Reachsak Ly, Ph.D., LEED GA
Assistant Professor
Department of Construction Management
School of Technology
Eastern Illinois University
Charleston, IL 61920

September 2025
Department of Civil and Architectural Engineering and Construction Management
University of Wyoming

Dear Search Committee Members,

I am writing to express my interest in the Assistant Professor in Construction Management position at the Department of Civil and Architectural Engineering and Construction Management at the University of Wyoming. I received my Ph.D. from Virginia Polytechnic Institute and State University's Myers-Lawson School of Construction. Prior to Virginia Tech, I also received a Bachelor of Engineering in Civil Engineering from Zhejiang University with a specialization in Structural Engineering.

Most of my current research work focuses on data analytics, digital innovation, and the application of emerging technologies in the built environment. My primary research interests are smart and autonomous buildings, human building interaction, construction automation, construction robotics, digital twin and smart cities, construction informatics, generative artificial intelligence, such as large language models and Vision language models, machine learning, and Internet of Things. I have been awarded the Pratt Fellowship for outstanding PhD students from the College of Engineering Office of Research and Innovation at Virginia Tech for my research in Generative AI in built environments, including the application of large language models (LLMs) for human-building interaction and Extended Reality environments. I've also had experience working on a Generative AI application in smart building cybersecurity, a project funded by the Commonwealth Cyber Initiative (CCI) Southwest Virginia. Please refer to my project list attached to this application for further details, including open-sourced code and prototype demonstration.

I have disseminated my research findings in a multitude of venues, including peer-reviewed journals and conferences. Most of my work constitutes multidisciplinary research. I have collaborated with faculty members and students from a variety of disciplines, including Civil Engineering, Construction Management, and Computer Science. I have also been actively involved in grant proposal writing, including a recent proposal submission to federal agencies such as the NSF Cyber-Physical Systems program and Research on Innovative Technologies for Enhanced Learning program, as well as proposals for industry-related grants such as Charles Pankow Research Grants.

I also have teaching experience in both fundamental undergraduate and advanced graduate construction management topics at Virginia Tech and Eastern Illinois University. I have taught live and online classes using diverse instructional formats, including lectures, project-based studios, and blended learning environments. The topics I have covered include, but are not limited to, building information modeling, capstone projects, construction project management, research methodology, construction estimating, scheduling, planning and control, risk and uncertainty management, and emerging technologies in the built environment, such as Mixed reality, Augmented Reality, Machine Learning, and Generative artificial intelligence. My teaching philosophy emphasizes active and project-based learning, encouraging students to apply theoretical knowledge to real-world challenges. I am committed to continuously improving my teaching, research, and knowledge of current and future trends in my field. For example, I have participated in teaching skills and pedagogical strategies training offered by Virginia Tech's Center for the Integration of Research, Teaching, and Learning (CIRTL) program and have received the Future Professoriate Graduate Certificate, both of which have supported my efforts in developing and implementing new courses and degree programs. If given the opportunity, I am looking forward to bringing my teaching philosophy and methods to your program. Please refer to my research and teaching statements for further details.

In addition, I've also been actively involved in student mentorship and outreach activities. At Virginia Tech, I've mentored a student team from the School of Construction in the U.S. Department of Energy Solar Decathlon competition. I am also involved in outreach efforts, including volunteering as a speaker in workshops and summer camps organized by different organizations, such as the Virginia Space Grant Consortium and the Virginia 4-H Youth Development Program. I've also mentored graduate students for their master's research at Eastern Illinois University.

In addition, I have over three years of professional experience in the construction industry, where I worked primarily with China Railway Construction Corporation (CRCC), one of the renowned construction firms in China and Asia. I have been involved in multiple phases of construction, from pre-construction planning to project completion**,** and have gained hands-on experience in supervising large teams, including quality control, managing construction schedules, and maintaining safety standards on-site.

Given the advertised job description, my professional experience, and my research and teaching expertise, I see myself as a great fit. If given the opportunity, I look forward to collaborating with researchers and industry partners across different disciplines at the University of Wyoming and teaching courses such as Introduction to Construction Management, Construction Materials and Methods, Construction Documents, Construction Safety, Construction Planning and Scheduling, Construction Estimating, Project Management, Heavy Civil Construction, Statics and Structural Systems, Building Information Modeling and Capstone Project courses at the Department of Civil and Architectural Engineering and Construction Management. I would also welcome the opportunity to develop new courses related to construction technologies such as connected and smart solutions in the built environment, Construction 4.0, Digital twins, Artificial Intelligence and Data Analytics for Construction, Design, and Operation and Facilities Management. Enclosed, please find a copy of my curriculum vitae, a personal statement outlining my research accomplishments, research interests and plans, teaching philosophy, and approach to student success; reference, and additional documents such as a degree diploma, transcript, sample research papers, awards, and a related project list. Please do not hesitate to contact me for any additional information or possible clarifications. Thank you for your time and consideration of my application.

Sincerely,

Reachsak Ly

Academic Reference List

Academic Reference for
Reachsak Ly
1311 Arthur Ave Apt 5
Charleston, Illinois, 61920
Tel: +1-540-605-0125
Profile: https://reachsak.github.io/

Alireza Shojaei
Assistant Professor,
Myers-Lawson School of Construction, Virginia Tech
Address: 320B Hitt Hall, 1385 Perry St, Blacksburg, VA 24061
Email: shojaei@vt.edu
Phone: (352) 214-1980
Profile: https://mlsoc.vt.edu/about/faculty-and-staff/alireza-shojaei.html
Working relationship: Doctoral advisor

Xinghua Gao
Associate Professor,
Myers-Lawson School of Construction, Virginia Tech
320J Hitt Hall 1385 Perry St Blacksburg VA 24061
Email: xinghua@vt.edu
Phone: (404) 488-9143
Profile: https://mlsoc.vt.edu/about/faculty-and-staff/xinghua-gao.html
Working relationship: Committee member

Philip Agee
Associate Professor, Building Construction
Assistant Director, Virginia Center for Housing Research
Myers-Lawson School of Construction, Virginia Tech
430B Bishop-Favrao Hall 1345 Perry St. Blacksburg VA 24061
Email: pragee@vt.edu
Phone: (804) 314-3997
Profile: https://mlsoc.vt.edu/about/faculty-and-staff/philip-agee.html
Working relationship: Committee member

1. Research statement

Past Research

I chose Construction Engineering and Management because I am passionate about improving how we design, build, and sustain the built environment, as well as enhancing the operational efficiency and resilience of our urban infrastructure. My primary research interests are smart and autonomous buildings, construction automation, digital twin and smart cities, artificial intelligence (AI), machine learning, and data analytics. I intend to continue my primary research goals, especially in generative artificial intelligence, digital twins, and machine learning, to develop innovative solutions that improve the efficiency and sustainability of processes or practices of construction operations, urban infrastructure systems, and smart cities. I have disseminated my research findings in a multitude of venues, including peer-reviewed journals, as well as highly competitive, rigorously reviewed conferences. The majority of my work constitutes multidisciplinary research. I have collaborated with faculty members and students from a variety of disciplines, including Civil Engineering, Construction Management, and Computer Science. I received my Bachelor of Engineering in Civil Engineering from Zhejiang University with a specialization in structural engineering. There, I have worked on different projects and co-authored multiple publications on the topic of artificial intelligence in structural health monitoring. I used deep learning to build machine-learning models for structural crack characteristics inspection and classification, as well as damage segmentation. This work contributes to the development of a more accurate and efficient structural health monitoring technique by enabling faster, real-time, and more reliable detection of damage in critical infrastructure. One of the papers in this series has been awarded an Excellent Award in the International Project Competition in Structural Health Monitoring organized by the University of Illinois Urbana-Champaign.

Current Research

My current research focuses on leveraging advanced digital technologies, including generative AI, machine learning, digital twins, blockchain governance, and mixed reality technology to develop intelligent and autonomous systems for smart construction, intelligent buildings, human-building interaction, civil infrastructure, and smart cities to enhance efficiency, sustainability in urban environment as well as enabling smart and connected solutions across the built environment. I am currently engaged in multiple projects at varying stages in the publication process, all of which reflect my overall research mission.

My Ph.D. dissertation was focused on leveraging generative artificial intelligence (Gen AI) and blockchain technologies to create smart, autonomous, and resilient building infrastructure. Specifically, I seek to distribute the dynamics and decision-making process of stakeholders within smart building facilities management operations and investigate how physical infrastructure can be owned and autonomously operated in a decentralized and self-sufficient manner in the future by using large language models (LLMs) and web3 technology. My dissertation comprises four main chapters. The first chapter focuses on enhancing the cybersecurity of smart building operations by developing secure, private blockchain-based protocols to protect building automation systems, as well as digital twin and IoT data.

The second chapter focuses on creating an AI assistant and data-driven decentralized governance platform to empower smart-related stakeholders to collaboratively participate in the management and coordination of building operations. The developed LLM-based AI assistant can analyze IoT data and provide insights and recommendations to support informed facility management decisions, including analysis of building performance, energy consumption, and occupancy patterns. Additionally, this research leverages embedded IoT sensors and a Raspberry Pi to provide a visual decision support framework through digital building twins.

The third chapter mainly focuses on enforcing community-based facility management within a built infrastructure using blockchain incentives and decentralized governance. In this work, building occupants will be rewarded with blockchain-based incentive tokens for reporting any building maintenance issues and providing relevant feedback in contributing to the maintenance and enhancement of building infrastructure.

This research aims to foster a sense of collective ownership for all related stakeholders and encourages them to actively contribute to the upkeep, improvement, and sustainability of the shared built environment.

In the final chapter, I proposed a concept of the decentralized autonomous building cyber-physical system, which is defined as a community-governed building infrastructure with operational and financial autonomy that is powered by AI-powered automation and blockchain-based decentralized governance. My developed prototype of the proposed building can generate revenue by providing rental services to occupants and paying its necessary operational expenses, such as electricity fees. In this work, the AI virtual assistant allows users to control smart building facilities through voice and text modality with high contextual understanding. The AI agent also powers the autonomous building operations by autonomously adjusting smart appliances such as lighting and HVAC based on occupancy level and the baseline environmental comfort threshold. The results and findings from my dissertation research have also served as the foundation of one of my submitted grant proposals to the NSF Cyber-Physical Systems program (NSF 24-581). This proposal aims to push the boundaries of existing autonomous buildings and further develop a secure, autonomous, self-sustaining, and intelligent building infrastructure for the built environment.

