects of the voting procedure in the DAO (Ding et al. 2023a). The voting rules and procedures are predefined in the DAO's smart contract code. This includes criteria like who is allowed to vote, the options to vote on, voting period, voting delay, required votes to meet quorum/thresholds, etc. Before the actual on-chain voting process commences, DAO members typically engage in a series of off-chain activities aimed at fostering community engagement, consensus-building, and informed decision-making. These activities often involve proposing, refining, and discussing proposals through various communication channels such as forums, chat groups, and virtual meetings (Zhao et al. 2022b). Community feedback will be incorporated into proposal revisions, ensuring that the final proposal reflects the collective wisdom and consensus of the DAO members. DAO members may also employ off-chain voting mechanisms such as signal voting, which functions as polling software that enables the DAO community to express its intentions without immediate execution of actions on the blockchain. Currently, Snapshot is a popular platform for off-chain voting (Wang et al. 2022b). Once the proposal is submitted for on-chain voting, a voting delay period will be activated. This delay allows voter ample time to review the proposal thoroughly, engage in discussions, to make an informed decision-making before casting their votes. Once the voting period starts, the voting smart contract activates, and eligible member can cast their votes by submitting transactions to the smart contract with the results transparently recorded on the ledger. DAO members may opt to use the native voting functionality on the DAO platform or multi-signature voting platforms such as Gnosis Safe to collectively manage funds and vote on proposals (Ding et al. 2023b). The votes are recorded on the blockchain as transactions interacting with the smart contract and will be calculated at the end of the voting period (Monteiro and Correia 2023). Following the voting period, a minimum delay period will be activated before the contract execution. This delay provides a window for members to challenge the decision or withdraw their support, if necessary, thereby ensuring that decisions are made with careful consideration and preventing hasty or impulsive actions. If the vote thresholds are met, the smart contract will automatically trigger corresponding actions and update the ledger accordingly. Those actions may include fund transfers, contract updates, etc. The interactions between the voting mechanisms, smart contracts, and distributed ledger technology are illustrated in Fig. 8. Voting incentives in the form of token rewards, reputation points, or governance rights, can also be implemented to increase voter turnout and ensure that decisions are made with the input of a diverse and engaged community (Liu et al. 2022).

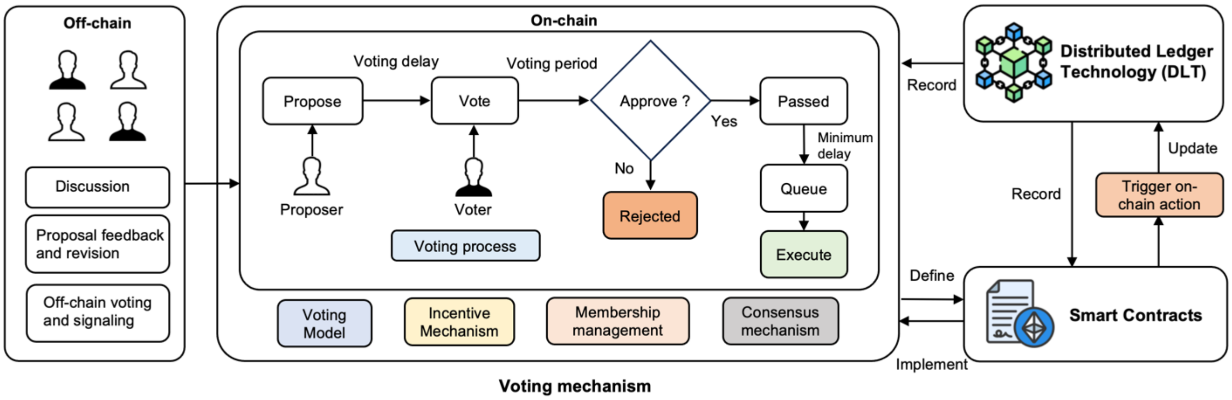

Fig. 8 Relationship between voting mechanism, smart contracts, and distributed ledger technology

4.2.4. Voting mechanisms

This study has identified ten distinct voting mechanisms that are used in DAO. These include token-based quorum voting, quadratic voting, conviction voting, holographic consensus, liquid democracy, rage quitting voting, multi-sig voting, knowledge-extractable voting, permissioned relative majority, and reputation-based voting (Ding et al. 2023b; Fan et al. 2023).

Token-based quorum voting is one of the widely adopted DAO voting mechanisms where the number of tokens equals the number of voting rights (Bellavitis et al. 2022). For a resolution to pass, a particular percentage of DAO members are required to cast their votes. The decision must receive enough votes to meet the pre-defined threshold to win.

Permissioned Relative Majority (PRM) is a DAO's voting system that doesn't require the attention of the majority of DAO members to reach a decision (Fan et al. 2023). PRM only considers the relative majority to determine the approval or rejection of a proposal, without imposing any requirement on the number of members participating in each voting process. The threshold for approving the proposal is determined as fifty percent of the total votes counted in this proposal.

Quadratic voting is an alternative voting scheme where the weight of the ballots is proportionate to the number of tokens (Ferreira et al. 2023). In this model, the number of votes is equivalent to the token's square value. One of the important goals of this model is to mitigate token concentration and offer a fairer voting system.

The conviction voting system values the firm commitment of voters on a particular subject matter where the influence of a vote is correlated to the amount of time of the unchanged decision (Ding et al. 2023b). The voter needs to stake their token to cast their vote and the longer the members hold on to their votes, the more powerful the votes become.

Holographic consensus is another form of DAO-distributed consensus. It was created by DAOstack to improve proposal selection, voting, and user engagement in DAO. In this model, users are incentivized to predict which proposals are most likely to be successful by staking their GEN tokens for or against proposals. Users are rewarded with more GEN tokens if their prediction is consistent with the final voting result, otherwise their staked GEN tokens will be taken.

In addition, the Liquid democracy voting model provides members the option to either cast the vote themselves or delegate their votes to a representative with higher expertise (Fan et al. 2019). This voting method increases the effectiveness in terms of informed decision-making as the representative is generally more knowledgeable than the typical DAO member.

Multi-sig voting is another DAO voting scheme in which multiple signatures and approvals from different stakeholders are required to execute any transactions or governance actions (Hardwick et al. 2018). This is to ensure that no single entity can independently take control of the organization's decision. This promotes decentralization and alignment with community interests.

Rage quitting is a voting mechanism where voters are allowed to withdraw their funds or tokens from a DAO if they have any dissatisfaction with proposals or outcomes of votes. Therefore, this voting scheme incentivizes DAO members to avoid proposing an initiative that doesn't serve the interest of the majority of voters.

Knowledge-extractable voting (KEV) is a voting mechanism that is designed to incorporate domain-specific knowledge or expertise as well as the reputation of the community member for the DAO's decision-making process to create a so-called expertise-based governance system (Fan et al. 2023). In a traditional one-token-one-vote system, decisions are made based on the number of tokens held by each voter, regardless of their actual knowledge or expertise in the matter being voted upon. KEV seeks to address this limitation by introducing a mechanism that weights votes based on the relevant domain knowledge, expertise, and reputation of the voters. Voters will be rewarded with more reputational tokens if their endorsed proposals are approved. Conversely, their token will be reduced if the proposals are unsuccessful.

Finally, Reputation-based voting is another voting model where the voters' influence is determined by their credibility or reputation within the community (Saito and Rose 2023). Compared to pure token-based voting where wealth equals power, this mechanism gives more governance influence to the member who invested in the advancing DAO success.

In summary, each DAO voting method offers unique mechanisms to solve issues like participation, representation, and incentivization in decentralized governance. However, they also carry trade-offs between complexity, efficiency, and potential limitation. The advantages and disadvantages of each voting mechanism are listed in Table 4.

Table 4 Comparison of different DAO voting models

Voting Models	Characteristics	Strengths	Weaknesses
Token-based quorum voting	The number of tokens equals the number of voting rights.	Encourage a high level of participation which helps ensure that the decisions reflect a broader consensus of the community.	Risk of token concentration and voting manipulation. Low participation rates can result in decision deadlock.
Permissioned Relative Majority	The proposal's approval threshold is fifty percent of the total votes cast.	Enable quicker decision-making with no required of higher participation.	Vulnerable to slip-through proposals without the awareness of the member. Risk of concentrated power.
Quadratic voting	The number of votes is equivalent to the token's square value. (e.g., 1 token = 1 vote and 4 tokens = 2 votes).	Encourage thoughtful and informed voting. The additional cost of casting more votes help minimize power concentration.	Possess the risk of token concentration and voting manipulation. Vulnerable to Sybil attack where malicious actor create multiple identities (or wallet address) to accumulate more voting power and manipulate the outcome of the voting process.
Conviction voting	Voters are required to stake their token to cast their vote and the longer they hold on to their votes, the greater the influence of their votes.	Demonstrate voter's interest and commitment with the community's long-term goals	Impractical for time-sensitive decision
Holographic consensus	Voters are incentivized to predict the successful proposal by staking their tokens for or against proposals.	Encourage thoughtful and informed voting.	Complex to implement. Risk of having hyped and biased prediction.
Liquid Democracy	Voters can cast the vote themselves or delegate their votes to a representative.	Voting flexibility and efficiency	Lack of community cohesion and engagement. Reduced level of decentralization.

The multi-sig voting	Multiple approvals from different stakeholders are needed to execute any transactions or governance actions.	Mitigate consolidated power, promote decentralization and alignment with community interests	Decision deadlock if no consensus reached
Rage quitting voting	Voters have the option to withdraw their funds from a DAO if they are dissatisfied with proposal outcomes.	Encourages proposals that align with the interests of the majority	Impractical for time-sensitive decision due to implemented grace period
Knowledge-extractable voting	Integrate the knowledge, expertise, and reputation of the community members for the effective DAO's decision-making.	Expertise-based governance More informed decision and better outcome	Complexity in implementation as it is challenging to design the algorithms to accurately measure and quantify the expertise and reputation of community members and assess the quality of their contributions.
Reputation-based voting	Voters' influence is determined by their credibility or reputation within the community.	Promote meritocratic decision-making by giving more power to those with more contributions	Effective reputation system is relatively complex to implement

4.3. Application of DAO in built environment

This section presents the review of existing use cases of DAO in seven key categories as follows: (1) Design, (2) Construction management, (3) Smart cities, (4) Smart government, (5) Transportation (6) Self-governing entities and (7) Business and organizational structure. These areas represent major domains within the built environment that benefit from decentralized, autonomous systems enabled by DAO. In the field of design, DAO can facilitate more collaborative, decentralized design processes. DAO is relevant to the field of construction management domain due to its capability to enhance project governance, planning, and transparency. Smart cities, smart government, and transportation are also the areas where coordination and governance can be enhanced with the given ability and characteristics of DAO. The autonomous nature of DAO can also directly benefit the application of self-governing entities. Finally, business and organizational structure can also be improved by DAO principles with decentralization of the processes and decision-making. The summary of the concepts, potential use cases, and existing application of DAO discussed in this section are shown in Table 5.

4.3.1. Design

The collaborative design processes in the construction are based on centralized control and lack of transparency (Singh and Ashuri 2019; Tao et al. 2022). Design decisions are highly concentrated by a small group of people without all stakeholders' consensus which can lead to dissatisfactory results for the users. DAO could address these problems by employing decentralized governance models that promote transparency and democracy in participation and the collective decision-making process.

Studies have highlighted that implementation of DAO in collaborative design could foster collaboration between related stakeholders that could lead to a more effective design solution. In the work undertaken by Dounas et al. (2022), the integration of the stigmergic principle, blockchain immutability, and DAO's decentralized governance was proposed to foster collaboration and collective ownership in architectural design. The proposed system, ArchiDAO, essentially operates as a decentralized design studio based on blockchain where any designer can join and work collaboratively on the project. The ArchiDAO non-fungible tokens are used for governance purposes and project engagement records. Also, members can post new projects and specify the requirements and skill preferences whereas any qualified members can stake their tokens to participate to earn fungible tokens as incentives. Similarly, Dounas and Lombardi (2019) proposed a reputation system-based DAO for architectural design with shape grammars within a decentralized application (DApp) (Cai et al. 2018). In their proposed platform, grammar rules submitted by grammatists/members will undergo a voting process to be selected and used in the subsequent phases of the design.

DAO-issued token, GEN token, and each member's reputation both play important roles in voting. Senior grammatists often have more voting power depending on their reputation, experience, and contribution to the DAO.

In these innovative works, the utilization of DAOs empowers collaboration between designers and stakeholders and contributes to the democratization of architectural design processes. This decentralization and collective ownership not only promote creativity and collaboration but also enhance transparency and fairness in decision-making within the architectural design community.

4.3.2. Construction management

In traditional construction projects, decision-making power typically resides among a small number of people such as managers or executives (Senaratne and Samaraweera 2015). The decision may serve the interests of a few rather than the collective benefits of all involved stakeholders. DAO offers a model to decentralize and democratize construction management by implementing voting for the decision for the project's related activities such as resource allocation. Using the platform-based DAO approach (Aragon), Darabseh and Poças Martins (2023) have demonstrated a DAO use case in real-world construction practice by creating a prototype of a decentralized governance system for construction projects. The developed platform aims to provide a trustless management system that can decentralize decision-making and improve the project workflow. In this proposed approach, DAO is used for resource pooling purposes where multiple contractors can come together into a blockchain DAO and achieve a particular goal, such as funding an innovative solution to enhance their business operations and projects. The member needs to contribute some money to the DAO treasury and, in turn, gain the voting power to decide on the future proposal. However, the process within the construction project can be extremely complex and further studies are needed to examine the best practice for streamlining the project data to the DAO's smart contract in enabling automated decisions and execution.