Additionally, I am also working on the application of generative AI to smart building environments, with a particular focus on edge AI solutions in the built infrastructure. In this work, I deployed open-source small language models (SLMs) onto low-cost single-board computers, such as Raspberry Pi and Jetson Nano, for smart home assistant applications. The AI assistant facilitates the interaction between building occupants and building systems through conversational interfaces for smart building control. This project seeks to integrate advanced AI decision-making directly into building infrastructure through edge computing and eliminate the need for commercial AI cloud services. Additionally, this research not only accelerates the adoption of AI in smart buildings by making these technologies more accessible and cost-effective but also lays a solid foundation for integrating edge AI solutions into broader smart city initiatives, which could contribute to the development of more responsive, efficient, and interconnected urban environments.

Another of my ongoing projects focuses on developing an LLM-based AI system to enhance digital twin data analysis. This includes performing data analytics on historical sensor data, generating visualizations to support facility management decisions, and enabling real-time inquiries into building performance data. The broader application of this work could extend to smart cities, where AI agents can be employed to monitor, analyze, and optimize urban infrastructure, thereby leading to more efficient and intelligent city management.

Another related research project I am working on involves the integration of artificial intelligence and extended reality (XR) for remote smart building control. In this work, I deployed the developed LLM-based AI assistant and digital building twin onto the extended reality environment with Microsoft HoloLens 2. Users can view real-time building performance visualization and interact with the AI agents through voice commands for building facilities control. This project aims to enable future facility managers and occupants to remotely interact with and control smart buildings through an AI-enhanced, immersive digital environment. I have also conducted an interactive demonstration of the prototype of the proposed system to students from the Building Leaders for Advancing Science and Technology (BLAST) program at Virginia Tech's Myers Lawson School of Construction.

One other active research track that I am following is the application of generative AI for construction automation. One of my ongoing projects in this research track involves developing a vision language model-based AI system for automated construction safety monitoring and reporting. In this work, the developed prototype of the AI agents can autonomously analyze live video feeds to detect unsafe worker behavior and generate corresponding reports or alerts using their video analysis and text generation capabilities. This research could enable more proactive and effective safety management on construction sites. Additionally, I've also built a construction safety-focused AI chatbot with Retrieval-Augmented Generation (RAG), open-sourced LLMs such as LLaMA 3, Llamaindex, and a vector database. Users can interact with the chatbot through voice, text, chat, and image-based queries to receive accurate and contextually relevant safety information from the official standardized database on worker safety. This chatbot is designed to facilitate faster retrieval of construction safety knowledge and protocols, thereby increasing workers' safety awareness and ultimately creating a safer built environment.

I also have experience in large-scale data analytics and urban sensing. As part of a grant-funded project on remote sensing and the prediction of environmental noise in schools and hospitals in Florida, I conducted extensive analysis of noise datasets. This included applying descriptive and inferential statistical techniques to assess temporal variations in noise levels and performing time-series data visualization to uncover patterns that provide valuable insights into the social and health impacts of environmental noise.

I've also had experience working on a Generative AI application in cybersecurity. I'm one of the primary contributors to a cybersecurity project for the Smart Home at Virginia Tech, which was funded by the Commonwealth Cyber Initiative (CCI) Southwest Virginia. In this project, I mainly worked on designing and developing a GenAI-powered chatbot for Detecting Defects and Vulnerabilities in Smart Home Automation Systems using open-source LLMs such as LLaMA and GPT-OSS. Please refer to my project list attached to this application for further details, including open-sourced code and prototype demonstration.

Future Research

My future research will focus on exploring the design, construction, operation, and maintenance of smart, interconnected buildings, resilient infrastructure, and urban environments. I plan to accomplish this by applying my expertise in building systems and building science, AI and machine learning, data science, computational modeling and simulation, intelligent and autonomous infrastructure, and advanced information and communication technologies. The following are a few of the projects that I will prioritize over other aspects of my research:

- Investigating the AI-enhanced Human-building Interaction in smart infrastructure where occupants can seamlessly communicate with a personal, generative AI-based assistant for the autonomous building operations and facilities management task.
- Exploring the use of Extended Reality (XR) and Generative AI in civil engineering and construction education by developing immersive learning environments for students with embedded multimodal AI assistants capable of textual, voice, and visual understanding to enhance student engagement and improve learning outcomes.
- Investigating deeper integration of Small Language Models (SLMs) with edge computing techniques in enhancing the performance and scalability of AI systems in smart cities, particularly in real-time data processing and decision-making to optimize urban infrastructure management.
- Automate construction site safety inspection, reporting, and site progress monitoring by integrating quadruped robots/surveillance systems with multimodal generative AI such as Vision-Language Models (VLMs) to analyze site conditions and provide actionable insights for improving site safety and project timelines.
- Exploring deeper integration of machine learning, generative AI, extended reality (XR), and digital twins to revolutionize smart building control and urban infrastructure management by enabling remote, immersive monitoring of urban assets through human-AI interaction.

My goal is to actively seek grants from federal and private entities by submitting grant proposals in my research areas to sustain an up-to-date research agenda. I plan to pursue funding from NSF programs such as Smart and Connected Communities (S&CC), Cyber-Physical Systems (CPS), Future of Work at the Human-Technology Frontier (FW-HTF), and Engineering Research in Artificial Intelligence (ENG-AI). To advance these research goals, I will also actively engage and support a team of undergraduate and graduate students as my research team. I have a strong passion for conducting multidisciplinary research in collaboration with my fellow faculty members, as I believe this type of research tends to have more impact on the community and yields more significant results in real life.

2. Teaching statement

Having worked in structural design and construction firms, I understand the significant impact high-quality teaching has on the future of the built environment and, ultimately, on society as a whole. As a researcher, I believe that the insights and knowledge we gain from exploring new areas and solving complex problems hold little value if they aren't passed on to the next generation. Therefore, I view teaching as a crucial part of a faculty job.

I believe the primary duty of an educator is to teach students to think critically and independently and to prepare them for an uncertain future. The idea of learning in higher education extends beyond just the acquisition of information and skills. It involves the growth of analytical, decision-making, and problem-solving abilities, as well as the capacity to use knowledge in practical settings. I also believe student learning is a continuous process that demands involvement, active engagement, and constructive interaction between students, the content, and the teacher. When students are inspired, challenged, and motivated, they tend to learn more effectively. Therefore, it is also essential for an educator to create a supportive and inclusive learning atmosphere that encourages students to take risks, explore novel concepts, and develop their critical thinking skills.

My teaching philosophy centers on creating an inclusive learning environment and utilizing active and project-based learning methods where students learn how to apply the content to real-world problems to prepare them for their future careers. The projects I design are multi-dimensional, which involve multifaceted problems that require students to draw on various skills and knowledge areas to complete them. I also place a strong emphasis on teamwork and critical thinking, as I believe these are essential intellectual tools students need to succeed in their future roles. Additionally, I also strive to teach my students the value of collaboration, as both society and our industry are highly human-centered. Being an effective collaborator is a crucial skill for success in the professional world. In my class, I generally encourage a self-directed learning approach, where students actively participate in class and learn from each other. I also value the use of guest lectures and a mixture of delivery methods, which I've found to be an effective way of sparking students' interest in the subject. Another key method I use is having students present and discuss their ideas for possible solutions. These presentations not only build self-confidence but also promote critical thinking. I also believe that advising and mentoring are essential responsibilities for a successful faculty member. I'm proud of the role I play in my students' development, as I can see how much it helps them grow. I encourage students to meet with me face-to-face if they need help or guidance with course content. In addition, diversity is a critical component of a successful classroom. It is important to recognize the diversity of students, including their different cultures, backgrounds, and experiences. I believe that a diverse classroom provides a unique opportunity for students to learn from one another and broaden their perspectives. In my class, I aim to create an inclusive learning environment where every student feels valued and respected.

My objective as an educator is to prepare students for problem-solving and collaboration in future environments of uncertainty and equip them with skills and tools to succeed in their careers. I will engage students by focusing on the learning process rather than just getting the right answer or the result. This teaching philosophy aids in making students agile problem-solvers for the future collaborative environment. Furthermore, rather than depend on the end-of-semester surveys, I focus on continuous improvement of my supervising and teaching skills by seeking students' feedback throughout the semester. As a result, I can make timely adjustments to my teaching, and students can see how their feedback directly influences the course, helping them feel more engaged and invested in the classroom.

At Virginia Tech, I have served as a teaching assistant for four courses, BC 4434, BC 4444, BC 4164, and BC 5984, since 2022. BC 4434 covers a wide range of topics in construction management practices in vertical construction projects. I conduct lab sessions, grade assignments and exams, and instruct students on different topics, including work breakdown structure, planning, and scheduling, cash flow forecasting and analysis, as well as assembly estimating. BC 4444 is a capstone course with a focus on the Design-

Build project. I guided students through their capstone projects, which involved responding to real-life Design-Build RFPs using industry-standard software like Revit, MS Project, and RS Means for cost estimation. I also provide continuous feedback on the design quality of each project milestone throughout the semester. BC 4164 aims to provide students with knowledge of construction systems, such as relationships between subsystems in the construction process, queuing systems, process modeling, and simulation. In this course, I instructed students on using Oracle's Primavera Cloud for project management software with a focus on scheduling, process planning, and productivity analysis. I hold regular office hours for student guidance and feedback on their assignment, as well as provide hands-on guidance and model the project from start to end for the students, thus ensuring that they experience the real-life construction management workflow. Each session of this course included approximately 60 students. I have helped instructors with grading, exam preparation, and occasional teaching of live sessions. BC 5984 aims to provide students with theories, methodologies, and tools used in decision-making and risk management in construction management. I supervised students in decision tree analysis as well as performing calculations for planned and expected values for decision-making in construction projects. I have also participated in teaching skills and pedagogical strategies training offered by Virginia Tech's Center for the Integration of Research, Teaching, and Learning (CIRTL) program and have received Virginia Tech's Future Professoriate Graduate Certificate.

At Eastern Illinois University, I have served as the primary instructor for three courses: CMG 1000 (Introduction to Construction Management), CMG 2223 (Print Reading and Introduction to BIM), and TEC 5143 (Research in Technology). The CMG 1000 course introduces students to construction management processes and procedures, relationships, practices, terminology, project types, procurement methods, industry standards, contract documents, project delivery methods, bidding and award documents and procedures; construction budgets; cost estimating; construction planning and scheduling; cost control; sustainability; and technology. The CMG 2223 course introduces reading and interpreting construction drawings and specifications, along with an entry-level exploration of Building Information Modeling (BIM). The TEC 5143 course introduces the means and methods of research used to define and investigate problems in technology-related fields. Topics include problem and scope definition, literature review, research methodologies, data collection, and data analysis.