4.3.3. Smart cities

Smart cities utilize digital technology to improve city governance's operation and management efficiency and utilize innovative technological solutions with the city infrastructure to improve public service and people's welfare (Petrolo et al. 2017). However, most smart cities' infrastructure still heavily relies on centralized systems, which are prone to security risk and are inefficient (Cui et al. 2018). With such a centralized management system, citizens also tend to have less participation in decision-making and influence on decisions that impact their lives (Oliveira et al. 2020). The service provided by such a system might not be efficient enough to meet the community's requirements.

Research has shown that DAO could offer an opportunity to shift the power dynamics with the use of decentralized governance to enable fair public involvement in city policies, resource allocation, infrastructure projects, and more. To provide stakeholders and citizens control over their city's public resource allocations and decisions, a DAO-powered and civic collaborative framework for smart cities, Arbiter has been developed (Mendoza and Behrens 2020). The system suggested by the study integrated the cyber-physical system of the city infrastructure, edge-based computing technology, and DAO's collective decision-making mechanism to provide decentralized management and enhanced data privacy on top of the optimized public services. In addition, different studies have implemented blockchain-based systems to efficiently and transparently track and trade carbon credits in different building life cycle phases (Woo et al. 2021; Yang et al. 2023). In the quest to address the climate change problem and eliminate fraud in carbon trading, Rawat et al. (2022) developed a blockchain-driven model for carbon accounting and governance. In addition to the conventional capability of blockchain technology, the proposed framework possesses a DAO-based decentralized governance mechanism that allows stakeholders to engage and vote on critical decisions. This enhances transparency and accountability and ensures that the system aligns with the broader goals of the global effort to tackle environmental problems. Also, Bernovskis et al. (2023) proposed the idea of integrating gamification with DAO and blockchain-related technology such as tokenization to incentivize and encourage sustainable and prosocial activities among residents in smart cities. In their framework, different token types such as utility, security, and governance tokens NFT can be used for transactions, governance, and incentives within DAO.

Overall, DAO offers opportunities for decentralized governance and empowerment in cities. However, the studies also acknowledge several challenges in DAO adoption in cities which include regulatory and legal problems and security risks. Thus, additional studies are required to address the related problems and develop best practices for DAO implementation in cities.

4.3.4. Smart government

Urban governance and public service often suffer from inefficiency, lack of transparency, and inadequate public participation (Fourie and Poggenpoel 2017). Studies have highlighted the potential of DAO's novel governance model that could address these challenges and transform the nature of public services and management model by providing transparent, secure, automated processes, transparent decision-making frameworks that could foster efficiency, cost reductions and increased citizens' engagement in their communities' decision. In the work undertaken by Diallo et al. (2018), eGov-DAO, an integrated DAO and e-government system has been proposed to enhance collaboration for e-governance. This innovative framework aims to offer a secure, robust, and transparent platform for government services. To assess the effectiveness of the framework, this study also provided a practical use case in the context of government contracting services. The research found that the proposed system can handle the complex and high-volume workloads of modern governments although with minimal performance limitations. Further improvements to blockchain's scalability such as decreased latency and transaction throughput are still needed. CityDAO is another DAO-based project that demonstrated the concept of decentralized asset ownership in the world of blockchain (CityDAO 2021). CityDAO aims to build a future blockchain-based city by using the concept of land tokenization and decentralized governance. Through smart contracts, users can purchase certificates to gain citizenship of that land. The CityDAO citizens decide the policy and regulations of that land through DAO's voting mechanism. In the proposed system, the token holder or citizen can decide on the location of a new structure to be built on the ground or which land to buy next for further expansion in the future. Similarly, the Decentraland platform further demonstrates the potential of DAO's governance capability in the metaverse (Guidi and Michienzi 2022). Decentraland is a DAO-driven 3D virtual platform that enables users to exchange goods ownership and services on the blockchain network. It utilizes a gaming-like environment, integrating a DAO's features, such as governance tokens and a decentralized government mechanism.

4.3.5. Transportation

The complexity of modern transportation systems has raised several management challenges including governance, lack of collaborative framework between different systems, and data security (Khoshavi et al. 2021). To address these governance problems, Hou et al. (2021) developed a DAO-based model for an Intelligent Transportation System (ITS). In the proposed framework, the data collected by the physical components such as transportation and logistics systems will be securely stored on blockchain and analyzed using artificial intelligence and big data. DAO's voting mechanism provides collaborative decision-making whereas smart contracts then automate tasks and execute governance decisions. Together, the physical data sources, technical systems, governance, and automation mechanisms collectively address the existing trust, collaboration, and decision-making challenges in ITS. Similarly, Zhao et al. (2022) contributed to the advancement of intelligent transportation management by developing TransVerse, a DAO-powered ITS framework. TransVerse aims to establish a federated intelligence network to enable smart mobility and address the challenges associated with top-down management in transportation systems. The study also demonstrated the use cases of the system in traffic signal coordination. In the ride-sharing industry, Copel and Ater (2017) presented the concept of the Decentralized Autonomous Vehicle (DAV), a DAO-based decentralized transportation network aiming to link self-driving vehicles together and provide a platform to make those vehicles discoverable by the users who need them. The platform, with its vast IoT network, aims to provide users access to vast networks of self-driving vehicles available to them on demand. At the same time, with blockchain tokenization, self-driving car owners can also make revenue from the vehicle when they're not using it.

4.3.6. Self-governing entities

In recent years, different research and prototypes have demonstrated the potential of employing DAO in the creation of web3-inspired autonomous systems and entities. Wang et al. (2022) introduced the engineered ownership concept by proposing a blockchain-based system with automation capabilities with distributed rights and power shared between autonomous agents. Similarly, Chang and Johar (2022) also proposed the concept of a civic, self-owned, and autonomous infrastructure using blockchain technology. DAO could be the potential core enabling technology in the operation of these autonomous entities. In such cases, the entities' daily operations will be run by pre-defined rules on smart contracts while having funds and financial records stored on the blockchain. The organization's governance, rules, and decisions are made by its members through a secure voting mechanism and automatically executed with a smart contract. Recent work by Hunhevicz et al. (2021) has also explored the idea of a decentralized autonomous space with the prototypes of the self-governing meditation space. This application illustrates how DAO can be operated on a tangible entity. The proposed system operates autonomously in creation (design and construction) and operational management (finance, operation, and maintenance) by following the written instructions in the smart contract. This has given rise to the idea of self-owning a physical space, a constructed environment that is self-sustaining. Similarly, the Terra0 project explores what can happen when a DAO is applied to organic matter or ecological entities like a forest (Seidler et al. 2016). The case of Terra0 illustrates a scenario where a forest can intelligently exploit its resources by selling its logging license with blockchain's smart contract automation process. These applications showcase the possibility of the entity in the built environment capable of managing and sustaining itself with only a set of self-executing mechanisms controlled by smart contracts and without the need for intervention from centralized management.