My teaching interests include a variety of fundamental undergraduate-level and advanced graduate-level civil engineering and construction management topics. I can contribute by teaching courses such as Introduction to Construction Management, Construction Materials and Methods, Construction Documents, Construction Safety, Construction Scheduling, Construction Estimating, Project Management, Heavy Civil Construction, Statics and Structural Systems, Building Information Modeling, and Capstone Project courses at the Department of Civil and Architectural Engineering and Construction Management. I would also welcome the opportunity to use my background and research agenda to develop new courses related to emerging technologies in engineering and management, such as Construction 4.0, Digital Twins, Artificial Intelligence for Construction, Design, and Operation, as well as Data Analytics for Construction and Facilities Management.

3. Approach to Student Success

My approach to student success centers on creating an inclusive learning environment that provides meaningful learning opportunities, individualized support, and sustained mentorship. I believe that student achievement is fostered not only through strong academic instruction but also through intentional efforts to ensure that every student, regardless of background, feels welcomed, supported, and empowered to thrive.

It is crucial to create teaching strategies that enhance the educational experiences of underrepresented students in higher education. In my teaching, I strive to create an inclusive and equitable learning environment. I employ varied teaching methods to accommodate different learning styles and abilities, ensuring that all students have equal opportunities to succeed. I actively work to create a classroom atmosphere where students from all backgrounds feel comfortable sharing their perspectives and experiences. My teaching philosophy emphasizes designing courses that are meaningful, relevant, and accessible to all students. I strive to create a welcoming atmosphere for marginalized students, including racial and ethnic minorities, and women in male-dominated fields such as the Construction industry. I am dedicated to leveraging my faculty role to guide and help students, including individuals with disabilities, historically underrepresented communities like Black students, and first-generation college students who may be unaware of the intellectual and life opportunities available at the university.

In addition, a diverse classroom with a constructive atmosphere offers significant benefits to students, including enhancing their critical thinking skills and broadening their perspectives by exposing them to different viewpoints, cultures, and experiences. One approach I use to cultivate an inclusive classroom is having students write a page about themselves at the beginning of the semester, detailing their interests, values, learning goals for the class, and any concerns they may have about the class. This not only helps me understand their individual needs but also helps establish a strong student-teacher relationship and mutual understanding. Another strategy that I employ in my classrooms is holding small group discussions to build a sense of community amongst students. My goal is to foster a culture of learning that engages all students and enables students from underrepresented backgrounds to participate fully.

The following are additional strategies I use in my classes to foster an inclusive environment: attending to social relations within the classroom, establishing community agreements at the start of the course, being vigilant about biased comments or interactions, recognizing students' emotions, emphasizing student growth and the learning process over the final outcomes, and regularly checking in with students and obtaining anonymous feedback. Additionally, I'm always prepared to address diversity flashpoints when they occur in the classroom. My strategies include acknowledging the issue openly, encouraging respectful dialogue among students, and focusing on ideas rather than individuals. Throughout all these efforts, my ultimate goal is to create a diverse classroom that enhances critical thinking skills and prepares all students for success in their academic and professional lives, regardless of their background or identity.

In addition, I have over three years of professional experience in the construction industry, where I worked primarily as a Project Engineer with China Railway Construction Corporation (CRCC), one of the renowned construction firms in China and Asia. I have been involved in multiple phases of construction, from pre-construction planning to project completion, and have gained hands-on experience in supervising large teams, including quality control, managing construction schedules, and maintaining safety standards on-site. At the University of Wyoming, I will leverage this experience to effectively teach and mentor students in the construction management program.

I've also been actively involved in student mentorship and outreach activities. At Virginia Tech, I've also mentored a student team in the U.S. Department of Energy Solar Decathlon competition. I mainly guided them in the development of AI models and digital twins for the team's Net Zero Energy Buildings Project. Additionally, I also actively engage in outreach programs with the aim of encouraging underrepresented students to explore different technologies used in research. For example, at the Myers-Lawson School of Construction, I conducted interactive research demonstrations for high school students in the Building

Leaders for Advancing Science and Technology (BLAST) program by showcasing the application of extended reality and generative AI in smart building control. I also facilitated a similar workshop for the Virginia 4-H Youth Development program by introducing high school students to the application of quadruped robots.

At Eastern Illinois University, I have also mentored multiple graduate students for their master's research, including guidance on the process of developing their research proposals, refining their writing for academic papers, and providing resources and tools necessary to conduct high-quality research. Also, I am currently serving as a faculty volunteer on the Student Research Planning Team at Eastern Illinois University, a university-wide committee responsible for organizing Student Research Day with the goals of promoting undergraduate and graduate research engagement across the diverse student body. In addition, I am also organizing site visits and experiential learning opportunities for undergraduate construction management students, such as coordinating student participation in the Chicago Build Expo 2025. These activities are designed to enhance students' exposure to industry innovations, strengthen their professional networks, and deepen their understanding of real-world construction practices beyond the classroom. At the University of Wyoming, I aim to expand these efforts by collaborating with local industry leaders to enhance educational opportunities and strengthen the pipeline of talent entering the construction field.

Reachsak Ly, Ph.D., LEED GA

School of Technology
Department of Construction Management
Klehm 4014
Charleston, IL 61920
Website:reachsak.github.io
Email: rly@eiu.edu
Cell: 540-605-0125

EDUCATION

2022 – 2025 | **Ph.D. in Environmental Design and Planning**
Dissertation: "Leveraging Artificial Intelligence and Distributed Ledger Technologies Toward Smart and Autonomous Buildings"
Myers Lawson School of Construction,
Virginia Polytechnic Institute and State University, Blacksburg, VA

2017 – 2021 | **Bachelor of Engineering** in Civil Engineering
Specialization: Structural Engineering
Zhejiang University, China

RESEARCH AND TEACHING INTERESTS

- Artificial Intelligence and Data Analytics
- Smart buildings and Smart cities
- Generative AI, Vision and Large language models (VLMs and LLMs)
- Human Building Interaction
- Human-computer interaction, Embodied Generative AI and Mixed Reality (MR)
- Project Management and Economics

ACADEMIC APPOINTMENTS

08/25 – Present | **Assistant Professor (Tenure-Track)**
Construction Project Management Department,
School of Technology,
Eastern Illinois University, Charleston, IL

2022 – 2025 | **Graduate Research Assistant**
Department of Building Construction,
Myers Lawson School of Construction,
Virginia Polytechnic Institute and State University, Blacksburg, VA

2022 – 2025 | **Graduate Teaching Assistant**
Department of Building Construction,
Myers Lawson School of Construction,
Virginia Polytechnic Institute and State University, Blacksburg, VA

2019 – 2021 | **Undergraduate Research Assistant**
School of Civil Engineering and Architecture,
Zhejiang University, China

PROFESSIONAL EXPERIENCE

May 2019- June 2022 — Project Engineer - China Railway Construction Corporation (CRCC)

- **Duties:** Coordinate with architects and construction team to ensure compliance with building codes and safety regulations. Conduct site inspections to monitor the quality and progress of construction. Provide technical advice and solutions during the construction phase.

FELLOWSHIPS & AWARDS

2025 **Pratt Fellowship for Outstanding PhD Students** | *Virginia Tech, College of Engineering Office of Research and Innovation)* (*Award*)

Award Amount: $2,289.20 – Fellowship awarded in recognition of outstanding research contributions and academic excellence.

2025 **Outstanding Graduate Student Award** | *Myers-Lawson School of Construction*

2025 **Graduate Teaching Assistant Award** | *Myers-Lawson School of Construction*

2025 **Torgersen Research Excellence Award** | Finalist, *Virginia Tech College of Engineering*

2023 **Student Award recipient for the IIBEC International Convention and Trade Show |** *RCI-IIBEC Foundation | USA*

2021 **Excellent Award |** *The International Project Competition in Structural Health Monitoring | 2021, University of Illinois Urbana-Champaign and Harbin Institute of Technology.*

2020 **Outstanding International Student Leader |** *Zhejiang University, China.*

2016 **Fully-funded scholarship for the undergraduate program** | *Zhejiang University, China.*

2016 **Microsoft Hackathon (1st Place)** | *Window App Studio Challenge. Microsoft*

REFEREED JOURNAL

2025 **Reachsak Ly**, Alireza Shojaei. Decentralized autonomous organizations in Built Environments: Applications, Potentials and Limitations. *Information Systems and e-Business Management Journal*. DOI:10.1007/s10257-025-00699-1

2023 Hossein Naderi, Alireza Shojaei, **Reachsak Ly**. Autonomous construction safety incentive mechanism using blockchain-enabled tokens and vision-based techniques. *Automation in Construction*. Vol. 153 DOI:10.1016/j.autcon.2023.104959

2023 Alireza Shojaei, **Reachsak Ly**, Saeed Rokooei, Amirsamman Mahdavian, Ahmed Al-Bayati Virtual site visits in Construction Management education: A practical alternative to physical site visits. *Journal of Information Technology in Construction (ITcon)*. DOI:10.36680/j.itcon.2023.036

2023 Saeed Rokooei, Alireza Shojaei, **Reachsak Ly**. Faculty development program to enhance teaching quality in construction. *International Journal of Construction Management*. DOI: 10.1080/15623599.2024.2304475

REFEREED CONFERENCE PROCEEDINGS

2025 **Reachsak Ly**, Alireza Shojaei, Xinghua Gao. Smart Building Operations and Virtual Assistants Using LLM. In *Companion Proceedings of the 33rd ACM Symposium on the Foundations of Software Engineering*, June 23-27, 2025, Trondheim, Norway (*Accepted*) DOI: 10.1145/3696630.3728706

2024 **Reachsak Ly**, Alireza Shojaei; Hossein Naderi. DT-DAO: Digital Twin and Blockchain-Based DAO Integration Framework for Smart Building Facility Management. In *Construction Research Congress 2024*, pp. 796-805. American Society of Civil Engineers. 2024-03-18, Des Moines, Iowa. DOI: 10.1061/9780784485262.081