4.3.7. Business and organizational structure

The autonomous, automated, and decentralized characteristics of DAO combined with tokenization allow for the creation of innovative business models for future organization design (Saurabh et al. 2022). To address the problem of information asymmetry and lack of transparency within the traditional centralized organization, Wang et al. (2023) developed EnDAO, a DAO-based parallel enterprise management model for a corporation's distributed management. In the proposed system, the digital version of the physical organization or enterprise is built and run on the blockchain network with the current state of physical entities in real time using the collected data from IoT or sensors. By using the parallel execution concept and interactive feedback between the digital and physical enterprise, EnDAO can provide intelligent management and prediction of physical entities thereby enhancing its decision-making capabilities. Similarly, Li et al. (2023) proposed another DAO-driven parallel management framework that enables interaction among people, machines, and virtual humans spanning the physical, psychological, and artificial space.

The integration of parallel management and DAO applied in the above works enables closed-loop feedback between virtual and real worlds to guide management decisions in a decentralized manner to enable smarter organization and operation. In addition, Monteiro and Correia (2023) developed a DAO-based public procurement platform using the Ethereum blockchain. The framework allows for direct and secure interaction between the public institution that issued the procurement contest and contractors, removing the need for any intermediaries. All procurement data like bids, contracts, and payments are transparently documented on blockchain. The decision on the selected offer is also made democratically through the DAO voting mechanisms by the board members with governance tokens.

Table 5 Summary of the reviewed literature on DAO use cases in the built environment

Domain	Reference	Summary of findings	DAO Framework	Tokenization model	Key methodology	Level of development
Design	(Dounas et al. 2022b)	A DAO and blockchain-based framework for decentralized collaborations and collective authorship in architectural design	Ethereum	NFT-based governance Tokens, Fungible toke n as Incentive tokens	DAO, Smart contract, Stigmergic Principles	Proof of Concept
	(Dounas and Lombardi 2019)	Ethereum blockchain-based DAO for decentralized collaboration in architectural design using shape grammars	Ethereum	GEN Tokens, Reputation-based token	DAO, Smart contract	Proof of Concept
Construction management	(Darabseh and Poças Martins 2023)	A governance DAO for collaborative decision-making in construction project with proof-	Aragon platform	ERC20 tokens for transaction	Platform-based DAO	Proof of Concept

		of-concept implementation on platform-based DAO				
Smart cities	(Mendoza and Behrens 2020)	A DAO-based communication framework for smart cities for improving socioeconomic equity	N/A	Governance Tokens	Cyber-physical-system, Edge and fog network, DAO, Smart contract	Theoretical framework
	(Bernovskis et al. 2023)	Framework for integration of gamification and DAO to incentivize socially and environmentally sustainable smart cities	Ethereum	NFT-based incentive tokens Governance Token	Gamification, DAO, Smart contract	Theoretical framework
	(Rawat et al. 2022)	Trustless environment for carbon trading with decentralized governance mechanism using blockchain and DAO	Ethereum	ERC-20 tokens for trading, NFT Token for certificate	DAO, Smart contract	Theoretical framework
Transportation	(Copel and Ater 2017)	A decentralized autonomous vehicle for ride-sharing application	Ethereum	DAV tokens for payment	Internet of Things, sensors, DAO, Smart contract	Theoretical framework
	(Hou et al. 2021)	DAO framework for intelligent transportation system capable of addressing trust-related issue and fostering effective decision-making and execution of ITS	Ethereum	Reputation-based token, Incentive tokens, Governance tokens	Artificial intelligence, big data, Internet of Mind, DAO, Smart contract	Theoretical framework
	(Zhao et al. 2022a)	Integration of blockchain and DAO-based governance with parrel execution approach to create intelligent transportation	N/A	NFT-based incentive tokens	Cyber-physical-social-systems, Metaverse, DAO, Smart contract, Federated intelligence	Theoretical framework

		management framework				
Smart government	(Diallo et al. 2018)	A DAO-based government framework capable of monitoring and analysis of e-government service in real time	N/A	Governance Token	DAO, Smart contract	Theoretical framework
	(CityDAO 2021)	City DAO: A DAO-based community with the collective land ownership and tokenization with the blockchain-based governance	Ethereum	NFT as ownership tokens, Governance Token	DAO, Smart contract	Prototype
	(Guidi and Michienzi 2022)	Decentraland: An Ethereum blockchain and DAO-powered virtual space	Ethereum	NFT as ownership tokens, ERC-20 token for transaction	DAO, Smart contract, metaverse	Prototype
Business and organizational structure	(Wang et al. 2023)	Integrating the concept of parallel management and DAO for enterprise's decentralized management	N/A	Governance Tokens, NFT-based incentive tokens	Parallel intelligence theory, DAO, smart contract	Theoretical framework
	(Li et al. 2023)	A DAO and parallel management driven framework for future smart organization and intelligent operations	N/A	Governance Tokens	Cyber–physical-social systems, DAO, smart contract, Metaverse, Parallel management	Theoretical framework
	(Monteiro and Correia 2023)	DAO-based procurement framework with roof of concept implementation	Ethereum	ERC-20 Governance tokens	DAO, Smart contract	Proof of Concept
Self-governing entities	(Hunhevicz et al. 2021)	Concept of decentralized autonomous space (DAS) using DAO and Blockchain with a prototypes	Ethereum	Use of tokens for payment and maintenance	Internet of Things, sensors, DAO, Smart contract	Prototype

		of self-governing meditation space				
	(Seidler et al. 2016)	A prototype of an Ethereum blockchain based, self-governing forest	Ethereum	Terra0 tokens as ownership	DAO, Smart contract	Prototype

4.4. Challenges of DAO implementation in the built environment

This subsection presents a compilation of challenges related to the implementation of DAO that was extracted from the reviewed literature. The limitations of DAO, in general, will be first discussed before providing the implication of the prospective hindrance in DAO adoption within the subdomain of the built environment. The summary of each category of challenges and their corresponding description are also shown in Table 6.

4.4.1. Security risk

The potential security problems of DAO are mostly inherited from the vulnerability of blockchain technology. The commonly known blockchain security risks include 51% vulnerability, private key security, double spending, leakage of transaction information, and smart contract vulnerability (Guo and Yu 2022). In the context of the built environment, services like transportation, energy, or public systems managed by the city DAO could be disrupted by hackers due to smart contract vulnerabilities (Mendoza and Behrens 2020; Bernovskis et al. 2023). In addition, the DAO's monetary assets in business organizations, government programs, construction, or design projects could also be lost due to these security issues. Furthermore, due to the immutable characteristics of blockchain, it's hard to adjust DAO's smart contract codes after being deployed (Wang et al. 2019a). This will make it difficult to fix DAO smart contracts' security bugs in the operational phase which will leave DAO vulnerable to a variety of attacks from outsiders. The complexity of upgradable smart contracts could result in inefficiencies across subdomains like construction management and self-governing entities. Inflexible governance principles and decision-making protocols could also cause problems in areas like design, transportation, smart cities, and governments, where rules and regulations require adaptability. Further research in developing secure and innovative smart contract designs is needed to improve the resilience and efficiency of DAOs.

Also, DAO heavily relies on voting mechanisms to make critical decisions, but the inherent vulnerabilities in those mechanisms can pose security risks for the organization and its members. For instance, the permission relative majority voting model doesn't require the participation of all DAO members to pass the proposal. Attackers can exploit this oversight by slipping in proposals with hidden malicious acts, potentially leading to actions that harm the DAO and its members (Fan et al. 2023).

4.4.2. Technical limitations

One technical barrier that restricts the flexibility and implementation of DAO is the difficulty of translating legal rules into computer codes (Wang et al. 2019a). The traditional rules are generally drafted in natural language with greater flexibility and versatility whereas smart contract code must be explicitly and precisely written with a programming language. This will inevitably lead to errors, ambiguous language, and potential deviation from the original meaning during the translations. In fields like construction management, design, transportation, and government administration, it is challenging to ensure the accurate translation of complex policies and protocols into smart contract codes.

The scalability problem of blockchain could also affect the potential of DAO. Blockchain's scalability problem is regarded as the major hindrance to its adoption in real-world commercial use (Liu et al. 2021). The common scalability issues include transaction latency and low throughput, which mostly occur when there is a large volume of transactions on a major blockchain network. This is because each node has to store and perform some computations to validate the transaction, which is time-consuming when the number of nodes increases. This scalability problem can pose additional concerns to applications like design collaboration, government services, smart cities, and transportation operations as it will cause serious time delays in the execution of any on-chain activities which result in low efficiency and negative user experience.

Interoperability is another key limitation of blockchain applications (Van Der Heijden 2023). For instance, different applications used in the design and construction may also possess different communication protocols and data formats which could pose problems in the data transfer (Li et al. 2019). This lack of interoperability could also be a problem for DAO implementation as the DAO participants need to be able to interact seamlessly in the collaborative workflow to create effective collective decision-making.

4.4.3. Privacy concerns

Blockchains are inherently transparent as the transaction details are visible to all participants. This lack of privacy sometimes becomes problematic due to the disclosure of sensitive data (Wang et al. 2019b). For example, in procurement applications, a contractor may not want competitors to see their pricing, bid strategies, or deal terms encoded on a public blockchain (Monteiro and Correia 2023). Likewise, smart city applications may also need to acquire citizens' personal information such as energy usage or transit patterns (Mendoza and Behrens 2020). The government service sector might also gather sensitive personal information such as citizens' records including IDs, tax returns, etc. Some data might require an immutable public ledger while others might be best to remain private. Future DAO developer should balance transparency and privacy based on the purpose of their application.

4.4.4. Legal and regulatory uncertainty

The uncertainty of DAO’s legal status, applicable laws, and jurisdiction-related issues are still the primary concerns for its users. The majority of operating DAOs are not regulated, and most of their members are anonymous (Bellavitis et al. 2022). This leads to significant uncertainty about whether the DAO and its members will be subjected to laws and held responsible for any legal issues and related liabilities (e.g. tax) (Shakow 2018; Wang et al. 2019a). This uncertainty surrounding the accountability and liability of the DAO is also a contributing factor to the hindrance of DAO adoption in the built environment domain. It could be challenging to determine who is legally accountable for decisions, actions, or mistakes made by the DAO. For instance, smart cities and transportation-related DAO applications may hesitate to enforce safety standards and financial-related policies without a clear legal framework (Bernovskis et al. 2023). Collaboration between regulators, and DAO-associated stakeholders is crucial to define a clear scope of laws for DAO so that the entity and its members can be subjected to corresponding obligations and legal liabilities.

4.4.5. Efficiency problems

User engagement is also another common problem in DAO governance. Researchers have demonstrated that the majority of users in virtual communities tend to be passive and unengaged in community-related activities (Antelmi et al. 2019). This is also the case with DAO’s decentralized community, where most token holders with voting power are not actively participating in governance, leading to low voter turnout and voter fatigue (Slavin and Werbach 2022). Despite the benefits of a transparent and democratized type of governance, the consensus-based mechanism in DAO can also result in inefficiencies in communication (Fan et al. 2023). In the token-based voting system, a certain proportion of users are required to cast their vote to pass a proposal and sometimes it could take a significant amount of time for the verdict to be reached which reduces efficiency (Bellavitis et al. 2022). For example, the smart city-related DAO may struggle to pass policy proposals in a timely manner if most token-holding citizens are inactive in governance activities. DAO architects must find the balance between the level of decentralization and efficiency in the built environment domain that relies on timely planning, coordination, and decision-making.

4.4.6. Skills gaps

The other noticeable hindrance in the broad adoption of DAO, for instance in the domain of built environment, is the cost of understanding the technical detail and operational mechanism behind it (Bellavitis et al. 2022). Users and developers first have to invest a considerable number of resources in acquainting themselves with the blockchain and related concepts such as smart contracts, tokenized systems, etc. (Li et al. 2019). In addition, they have to understand another layer of concept including DAO’s related technical terms, voting models, and governance mechanisms to efficiently work with decentralized autonomous frameworks. The shift from centralized to autonomous workflow of built environment operation will require both the technical development of the DAO use cases and the training for DAO participants in that application.