2024 Hossein Naderi, **Reachsak Ly**, Alireza Shojaei. From Data to Value: Introducing an NFT-Powered Framework for Data Exchange of Digital Twins in the AEC Industry. In *Construction Research Congress 2024*, pp. 299-308. American Society of Civil Engineers. 2024-03-18, Des Moines, Iowa. DOI: 10.1061/9780784485262.031

2024 Hassan Azad, Alireza Shojaei, **Reachsak Ly**, Saleh Naseer, Laurie M. Heller. Assessment of annoyance from traffic noise in a school and a hospital. In *Inter-Noise 2024 Conference*, pp. 9000 - 9994, 2024-08-27, Nantes, France. DOI: 10.3397/IN_2024_4264

2021 Jiawei Zhang, Jiangpeng Shu , **Reachsak Ly**, Yiran Ji (2021). Continual-learning-based framework for structural damage recognition. In *The 10th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, 2021-06-30-2021-07-02, Porto, Portugal. [PDF]

2020 Jiawei Zhang, **Reachsak Ly**, Weijian Zhao, Yunyi Liu. Image-Based Structural Damage Recognition using Deep Convolutional Neural Networks. In *Proceeding of the Fib Symposium 2020 Concrete Structure for Resilience Society*, 2020-22-11 to 2020-24-11, Shanghai, China. [PDF]

REFEREED JOURNAL (Under Review)

2025 **Reachsak Ly**; Alireza Shojaei; Xinghua Gao; Philip Agee; Abiola Akanmu. Autonomous Building Cyber-Physical Systems Using Decentralized Autonomous Organizations, Digital Twins, and Large Language Model. (*Under Review, Automation in Construction*) (Preprint: arXiv:2410.19262)

2025 **Reachsak Ly**; Alireza Shojaei. Public and private blockchain for decentralized digital building twins and building automation system. (*Submitted to Information Systems and e-Business Management*) (PDF)

2025 **Reachsak Ly**; Alireza Shojaei; Abiola Akanmu; Xinghua Gao; Philip Agee . Data-driven and distributed governance of building facilities management using decentralized autonomous organization, digital twin, and large language models. (*Submitted to Frontiers of Engineering Management*) (PDF)

2025 **Reachsak Ly**; Alireza Shojaei; Xinghua Gao; Philip Agee; Abiola Akanmu . Decentralized autonomous organization and blockchain-based incentivization framework for community-based facilities management.(*Submitted to Information Systems Frontiers*) (PDF)

2025 MohammadHossein Heydari; Hossein Naderi; **Reachsak Ly**; Alireza Shojaei. Industry Perspectives on the Role of Education Programs in Supporting Construction Diversity and Inclusion in U.S. Construction. (Manuscript submitted to *Innovative Higher Education*)

RESEARCH REPORTS

2024 **Reachsak Ly**, Mohammad Hossein Heydari, Hossein Naderi, Josh Iorio, Alireza Shojaei. Investigation of Gender and Racial Diversity in U.S. Construction Higher Education. (PDF)

2021 Jiawei Zhang, Jun Li, **Reachsak Ly**, Yunyi Liu and Jiangpeng Shu. Deep Learning-Based Fatigue Cracks Detection in Bridge Girders using Feature Pyramid Networks. In *The 1st International Project Competition for Structural Health Monitoring*. 2020-15-06 to 2020-30-09, Harbin, China (arXiv:2410.21175)

2021 Jiangpeng Shu, Jiawei Zhang, **Reachsak Ly**, Fangzheng Lin, Yuanfeng Duan. Continual-learning-based framework for structural damage recognition. (arXiv:2408.15513)

2019 **Reachsak Ly**, Lou Tao Shen, Yu Yuansheng, Maosi Geng, Yinan Dong, Ce Wang. Renovation proposal of Santa Clara Street in San Jose. In *The 2019 ASCE Mid-Pacific Student Conference*, Transportation Challenge.2019-14-04-2019-19-04, San Jose, CA [PDF]

INTELLECTUAL PROPERTY DISCLOSURES

2025 Decentralized Autonomous Building Cyber-Physical System (DAB-CPS), *Virginia Tech IP Disclosure*, *Invention Id: INV2025-123*, Inventors: **Reachsak Ly**, Alireza Shojaei (***Approved***, April 2025) (PDF)

2025 Large Language Models-based Autonomous Building Operations and Virtual Assistants for Smart Buildings, *Virginia Tech IP Disclosure*, *Invention Id: INV2025-121*, Inventors: **Reachsak Ly**, Alireza Shojaei (***Approved,*** April 2025) (PDF)

POSTER PRESENTATION

2025 Autonomous Building Operations and Virtual Assistants Using Generative AI. *Poster presentation as part of the 2025 Paul E. Torgersen Graduate Student Research Excellence Award*, *Virginia Tech, Blacksburg, VA*. (PDF)

CONTRIBUTION TO PRIOR FUNDED RESEARCH

(Commonwealth Cyber Initiative Southwest Virginia) SmartHomeSecure: A GenAI-Powered Prototype for Detecting Defects and Vulnerabilities in Smart Home Automation Systems

Award Amount: USD 50,000

- Developed Generative AI Chatbot to enhance smart home security and reliability using LLaMA 3 and GPT-OSS

(NSF SCC-PG) Remote Sensing and Prediction of Environmental Noise to Facilitate Addressing the Social and Health Issues of Noise - Pilot Study: Schools and Hospitals

Award Amount: USD 149,437, Award Number: 2125427.

- Data analysis on noise datasets collected from hospitals and schools.
- Applied descriptive and inferential statistical techniques to assess noise levels and identify correlations with times of the day.
- Performed time series data visualization to illustrate patterns of environmental noise.

Diversity and Inclusion Seed Investments fund (Institute for Critical Technology and Applied Science (ICTAS)) Research on Diversity and Inclusion in the Construction industry and education.

- Conducted data collection for the development of a comprehensive DEI database. Assisted with the design and development of the project website.
- Submitted a journal paper on Gender and Racial Diversity in U.S. Construction Higher Education

GRANT PROPOSALS

Smart and Autonomous Building Cyber-Physical Systems; (NSF 24-581 Cyber-Physical Systems); **Submitted: 08/12/25**;

- My dissertation research and preliminary data related to Blockchain and LLM in smart building are the basis for this grant proposal.
- Contributed to the development and writing of the proposal, including the overall research design, project justification, theoretical underpinning, broader impacts, and intellectual merit.

AI-Driven Augmented Reality for Construction Education: Leveraging Vision and Large Language Models for Immersive and Interactive Learning; (NSF 23-624 Research on Innovative Technologies for Enhanced Learning (RITEL)); **Submitted: 11/05/24**;

- My preliminary works and data on Extended Reality and LLM serve as the basis for this proposal.
- Contributed to the development and writing of the proposal, including the overall research design, project justification, theoretical underpinning, broader impacts, and intellectual merit.

A Real-time and Automated Construction Safety Monitoring and Reporting system using Multimodal Generative AI (Charles Pankow Foundation); **Submitted: 04/07/25**;

- Contributed to the development of the prototypes of the Generative AI system for construction safety monitoring and the writing of the proposal, including the overall research design, project justification, broader impacts, and intellectual merit.

Virginia's Nexus Horizon - Synergizing Urban-Rural Resilience for Sustainable Growth. (NSF 24-533 Sustainable Regional Systems Research Networks); **Submitted: 05/15/24**

- Assisted with the introduction section and data management plan.

AI and Blockchain-Powered Mentorship and Gamification for Empowering Minority STEM Students: Nurturing a Sense of Belonging; (NSF 24-601 Advancing Informal STEM Learning); **Submitted: 01/07/24**

- Assisted with the introduction section and data visualization.

RELEVANT RESEARCH PROJECT

2025 – Present **Vision Language Model for Construction Site Progress and Safety Monitoring**
Developed a vision language model-based AI system to monitor construction site progress and safety conditions, integrating natural language processing, computer vision, and function calling for comprehensive site analysis and automated reporting. (Github) *(Manuscript in preparation)*

2025 – Present **Vision Language Model-based AI agents and (XR) Extended Reality applications**
Developed vision language model-based AI agents and extended reality (XR) applications. This project leverages open-sourced vision language model (LLaVA), Text-to-speech (TTS), and Speech-to-Text (STT) model with Unity 3D to develop a multimodal AI application on Microsoft HoloLens 2 with text, image, and video understanding. (Github) *(Manuscript in preparation)*

2025 – Present **Small language model-based smart home devices for Human-Building Interaction**
Deployed small language models (Phi-3 mini, LLaMA 3.2) onto Raspberry Pi 5 for human-building interaction applications, including smart building systems control. (Github) *(Manuscript in preparation)*

2024 – Present **Large Language Model for Human-Building Interaction**
Designed and implemented a large language model-based chatbot/AI agent to facilitate natural language interactions between building occupants and facility management systems such as smart facilities control. (Github) *(Manuscript in preparation)*

2024 – Present **Retrieval-Augmented Generation (RAG) Chatbot for Construction Safety**
Developed a retrieval-augmented generation (RAG) chatbot utilizing LLM to provide real-time safety information and guidance on construction sites to enhance workers' understanding of safety protocols and awareness. (Github) *(Manuscript in preparation)*

TEACHING EXPERIENCE

Undergraduate level (Virginia Tech)

BC 4434 - Construction Practice I

This course delves into advanced business and management practices related to vertical construction projects. It covers a wide range of topics, including Work Breakdown Structure (WBS), planning and scheduling, cash flow forecasting and analysis, assemblies estimating, as well as estimating general conditions and overhead costs. Additionally, students will explore site logistics planning, construction contracts and insurance, and the review and management of Building Information Models (BIM). The course also introduces the Design-Build project delivery method.

- **Duties**: Conducted lab sessions and graded students' labs, homework, and exams. Instructed students on key topics such as Work Breakdown Structure (WBS), planning and scheduling, cash flow forecasting and analysis, and assembly estimating. Supervised and mentored students on these topics, held regular office hours for additional support, and provided personalized guidance to help students understand course material and industry practices.

BC 4444 - Capstone Project
This course explores and applies business and construction management practices related to the development and preparation of a response to an RFP to an actual Design-Build capstone project. Topics are reinforced through working on a real-life D/B project. This course is designed to prepare students to understand concepts and principles of the D/B contracting method through working on preparing and delivering responses to an RFP for a real-life D/B project.