Table 6 Overview of the challenges and limitations of DAO implementation

Categories	Challenges	Description	Reference
Security risk	Blockchain vulnerability	Blockchain security risk and smart contract vulnerability can expose DAO to security risks like theft of funds and assets	(Mendoza and Behrens 2020) (Bernovskis et al. 2023)
	Immutability of Blockchain	The immutable nature of blockchain causes complexity in the DAO's smart contract maintenance which can expose the loophole to malicious attack.	(Wang et al. 2019a)
	Voting mechanism vulnerability	DAO voting manipulation by malicious attacker using the slip through passed proposal and power lending method.	(Fan et al. 2023)
Technical limitations	Smart contract development	Difficulty in translating actual rules into DAO's smart contract code	(Wang et al. 2019a)
	Scalability of blockchain	Scalability problem in blockchain (e.g., low throughput and high transaction latency problem caused by high volume of transactions)	(Liu et al. 2021)
	Interoperability	Required integration of blockchain technology with legacy system/infrastructure	(Li et al. 2019)
Privacy concerns	Data privacy	The transparency of public blockchains-based DAO may compromise data privacy, as sensitive information may be visible to all participants	(Monteiro and Correia 2023)(Wang et al. 2019b)
Legal and regulatory uncertainty	Legal status indeterminacy	Most DAO are still unincorporated, the anonymity of DAO members, uncertain liability of involved stakeholder	(Bellavitis et al. 2022) (Bernovskis et al. 2023)
	Applicable laws and jurisdictional uncertainty	The uncertainty behind whether DAO members will be subjected to legal responsibility	(Wang et al. 2019a) (Shakow 2018)
Efficiency problems	Voter engagement	The token holders are not actively participating in governance and voting	(Slavin and Werbach 2022)
	Coordination inefficiency	Long duration of voting cause inefficiency for time-sensitive decision	(Bellavitis et al. 2022) (Fan et al. 2023)
Skills gaps	Participation cost	Required comprehensive understanding of blockchain and DAO-related concept to participate/implement	(Bellavitis et al. 2022) (Li et al. 2019)

5. Future perspectives

The results of the review have found that the Ethereum blockchain has been mainly used as the platform for DAO implementation compared to other blockchain architectures due to the level of maturity of its ecosystem and community. However, the inherent limitations of the Ethereum blockchain (transaction speed and cost) could constrain the scalability and feasibility of DAO in managing large-scale operations and assets. Platform-based DAOs such as Aragon do provide a more user-friendly interface for early DAO development, but they lack granularity in management and remain constrained to Ethereum's technical limitations. Alternative blockchain architectures like Solana and Hyperledger offer greater throughput, speed, reliability, and low transaction fees with some compromise to decentralization (Malik et al. 2019; Pierro and Tonelli 2022). These technical advantages can better accommodate the demands of large, active DAOs that require fast and affordable coordination, automation, and decision-making. Therefore, future DAO developers should assess technical requirements against the priorities of the DAO platform to determine optimal blockchain infrastructure.

The reviewed literature also presents a wide range of enabling technologies used in the current DAO applications. Smart contract is one of the core technologies and has seen extensive utilization across the majority of DAO use cases in the built environment. Future research can focus more on the development of secured and efficient smart contracts to increase the complexity, reliability, and security of DAO operations. Studies have also demonstrated the integration of IoT devices with DAO in prototypes of self-governing spaces and transportation systems (Hunhevicz et al. 2021). Broader adoptions of IoT and digital twin technology in DAO use cases could also foster the decentralized management and autonomous control of future urban infrastructure (Dounas et al. 2022a). The utilization of metaverse concepts in DAO-driven virtual spaces and intelligent transportation systems represents a futuristic approach to urban planning and transportation (Zhao et al. 2022a). Additional studies on the development of interoperable technological frameworks and user-friendly systems are crucial in integrating the metaverse and people's participation in the built environment. Moreover, the use of gamification and incentive structures within smart cities demonstrates an innovative approach to decentralized governance, collaboration, and sustainable practices (Bernovskis et al. 2023). Further research is needed to examine the best practice for integrating incentive models, and tokenization within DAO to increase participation and alignment with collective goals. Also, additional investigation into behavioral science is important to understand how different incentive systems translated into gamification elements can influence people’s behaviors (Kahya et al. 2021). In addition, to unlock the full capabilities of DAO in the built environment, future studies also need to concentrate on addressing scalability, interoperability, and data security problems as well as promoting cross-disciplinary collaboration and advancing real-world implementations.

The preceding sections of this study have reviewed both the existing applications and limitations of DAO across different subdomains of the built environment. The current body of research, while comprehensive, has yet to delve into certain unexplored domains within the built environment. The following subsections provide further discussion of potential opportunities for DAO applications in three areas of this domain: construction management, facility management, and the synergies of DAO and artificial intelligence. The three areas were selected as they represent critical domains within the built environment that could significantly benefit from the unique capabilities offered by DAO technology. Construction management plays a pivotal role in the development of built infrastructure, involving multiple stakeholders, complex processes, extensive coordination efforts, and resource management (Harris et al. 2021). Implementing DAO in this domain could streamline project delivery, procurement, and design coordination, as well as enhance transparency, and facilitate collaboration among stakeholders. Facility management, on the other hand, is crucial for the efficient operation and maintenance of built assets throughout their lifecycle (Potkany et al. 2015). DAO integration could enable autonomous building operations, predictive maintenance as well as interconnected DAO ecosystems for system-wide asset governance, thereby optimizing resource utilization and enhancing operational efficiency (Ly et al. 2024). While construction management and facility management represent essential phases in the built environment lifecycle, the synergies of DAO with artificial intelligence (AI) present a transformative frontier that cuts across multiple domains (Revoredo 2023). The integration of DAOs and AI could enable intelligent and inclusive decision-making processes that leverage data analytics, machine learning, and decentralized governance. AI-powered DAOs have the potential to automate administrative tasks, optimize resource allocation, improve operational efficiency, and increase productivity across various domains within the built environment, from autonomous infrastructure management to smart cities and transportation systems (Ly et al. 2024).

5.1. Construction management

One promising use case of DAO in construction management is Integrated project delivery (IPD). IPD seeks to improve the efficiency of construction projects through collaboration between stakeholders throughout the project. Previous study has demonstrated the potential of blockchain governance and the possibility of project coordination through the DAO implementation (Hunhevicz et al. 2022). Implementing a DAO for IPD could allow equitable participation across all stakeholders spanning from the initial design to the operational and maintenance phases. Also, blockchain enables transparency in the supply chain logistics of the construction project (Setaki and Van Timmeren 2022). DAO can be formed by the involved project stakeholders (Owner, General contractor, subcontractor, consultant, designer, etc.) with rules written on multiple smart contracts for different tasks such as payments, delivery deadline, quality inspection, audit of structural or architectural design, supply chain, and other related processes within the projects. The members can also vote to formalize collaborative choices. This concept should create an automated, transparent, and collaborative IPD ecosystem. Blockchain technology has also improved the procurement and tendering process in construction projects by providing a more secure and transparent procurement and e-tendering operation (Gong et al. 2022). These applications could be further extended with the use of DAO in the procurement process within construction projects. In such a scenario, a DAO can be created by property investors who are interested in starting a new construction project. The DAO members engage in open discussions, and voting, and release a tendering proposal (Request for Proposal) with project requirements. General contractors could then submit design ideas, budgets, and project schedules, with exchanges of documents facilitated through a decentralized file storage system. In the selection stage, submissions are evaluated and rated by experts or DAO members using a private blockchain system, with the winning bid determined through voting. This approach aims to make procurement and tendering in construction projects more secure, transparent, and efficient by leveraging DLT and decentralized governance.