- **Duties**: Guided students through the development and execution of their capstone projects, providing supervision on the use of design and project management software, including Revit, MS Project, and RSMeans for cost estimation. Assisted students in preparing responses to project RFPs, offering continuous feedback on design quality and project milestones. Graded student submissions and provided detailed feedback.

BC 4164 - Process Planning and Production Design for Construction
Course topics include production systems, behavior of construction systems and workers, relationships between subsystems in the construction process, queueing systems, process modeling, and simulation. This course gives students an understanding of the production process from both a theoretical and practical perspective. It also equips them with tools and techniques to design, analyze, and improve construction processes.

- **Duties**: Instructed students on the use of Primavera Cloud for project management, including scheduling, process planning, and production analysis. Provided hands-on guidance in utilizing the software to model and improve construction processes. Graded student assignments and projects, offering detailed feedback to enhance their understanding of production systems and process modeling.

Graduate level (Virginia Tech)
BC 5984 - Decision-Making and Risk Management
This course explores the theories, methodologies, and tools used in decision-making and risk management from a beginner to an advanced level. Students will gain insights into the complexities of making decisions in uncertain environments and learn strategies to manage and mitigate risks effectively. This course is designed to prepare students to think critically and become better decision-makers. It will also equip them with risk management knowledge to apply in various contexts.

- **Duties**: Supervised students in performing calculations related to planned and expected values for decision-making in project management. Guided them through the application of risk management strategies and techniques. Facilitated hands-on experience with project simulation using the Monte Carlo method to analyze and manage uncertainties in project outcomes.

Undergraduate level (Eastern Illinois University)

CMG 1000 – Introduction to Construction Management

This course introduces students to construction management processes and procedures, relationships, practices, terminology, project types, procurement methods, industry standards, contract documents, and career opportunities. Topics include the roles of the owner, architect, engineer, and contractor; project teams and organizations; their responsibilities and interrelationships; types of contracts; different project delivery methods; bidding and award documents and procedures; construction budgets; cost estimating; construction planning and scheduling; cost control; sustainability; technology.

CMG 2223 – Print Reading and Introduction to Building Information Management (BIM)
This course provides an introduction to reading and interpreting construction drawings and specifications, along with an entry-level exploration of Building Information Modeling (BIM). In the first portion of the course, students will learn how construction plans are organized and drawn, how to read and interpret architectural and engineering drawings, and how to apply this knowledge from conceptual design through final construction documentation. In the second part of the course, students are introduced to the fundamentals of BIM, with a focus on creating and modifying 3D building models using Autodesk Revit.

Graduate level (Eastern Illinois University)

TEC 5143 – Research in Technology

This course introduces the means and methods of research used to define and investigate problems in technology-related fields. Topics include problem and scope definition, literature review, research methodologies, data collection, and data analysis. Students will learn the processes and tools for conducting both experimental and non-experimental research, with an emphasis on research design, analysis, interpretation, and reporting. The course also guides students in writing of a research proposal.

GUEST LECTURE

BC4164 –Process Planning and Production Design for Construction ***Virginia Tech***

- Supervised and coordinated students in BC4164 class on the use of **Generative AI,** such as ChatGPT and Claude, and open-sourced LLM, such as Llama 3.2, for construction scheduling applications.

SKILLS

Application used
Autodesk Platform Service, Autodesk Tandem, Primavera P6, Autodesk Revit, Autodesk Naviswork, AutoCAD, Autodesk Recap, Faro Scene, Trimble Realworks, SPSS, Microsoft Projects, and Unity 3D.
Programming language
Python, R, Python, C#, Javascript, Java, HTML/CSS, ROS, Solidity and MATLAB

Data Science & Machine Learning: TensorFlow, PyTorch, Scikit-Learn, Pandas, NumPy, Matplotlib, MLX, CUDA, Llama.cpp, Llamaindex, Huggingface, Langchain, Unsloth AI and CrewAI

PROFESSIONAL AFFILIATION/ CERTIFICATION

- LEED Green Associate, *U.S. Green Building Council,* 2025
- Future Professoriate Certificate, *Graduate Certificate Program, Virginia Tech,* 2024
- CIRTL Certificate, *Center for the Integration of Research, Teaching & Learning, Virginia Tech, 2024*
- Student member, *Center for Human-Computer-Interaction (CHCI), Virginia Tech.*
- Student member*, International Institute of Building Enclosure Consultants (IIBEC).*

UNIVERSITY SERVICE

05/2025 – Present Committee Member – Student Research Planning Team, Eastern Illinois University

- **Duties:** Serve as a faculty volunteer on the university-wide committee responsible for planning and organizing Student Research Day, supporting undergraduate and graduate research engagement.

2024 – 05/2025 Research collaboration with the Diversity, Equity, and Inclusion (DEI) Committee at the Myers-Lawson School of Construction.

- **Duties:** Conduct research on the investigation of the relationship between racial and gender diversity among student graduates and their retention rates within the construction industry. Collaborate with multiple institutions to collect and analyze data on construction student graduates, focusing on diversity metrics. Assist with data collection, data visualization, and the development of the department's DEI website.

PROFESSIONAL SERVICE

Journal paper Reviewer

2024 – Present Automation in construction Journal
2024 – Present Journal of Construction Engineering and Management
2024 – Present Developments in the Built Environment Journal
2024 – Present Digital Engineering Journal
2024 – Present Journal of building engineering
2024 – Present Journal of Civil Engineering Education
2024 – Present Journal of Information Technology in Construction

Conference paper Reviewer

2025 ASCE International Conference on Computing in Civil Engineering (i3CE 2025)

OUTREACH / COMMUNITY SERVICE

2024 ***Building Leaders for Advancing Science and Technology (BLAST) program,*** Myers Lawson School of Construction, Virginia Tech, VA| July 09, 2024

- **Duties:** Conducted a research demonstration on the integration of LLM-based AI agents and Augmented Reality (AR) for smart building control. Presented the application of AR and LLM technologies, showcasing their potential future impact on the construction industry to high school students.

2024 ***Virginia 4-H Youth Development Program***, Myers Lawson School of Construction, Virginia Tech, VA| July 09, 2024

- **Duties:** Organized and conducted a workshop demonstrating the application of quadruped robots in the construction industry. Engaged high school students in hands-on activities and discussions about robotics technology and its potential impact on construction practices.

MENTORSHIP

07/2024 Student mentoring for the U.S. Department of Energy Solar Decathlon competition.

- Guiding students on the development of digital twins for the Zero Energy Buildings.

2022 – Present Undergraduate and Graduate Student mentoring (Virginia Tech and Eastern Illinois Univ.)

- Conducting one-on-one meetings with students to resolve challenges encountered in the taught courses.

2024 – Present Student mentoring for Research in Digital twin and Computer Vision (Object Detection).

- Mentee: Thyda Siv (M.S. in Building Construction and Facility Management, Georgia Institute of Technology)

08/2025 – Present Student Mentoring – Master's Thesis Research in Technology

- Precious Dodoo (M.S. in Business Administration, Eastern Illinois University)
- Kuladeep Perumalla (M.S. in Cybersecurity, Eastern Illinois University)

Office of Research and Innovation
3046 Torgersen (0217)
620 Drillfield Drive
Blacksburg, Virginia 24061
P: (540) 231-9171
F: (540) 231-3031
https://eng.vt.edu/research.html

February 28, 2025

Reachsak Ly - MLSoC

Dear Reachsak,

Congratulations! You have been awarded a fellowship from the College of Engineering Office of Research and Innovation in the amount of $2,289.20. This fellowship is a testament to your outstanding research contributions and the high regard in which you are held by faculty in your department.

This fellowship provides a stipend of $457.84 per pay period, starting 2/25/2025 and ending 5/9/2025. This award does not include payment of tuition or any fees.

Fellowships are not considered employment, and you will not receive a W2 form at the end of the year. Fellows are required to report the fellowship stipend income to IRS on a 1040 form. For more information see IRS Publication 970: *Tax Benefits for Education*.

Sincerely,

Nicole Akers
Assistant Director of Research
Office of Research & Innovation
VT College of Engineering

CERTIFICATE

This certificate is presented to

Jiawei Zhang, Jun Li, Reachsak Ly, Yunyi Liu, Jiangpeng Shu

for winning the *Excellence Award* *in the 1st International Project Competition for Structural Health Monitoring (IPC-SHM 2020) with paper entitled of "Deep Learning-Based Fatigue Cracks Detection in Bridge Girders using Feature Pyramid Networks"*

Congratulations!

January 15, 2021

Prof. Hui Li, Chair
Harbin Institute of Technology

January 15, 2021

Prof. Billie F. Spencer Jr, Co-Chair
University of Illinois at Urbana-Champaign

ANCRiSST
Lab of Intelligent Civil Infrastructure, Harbin Institute of Technology, China
Smart Structures Technology Lab, University of Illinois at Urbana-Champaign, USA
CCCC Highway Consultants Co., Ltd.

CCCC Civil Big Data Information Technology (Beijing) Co., Ltd.
State Key Lab for Health and Safety of Bridge Structures, China Railway Bridge Science Research Inst., Ltd.
State Key Lab on Safety and Health of In-service Long-span Bridges, JSTI Group, China

CERTIFICATE

OF APPRECIATION IS

Proudly Presented To

Reachsak Ly

in recognition of your exceptional dedication and exemplary service as a Graduate Teaching Assistant during the 2024-2025 academic year. With profound appreciation, we celebrate your unwavering commitment to academic excellence, student success, and to the advancement of learning.

ACHIEVEMENT
EXCELLENCE

VIRGINIA TECH.

COLLEGE OF ENGINEERING
MYERS-LAWSON
SCHOOL OF CONSTRUCTION
VIRGINIA TECH.

CERTIFICATE

OF

SCHOLARLY RECOGNITION

Proudly Presented To

Reachsak Ly

for his outstanding academic achievement and dedication to scholarly excellence during the 2024-2025 academic year. Your work stands as a testament to the pivotal role of diligent inquiry and research in advancing our industry. We commend your commitment to the highest standards of academic pursuits and celebrate the impact of your exceptional achievements.

VIRGINIA TECH

ACHIEVEMENT EXCELLENCE

COLLEGE OF ENGINEERING
MYERS-LAWSON
SCHOOL OF CONSTRUCTION
VIRGINIA TECH

LEED
GREEN
ASSOCIATE

11679119-GREEN-ASSOCIATE

CREDENTIAL ID

04 AUG 2025

ISSUED

03 AUG 2027

VALID THROUGH

GREEN BUSINESS CERTIFICATION INC. CERTIFIES THAT

REACHSAK LY

HAS ATTAINED THE DESIGNATION OF

LEED® Green Associate™

by demonstrating the knowledge and understanding of green building practices and principles needed to support the use of the LEED green building program.

PETER TEMPLETON
PRESIDENT & CEO
U.S. GREEN BUILDING COUNCIL & GREEN BUSINESS CERTIFICATION INC.

Virginia Polytechnic Institute and State University

The Board of Visitors of the Virginia Polytechnic Institute and State University has conferred upon

Reachsak Ly

upon the recommendation of the Faculty, the degree of

Graduate Certificate

Future Professoriate

with all the rights, privileges and honors pertaining thereto.
In testimony whereof, the undersigned, by authority vested in them, have hereunto affixed their signatures and the seal of the University at Blacksburg, Virginia this fourteenth day of December, two thousand and twenty-three.

Edward H. Baine
Rector

Timothy D Sands
President

Aimée Surprenant
Dean

GRADUATE SCHOOL
VIRGINIA TECH

Admissions and Academic Progress
155 Otey Street
120 Graduate Life Center at Donaldson Brown
Blacksburg VA 24061-0325
(540) 231-8636

One-Click Degree Verification

Reachsak Ly

Institution: Virginia Tech
Certificate: Graduate Certificate
Completion Date: December 14, 2023

Aimée M. Surprenant, Dean of the Graduate School

This eDiploma was digitally Signed and Certified on Mar 12, 2024.

Michael Sutter
DOCUMENT CERTIFICATION SERVICES

eDiploma - Signed and Certified PDF

To validate the Signature and Certification of this eDiploma, you must open this PDF with Adobe Reader or Adobe Acrobat. You will see a Blue Ribbon at the top of the document validating the digital Signature used to Certify this eDiploma.

eDiploma on page 2

Microsoft

Certificate of Participation

is awarded to

Reaksar Ly

for participating in

"Visit Cambodia"
Windows App Studio Challenge for Destination Marketing

held on

10th March 2016

At Science & Engineering Festival Cambodia

David Lim

Director, Developer Evangelism & Experience, Microsoft APAC AHQ

VIRGINIA TECH | OFFICE OF THE UNIVERSITY REGISTRAR
Blacksburg, VA 24061

Student Name: Ly, Reachsak
Student ID: 906 50 7139
Date of Birth: JAN 06, 1998

STUDENT'S RECORD

Subject Title	Dept.	No.	Hrs.	Gr.	Qual. Cr.
Graduate Regular Post Masters					
MAJOR: Environmental Design and Planning					
Fall 2022					
Blt Env Info Modeling & Procng	CEE	5060	3	A	12.0
Computation for Data Sciences	CS	5045	3	A	12.0
Research and Dissertation	EDP	7994	5	EQ	EQU CR
GTA Training Workshop	GRAD	5004	1	P	P/F
Preparing Future Professoriate	GRAD	5104	3	A	12.0
			15		36.0
906 50 7139 TERM GPA: 4.00					
Cum GPA: 4.00					
Spring 2023					
Methods Const Research	CNST	5084	3	A	12.0
Blockchain Technologies	CS	5594	3	A	12.0
Research and Dissertation	EDP	7994	6	EQ	EQU CR
Contemporary Pedagogy	GRAD	5114	3	A	12.0
			15		36.0
906 50 7139 TERM GPA: 4.00					
Cum GPA: 4.00					
Fall 2023					
SS: AI for Design and Const	CNST	5984	3	A	12.0
Research and Dissertation	EDP	7994	6	EQ	EQU CR
Diversity for Global Society	GRAD	5214	3	A	12.0
Statistics in Research	STAT	5615	3	A	12.0
			15		36.0
906 50 7139 TERM GPA: 4.00					
Cum GPA: 4.00					

Awarded the Graduate Certificate in Future Professoriate
on DEC 14, 2023

Subject Title	Dept.	No.	Hrs.	Gr.	Qual. Cr.
Spring 2024					
SS: Decision Making & Risk Mgt	BC	5984	3	A	12.0
Adv Data Anlys & Viz for C&FM	CNST	5634	3	A	12.0
Research and Dissertation	EDP	7994	9	EQ	EQU CR
			15		24.0
906 50 7139 TERM GPA: 4.00					
Cum GPA: 4.00					
Graduate Doctoral					
Fall 2024					
Const Prof Competencies	CNST	5074	3	A	12.0
Research and Dissertation	EDP	7994	12	EQ	EQU CR
			15		12.0
906 50 7139 TERM GPA: 4.00					
Cum GPA: 4.00					
Spring 2025					
Research and Dissertation	EDP	7994	15	EQ	EQU CR
			15		
906 50 7139 TERM GPA: 0.00					
Cum GPA: 4.00					

Conferred the Doctor of Philosophy
Major -- Environmental Design and Planning
on MAY 14, 2025

Dissertation Title:
Leveraging Artificial Intelligence and Distributed Ledger Technologies Toward Smart and Autonomous Buildings

*****************End of Graduate Record*****************

*******************End of Transcript********************
Printed: MAY 30, 2025

Richard A. Sparks, Jr.
University Registrar

2S3U-3KBL-RKYK

Virginia Polytechnic Institute and State University

The Board of Visitors of the Virginia Polytechnic Institute
and State University has conferred upon

Reachsak Ly

upon the recommendation of the Faculty, the degree of

Doctor of Philosophy

Major - Environmental Design and Planning

with all the rights, privileges and honors pertaining thereto.
In testimony whereof, the undersigned, by authority
vested in them, have hereunto affixed their signatures
and the seal of the University at Blacksburg, Virginia
this fourteenth day of May, two thousand and twenty-five.

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
UT PROSIM

Rector

President

Dean

Dean

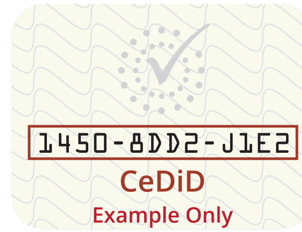
Secure Credential Validation

VIRGINIA TECH™

CeCredential Trust

The market leader in the generation of secure, portable digital credentials.

CeDiploma



For more information on CeCredential Trust, click here.

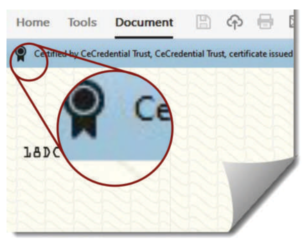
To validate this credential:

The CeDiD is located in the upper left-hand corner of the credential (page 1). The CeDiD is a unique identifier and is required for validation. Enter the CeDiD, using the link below to visit the institution’s official validation website. Validation includes complete degree information that is time and date stamped by the issuing authority.

Validate Now or visit https://apps.es.vt.edu/CeDiploma/validation

To verify the digital signature:

This credential is certified by **CeCredential Trust** and should read as such. The ribbon signifies that both pages of this document have not been modified since issued. Do not trust this document if any other symbol is displayed.



Valid and Certified
Authenticity and integrity are verfied
TRUST

Error!
Check internet connection
DO NOT TRUST

Error!
Authenticity and integrity not verfied
DO NOT TRUST

Attestation of the Registrar

This **Certified Electronic Diploma (CeDiploma)** acknowledged herein represents satisfactory completion or attainment of education as authorized by the institution identified.

This **CeDiploma (credential)** has legal standing, is non-repudiating, and can be validated through the Institution’s website to provide absolute confidence in the credential’s authenticity.
Questions should be directed to registrar@vt.edu.

Pursuant to Virginia Code, Section 23.1-900.01, “each public institution of higher education and private institution of higher education may provide any diploma or other proof of education to requesting individuals or entities using the method that it deems appropriate in either electronic or paper form.”

Sample Research Paper

Smart Building Operations and Virtual Assistants Using LLM

Reachsak Ly
Myers-Lawson School of Construction,
Virginia Tech
Blacksburg, Virginia, USA
reachsak@vt.edu

Alireza Shojaei
Myers-Lawson School of Construction,
Virginia Tech
Blacksburg, Virginia, USA
shojaei@vt.edu

Xinghua Gao
Myers-Lawson School of Construction,
Virginia Tech
Blacksburg, Virginia, USA
xinghua@vt.edu

ABSTRACT

Conventional AI-powered smart home assistants primarily function as voice-activated control systems with limited adaptability and contextual understanding. Similarly, while traditional artificial intelligence has advanced autonomous building research, it often relies on predefined rules and struggles with real-time decision-making in dynamic building environments. This paper introduces a novel Generative AI-driven framework that integrates Large Language Models (LLMs) to create a smart generative AI-based virtual assistant and an operation automation system for building infrastructure. The AI systems autonomously manage building operations by analyzing real-time occupancy patterns and adjusting environmental conditions based on predefined comfort thresholds. The proposed system also facilitates seamless human-building interaction through an LLM-powered virtual assistant. The framework is validated through a prototype implementation in a real-world building equipped with smart appliances, with evaluations focusing on the AI systems' accuracy, reliability, and scalability. The findings demonstrate that the prototype system can autonomously adjust building conditions, optimize energy usage, and provide intelligent assistance for building operation tasks.

CCS CONCEPTS

• Human-centered computing →Human-computer interaction (HCI)

KEYWORDS

Generative AI, Large Language Models, Smart Buildings, Autonomous Building Operations, Virtual Assistant

ACM Reference format:

Reachsak Ly, Alireza Shojaei and Xinghua Gao. 2025. Smart Building Operations and Virtual Assistants Using LLM. In *Companion Proceedings of the 33rd ACM Symposium on the Foundations of Software Engineering (FSE '25), June 23–28, 2025, Trondheim, Norway. ACM, New York, NY, USA, 7 pages.* https://doi.org/10.1145/3696630.3728706

ACM ISBN 979-8-4007-1276-0/2025/06.
https://doi.org/10.1145/3696630.3728706

1 Introduction

Research on autonomous buildings has become a promising frontier in the field of smart and sustainable infrastructure. Autonomous buildings are characterized by their ability to operate independently through self-management, self-sufficiency, and intelligent operation [1], [2]. Machine learning techniques and AI have played a pivotal role in enabling these advancements. Their capacity to analyze large volumes of data, recognize trends, and make well-informed choices has contributed significantly to improving energy efficiency, enhancing occupant comfort, and optimizing building performance [3], [4]. However, the functionality of this conventional machine learning model may rely on predefined rules or specific training data, which, in some circumstances, may not adequately capture the dynamic and complex nature of the building environment [5], [6]. Furthermore, they often struggle to adapt to evolving circumstances or to incorporate contextual information effectively [7].