In addition, DAO could also be used for coordination between the architectural and structural design teams in a design project's workflow. Sreckovic et al. (2020) demonstrated one use case of smart contracts in an architectural company by implementing an approval process workflow between the two design teams. In this scenario, DAO can be implemented as an auditor for either side. For instance, the structural team's DAO will be responsible for checking whether the conceptual architectural design complies with the engineering standard, etc. Design works (BIM, drawing, etc.) will be submitted by the architectural design team to the structural engineers. A list of required changes would be returned to the architect for resubmission if the initial submission was not approved. Depending on the voting result from the DAO member, a smart contract will determine whether the works are eligible or not to proceed to the next step.

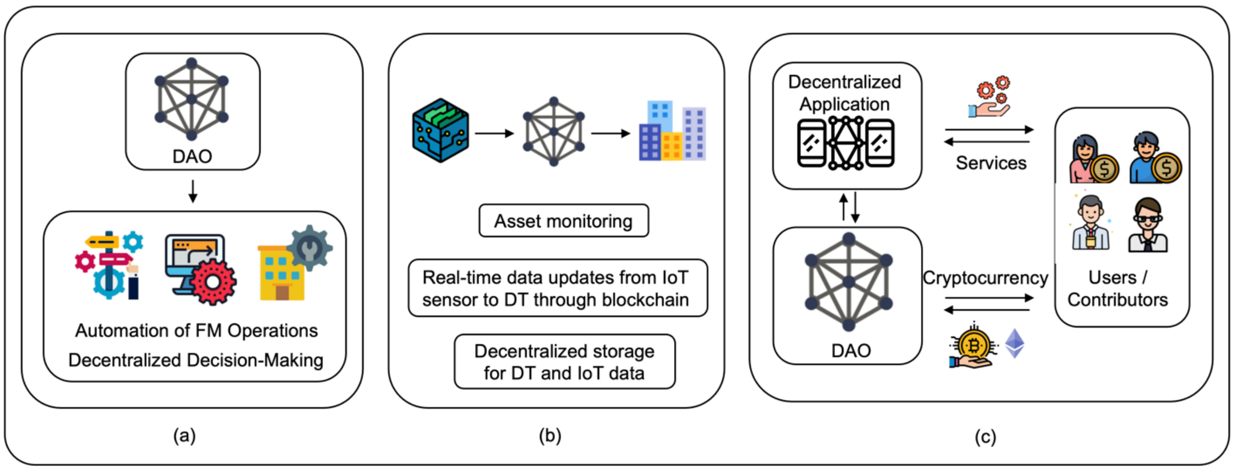

Fig. 9 Potential use cases of DAO in facility management

5.2. Facility management

DAO in facility management offers the potential for autonomous building infrastructure with self-governing capability which could transform how buildings and other civil infrastructure are managed and operated (Ye et al. 2018) (Fig. 9(a)). DAO could be programmed to access the data from the building's digital twin and monitor building performance, energy usage, and other infrastructure-related data. DAO can be deployed to control different aspects of the infrastructure's operations including operation automation, maintenance, and energy optimization. Internet of Things and sensors can act as the edge devices that will feed live sensors (oracle) and feed into the blockchain. These data can be used to trigger specific task execution given the predetermined condition or threshold is met in the written smart contract. Equipment and facilities within the physical infrastructure can be programmed to react to the smart contract feedback. Specifically, DAO's smart contracts could automatically control lighting and HVAC based on occupancy levels, and weather conditions. In addition, DAO could be coupled with IoT devices for maintenance work. In case of equipment breakdown, the embedded sensor can detect the damage and report the information back to DAO. Based on the written smart contract rules, DAO will perform corresponding responses such as contacting the maintenance team and purchasing replacements.

Moreover, the integration of DAO with digital twin technology, and IoT could enable real-time asset monitoring (Dounas et al. 2022a) (Fig. 9(b)). For example, if the data from the digital twin suggests that there are signs of failure in the building component, DAO would be notified through the real-time sensor data feed and trigger necessary predictive maintenance procedures to assess and prevent further damage. To ensure data security and integrity, the Decentralized oracles network (Ma et al. 2019) and decentralized data storage (Daniel and Tschorsch 2022) can be used to collect and store the retrieved sensor data.

The integration of digital twins and DAO could also enable smart autonomous infrastructure to provide value and services to users through DApp (Fig. 9(c)). For example, a DAO-powered retail space in a commercial building could generate revenue by leasing itself. Likewise, in an educational infrastructure, students and faculty could use DApp to view the live conditions of the room before reserving the space.

Furthermore, DAO could also be designed to communicate and link to the other DAO community to create a DAO ecosystem, a DAO of the DAO (Kaal 2021). In a built infrastructure context, multiple building's DAOs could communicate and trigger responses between each other. This complex interaction could enable efficient, system-wide asset management thereby fostering productivity and efficiency.

5.3. Integration of Artificial Intelligence and DAO

Another promising avenue for future research is the synergy of DAO and artificial intelligence in creating smart and autonomous systems. AI agents could potentially be programmed to manage data inputs, analyze information, and perform recommendations or conduct autonomous decisions on behalf of a DAO. The integration of artificial intelligence (AI) and DAO could revolutionize decision-making, solve governance-related challenges, improve governance mechanisms, and provide new opportunities across various domains in the built environment. Traditional DAOs operate based on the smart contract code written by a developer and through a voting mechanism. However, by utilizing adaptive machine learning and feedback loops, the AI-powered DAO can learn, make decisions, and automate administrative tasks that were typically done by humans (Benedict et al. 2022) (Fig. 10(a)). For instance, Singularity DAO uses AI to facilitate asset management and investment decisions based on user behavior (Singularity DAO 2021). In transportation, intelligent agent networks could coordinate autonomous mobility systems (Zhao et al. 2022a). Furthermore, within the domain of smart cities, Lin et al. (2023) have proposed the integration of DAO and parallel systems to facilitate AI applications. By fusing the physical and virtual environment with spatial symbiotic intelligence, the integrated and collaborative DAO and AI decision-making system could be created to address the needs of city residents. Additional study has also implemented parallel intelligence to create a more predictable governance of DAO to prevent loopholes in its operations (Ding et al. 2022).

Moreover, generative AI has also been integrated with DAO to create a self-sustaining digital organization whose revenue is generated by AI-generated content (Fig. 10(b)). Recent contributions by Yadlapalli et al.(2019) harnessed the potential of integrating AI and DAO by creating a digital, self-governing organization that sustains itself by the revenue from selling digital art that is automatically generated by a Generative Adversarial Network. Similarly, Guo et al. (2023) integrated artificial intelligence and DAO to build a human-machine collaborative painting system for artistic content creation.