The advent of large language models (LLMs) offers a promising avenue to overcome these limitations and unlock a new realm of possibilities for autonomous building operations. LLMs exhibit remarkable capabilities in natural language processing, which could enable seamless human-machine interactions and intelligent decision-making processes [8]. Unlike conventional machine learning algorithms such as deep learning, regression, clustering, and reinforcement learning, LLMs possess a deep understanding of contextual information and can engage in humanlike conversations [5], [6], which could allow for more intuitive and adaptive control of building systems. Despite its transformative potential, the application of LLMs in building automation and smart virtual assistants remains largely unexplored. This study aims to address these gaps by proposing a novel Generative AI-driven framework that seamlessly integrates LLMs into building automation systems for autonomous building management while providing an intelligent virtual assistant interface for enhanced human-building interaction.

2 Related work

Recent research has focused on applying machine learning to enhance smart home capabilities. For instance, researchers have proposed home automation based on activity recognition by using deep learning algorithms to recognize users' activities from accelerometer data [9]. Voice-based assistants have also been an

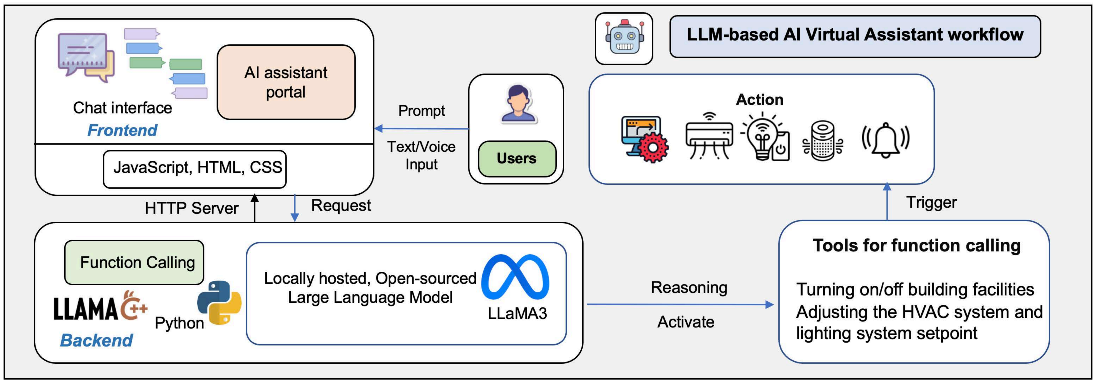


Figure 1: Overview of the LLM-based Virtual Assistant.

important focus area, with systems designed to understand users' voice commands through natural language processing (NLP). Rani et al. [10] developed a voice-controlled home automation system using NLP and IoT to control basic appliances. In addition, while commercial solutions like Google Assistant, Alexa, and Bixby offer user-friendly interfaces for handling various commands with advanced NLP techniques, they typically struggle with implicit and complex instructions [11]. These systems often fail when user utterances cannot be easily mapped to preprogrammed routines [12]. Web-based services like IFTTT [13], Zapier [14], and Home Assistant [15] enable users to create rules for controlling smart devices without extensive programming knowledge, though they lack the reasoning and context-awareness offered by LLMs.

To address these limitations, recent work has leveraged Large Language Models (LLMs) to better understand and execute complex user commands. Sasha [16] demonstrated that LLMs can produce reasonable behaviors in response to complex or vague commands by implementing a decision-making pipeline using LLM. However, Sasha's pipeline stages are manually defined and fixed, thereby limiting flexibility. Rivkin et al. [12] have also presented Smart Home Agent with Grounded Execution (SAGE), which overcomes these limitations using a scheme where user requests trigger an LLM-controlled sequence of discrete actions. In addition, LLM-powered autonomous agents are designed to perform complex tasks with minimal human intervention. Various agent architectures have been proposed [17], including Chain-of-Thought (CoT) [18], a prompting technique enabling complex reasoning through step-by-step planning while tools such as llama cpp agent [19] further extend LLM-based agent capabilities.

Furthermore, it is important to note that the existing research on the application of LLMs in the construction domain has primarily utilized commercialized GPT models, such as OpenAI's ChatGPT. The use of these cloud-based GPT models requires sensitive data to be transmitted to external servers for processing, potentially exposing it to unauthorized access or data breaches [20]. Another significant challenge lies in the cost and scalability aspects of these commercial LLM services. Therefore, there is also a need to explore alternative solutions, such as utilizing local and open-source LLMs that can improve inference speed while addressing data privacy concerns, as the data remains localized within the device or system. Our work builds upon these foundations while also addressing limitations in flexibility, scalability, and integration with building infrastructure's automation system using open-sourced LLMs.

3 Methodology

This research employs the Design Science Research (DSR) [21] methodology to develop and validate the LLM-powered building automation system and virtual assistant. Previous studies [12], [22] reveal significant gaps in current building automation systems, including limited contextual understanding of traditional AI approaches and insufficient research on LLM integration in smart building applications. To address these gaps, the research objectives focus on developing an innovative framework that integrates LLMs into building automation systems for enhanced human-building interaction and autonomous environmental control. The design and development phase encompasses creating the LLM-powered virtual assistant interface, developing the autonomous building control system, and implementing real-time monitoring capabilities. The system will be demonstrated in a real-world smart building environment equipped with various sensors and smart appliances. Evaluation will assess the system's performance through multiple metrics, including environmental control accuracy, system reliability, and scalability. Finally, the research findings and framework design will be disseminated through academic publications.

4 Proposed framework

The proposed AI system consists of two primary components: the LLM-based Virtual assistant and the LLM-based AI agent. The Virtual assistant functions as a conversational interface that leverages LLM's language understanding capabilities for human-building interaction while the AI agent operates independently to monitor environmental conditions, analyze sensor data, and automate building operations without direct human input.

4.1 LLM-based Virtual Assistant

The LLM-based virtual assistant aims to facilitate the human-building interaction aspect within the proposed framework. Users can communicate with the virtual assistant through text and voice input to control various building facilities, adjust set points for the

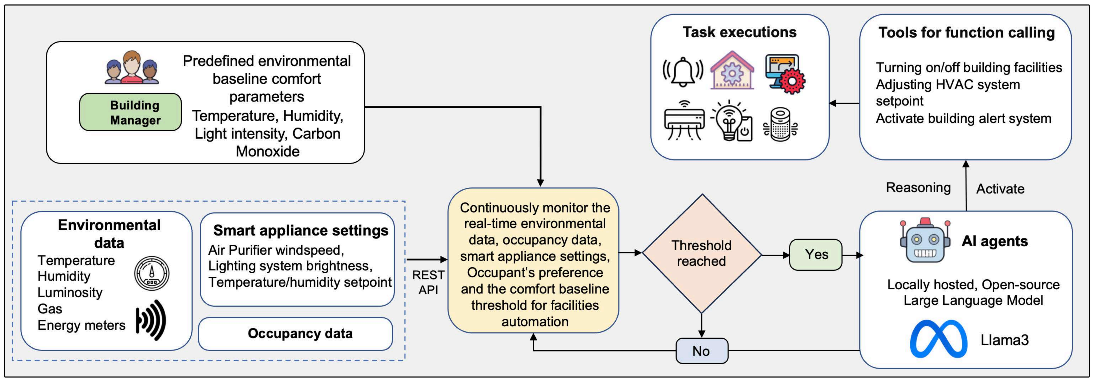


Figure 2: Overview of the LLM-powered autonomous building operation.

specific building smart facilities, or turn systems on or off as needed. Central to the virtual assistant is a locally hosted, open-source LLM and its function calling capabilities, specifically the LLaMA3 model by Meta [23]. The use of local and open-source LLM is driven by several factors, including enhanced data privacy and reduced operational costs. By keeping all interactions and data processing within the local infrastructure, the system also ensures independence from third-party entities and maintains strict control over sensitive information. The virtual assistant workflow is illustrated in Figure 1, which demonstrates the integration of frontend and backend components. Users interact with the system through a web-based chat interface. The submitted prompts by the user are transferred to the backend and processed by the local LLM model. Upon receiving a query, the LLM model leverages its reasoning and function-calling capabilities to understand the user's request and activates the appropriate predefined tools for task execution.

4.2 Autonomous building operation

The proposed LLM-based autonomous building operation framework leverages the integration of IoT devices and sensors, smart building facilities such as the HVAC and lighting system, and LLMs to create automated control of building systems (Figure 2). An array of environmental sensors and IoT Devices will be used to collect environmental data such as temperature, humidity, light intensity levels, carbon monoxide levels, as well as energy usage information, and occupancy levels within the physical space. Raspberry Pi devices are used to process these data and feed them into the AI agent through REST API. In addition, the threshold parameters are used for the automated smart building operation (e.g., max or min temperature, humidity, etc.). These threshold values are the baseline comfort parameters for ensuring optimal comfort and indoor environmental quality and are defined by users or building managers, who serve as administrators for the physical spaces. During the operation, the LLM-based AI agent will continuously compare real-time sensor data from the physical space against these predefined thresholds. When the environmental data values exceed these thresholds, the AI agent utilizes its function-calling capabilities to control various building systems, including smart lighting and HVAC systems. These operations involve adjusting set points, activating or deactivating devices, or triggering alerts to maintain optimal building conditions.

5 Proof of Concept

5.1 Implementation preparation

5.1.1 Smart home appliance. To simulate the required environmental management capabilities for the study, a range of smart home devices has been installed, allowing the virtual assistant to control air quality, humidity, lighting, and temperature within the physical space. To simulate air quality control within the space, this study uses a smart air purifier device, Xiaomi Smart Air Purifier 4 Compact, which is equipped with multiple fan speed configurations. In addition, a smart humidifier, the Govee Smart Humidifier H7141, is used to facilitate the adjustment of humidity levels within the room. It offers multiple fan speed settings. The Xiaomi Mi Smart Standing Fan 2 is also integrated into the system by offering multiple fan speeds for personalized airflow control. This device allows the AI system to demonstrate its ability to regulate air circulation within the space, simulating traditional HVAC systems. For lighting control, this study used a smart bulb, Yeelight Smart Light Bulbs W3. It offers adjustable brightness levels, which mimic the control of indoor lighting conditions.