Overall, combining AI and DAO could foster the robustness of decision-making, improve DAO's governance mechanism, and create values through generative AI applications. However, it is equally crucial to thoughtfully examine the ethical implications of using AI in decentralized systems to guarantee the alignment of its application to the values and principles of the DAO community.

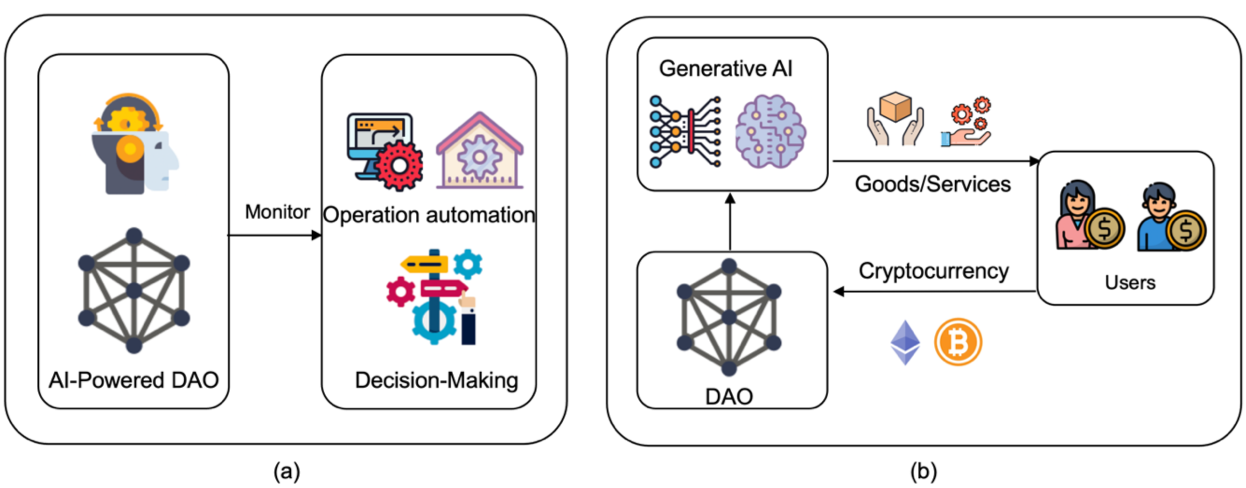

Fig. 10 Potential use cases of AI and DAO integration: (a) AI-powered DAO for decision-making and automation (b) Generative AI and DAO integration

6. Conclusions

The objective of this study is to give readers an in-depth comprehension of the concept of DAO, its related operational mechanism, and its limitations as well as the existing application and potential pathway for its future research in a built environment. As per the authors' understanding, this article is the first to offer an extensive review of DAO in the built environment. To address this study's objectives, data analysis was conducted on a body of literature from 47 DAO and built environment-related sources. This paper presents a comprehensive survey on DAO-related characteristics and governance mechanisms, relevant conceptual use cases, and existing implementation and provides an analysis of the potential challenges of its adoption within subdomains of the built environment.

This article begins by describing the fundamental concept of DAO which includes its governance structure, core characteristics, voting models, operation mechanism, and deployment guidelines. The study provides an overall methodology for DAO technical implementation as well as a comparison of the strengths and weaknesses of different voting mechanisms for future DAO users and creators. Seven different themes of DAO applications in the built environment were identified. These include design, construction management, smart cities, smart government, transportation, self-governing entities, and business and organizational structure. The results from the analysis of the DAO publications across built environment applications indicate that the current state research on DAO real-world use cases is still in the early stage of exploration. Proofs of concepts and theoretical frameworks still dominate most of the sub-areas of the built environment. This suggests that academics still assessing the potential implications of DAO. However, there are several DAO prototypes in self-governing entities, smart cities, and smart government domains. The existing proofs of concept also reveal that most of the DAO applications remain as theories and have yet to be tested in practice. To assess the DAO platform efficiency and real-world performance, more empirical research in DAO implementation is still needed.

This study also investigated the limitations of DAO and its implementation challenges in both general and the context of different areas in the built environment. Security issues, technical limitations, legal and regulatory challenges, privacy and efficiency problems, and the cost of participation are the primary limitations identified in the reviewed literature. Future research endeavors could focus on several key actions to address these limitations and increase DAO adoption. For instance, efforts should be directed toward enhancing the security and encryption methods for smart contract development practices. Additionally, innovative solutions are needed to overcome the blockchain's inherited technical limitations, such as scalability issues and transaction throughput limitation, through the exploration of optimization techniques and alternative blockchain architectures for DAO. In addition, the cost of participation and skill gaps should also be addressed with the development of a more feature-rich open-source tool kit, tutorials, and documentation for DAO development as well as user-friendly applications or platforms that minimize the need for extensive coding and blockchain knowledge.

Based on the analysis and insights from the studies, this study has also discussed the future perspective on the DAO development in the built environment domain by providing suggestions on DAO technical implementation strategy as well as suggestions on possible research direction. The study also outlined potential opportunities for DAO implementation in construction management and facility management which are the integral components of the built environment's infrastructure and operations. Additionally, the study also contributed to the body of knowledge of the domain of decentralized intelligence (Cao 2022) with the discussion on the potential synergies between DAOs and AI agents in automating decision-making processes within DAOs as well as highlighting the potential integration of DAO and generative AI in creating self-sustaining and autonomous digital organizations.

The findings presented in this literature review establish a valuable foundation for forthcoming research and exploration of DAO in the built environment domain. By extracting useful insights from existing DAO applications and providing its potential use cases, this review serves as a valuable resource to empower future academics and innovators to further advance the research and development of decentralized governance and DAO in the field of built environment.

Despite this paper's contribution to the body of knowledge of DAO in the built environment, it also possesses several limitations. This study mainly centers on the technical perspective of DAO by exploring only its technological mechanisms, characteristics, and applications without encompassing broader socio-technical implications such as social, cultural, political, and economic factors that could potentially shape the DAO integration and impacts. Future studies could build upon this research by looking beyond the technical lens into a more human-centric perspective to investigate how the socio-technical factor affects the adoption and implementation of DAO in a built environment. In addition, the subjective nature of the screening process can also affect the selection of studies for the review. Moreover, the articles included in this study also comprised whitepapers, preprints, and reports published by organizations actively involved in DAO development since they provided valuable insights into real-world use cases, proofs of concept, and practical implementations of DAOs. The inclusion of these additional sources through the snowballing technique may introduce biases or limitations. However, given the emerging nature of this field and the limited availability of peer-reviewed literature, it is also necessary to consider these alternative sources to capture a more comprehensive understanding of the current state of DAO applications in the built environment.

Declaration

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Competing interests
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