5.1.2 Deployment of the AI systems module. The proposed AI systems in this study are powered by LLaMA 3 8b, an open-source LLM with 8 billion parameters. The workstation used for the LLaMA3 model deployment in this study is an Apple MacBook Pro with an M1 Max chip and 32GB of RAM. To run the LLaMA 3 model efficiently, this study employs a quantized version of the model using the llama.cpp [24]. Llama cpp is a tool that allows the execution of quantized LLMs on local hardware with support for different types of GPU. Quantization is an essential operation for the reduction of the model's size and computational requirements, which is particularly important for deploying AI systems on local hardware [25]. This enables running complex models on devices with less computational power without severely compromising performance. The 8-bit quantized model of LLaMA 3 8b is used in this study. Function calling is one of the core features of the proposed virtual assistant. In this context, function calling refers to the AI's ability to analyze user requests, extract key information,

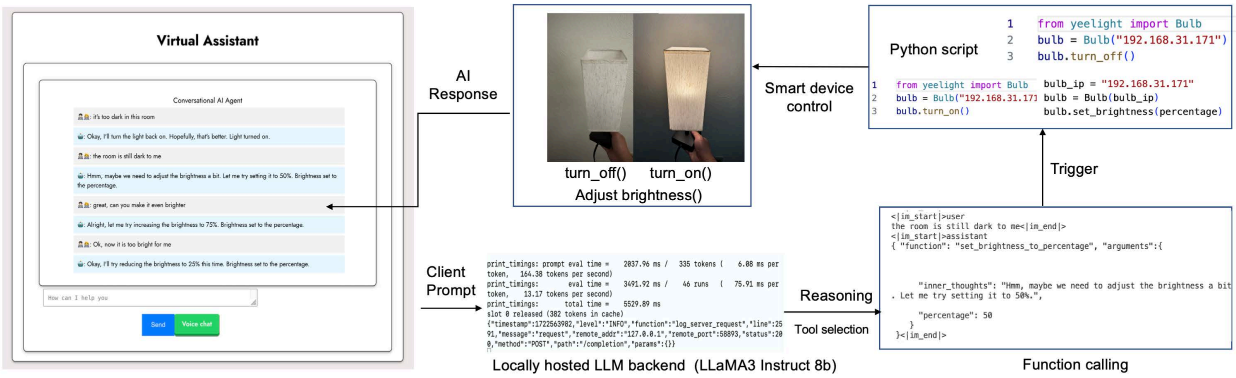


Figure 3: Smart building appliance control using LLM-based Virtual Assistant.

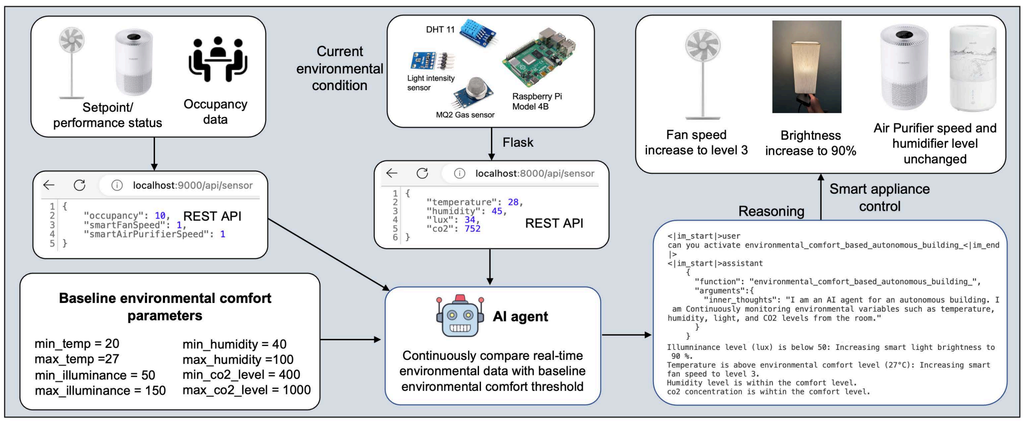


Figure 4: Autonomous smart appliance control using LLM-based AI agent.

and invoke predefined tools or functions to perform tasks. This study leverages llama-cpp-agent, a Python-based package, to implement the function-calling capabilities of the proposed virtual assistant.

5.2 Experiments

The first experiment aims to validate the LLM-based AI agent's ability to control smart building appliances. For this demonstration, the control of a smart light bulb was selected. Users can interact with the virtual assistant to issue voice commands, such as turning the light on or off. The user's prompts are then transmitted to the backend, where they are processed by the locally hosted LLMs. Upon receiving the request, the AI uses its function-calling capabilities to understand and act upon the user's instructions. It then activates a Python script that interfaces with the device's API, enabling it to control the smart light bulb as requested. In addition, instead of the simple on/off commands, users can also provide the context or hint, such as stating that the room is "too dark" or "too bright.". The virtual assistant, leveraging its context-awareness capabilities, can autonomously adjust the brightness level of the light bulb, which can be seen in Figure 3. This dynamic interaction demonstrates the enhanced functionality of the LLM-powered virtual assistant, distinguishing it from traditional AI systems that lack such nuanced environmental awareness.

The second experiment explores the role of the AI agent in managing smart devices for autonomous building operations through two distinct scenarios: automatic appliance control based on occupancy and autonomous adjustments according to environmental data. In the first case, this experiment uses the simulated occupancy data (randomly selected between 1 and 20) and is updated every 1 minute to test the AI agent's ability to autonomously control devices such as a smart fan and air purifier. For demonstration, this study defines low occupancy as fewer than five individuals, medium occupancy as five to nine individuals, and high occupancy as ten or more individuals. As demonstrated in Figure 4, the AI agent continuously monitors the fan and air purifier settings and occupancy data through RESTful API. Depending on the occupancy levels, the AI modifies the performance of the devices accordingly. If no occupants are detected, the AI will turn off all devices. In the case of low occupancy, it reduces the performance to a lower setting, while in the medium occupancy case, it sets the smart appliance to medium settings. Finally, in high occupancy scenarios, it increases the devices' performance to the maximum setting. Initially, both the smart fan and air purifier were set to low performance at level 1. During the experiment, the simulated occupancy was ten individuals, which led the AI to perform the contextual reasoning and raise the performance settings of the fan and air purifier to level 3 and level 7, respectively, to ensure environmental comfort in the physical space.

The second case aims to validate the AI agent's ability to autonomously adjust smart appliances based on baseline environmental comfort parameters. In this scenario, the smart appliance setpoints were initially configured at their lowest levels.

As shown in Figure 4, the AI retrieved the baseline comfort parameters, which include temperature (20°C-27°C), humidity (40%-100%), light intensity (50-150 lux), and carbon monoxide levels (0-50 ppm). The real-time room conditions of 28°C, 45% humidity, 34 lux, and 752 ppm were obtained through REST API. Upon processing this data, the AI agent determined that the temperature and luminance were outside the comfort range and automatically adjusted the smart fan to speed level 3 and the smart light to 90% brightness while leaving other appliance settings unchanged. This experiment demonstrates the AI agent's ability to autonomously regulate the indoor environment by adjusting smart devices based on real-time data and predefined comfort thresholds. The code for the technical implementation of the prototypes is available under an open-source license [26][27].

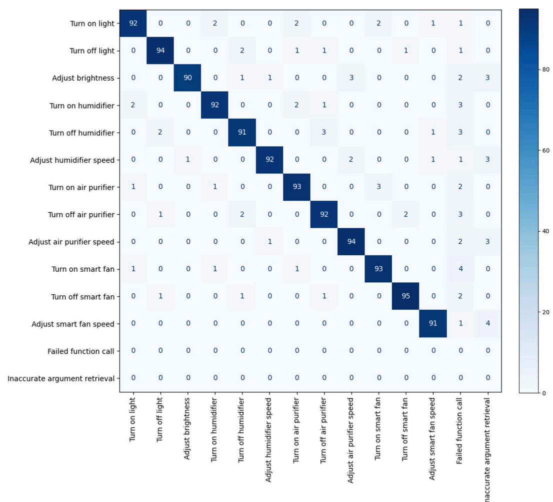


Figure 5: Confusion Matrix for Building Operations Using Virtual Assistant.

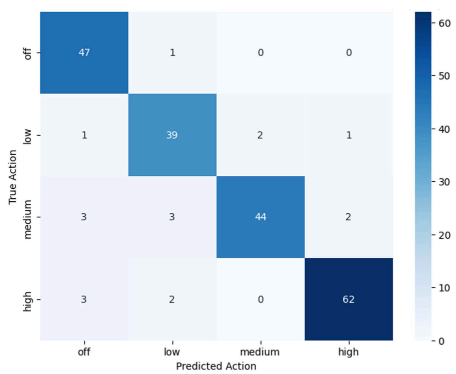


Figure 6: Confusion Matrix for Occupancy-based Autonomous Building Operations.

6 Evaluation

The LLM-based AI systems in this study are composed of two components: a Virtual assistant and an AI agent. The virtual assistants can take user commands and perform smart building tasks by activating tools using function calls. Additionally, the AI agent will monitor the environmental condition occupancy level and the performance of smart building facilities control using function calls. The performance of the AI systems will be evaluated on the speed, accuracy, and reliability of the function-calling capability of the AI systems. To evaluate the accuracy of the functions or tasks executed by the AI systems, this study uses five different metrics, including Precision, Recall, F1 Score, Overall Accuracy, and Reliability. These metrics are specifically useful for evaluating the model's performance when it successfully selects a function that is similar to the multiclass classification task. The reliability metric aims to examine how consistent the AI is in executing the function when responding to the same prompt.

6.1 Evaluation of the Virtual Assistant

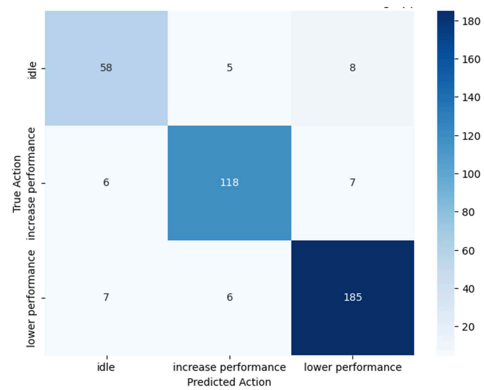


Figure 7: Confusion Matrix for Threshold-based Autonomous Building Operations.

There are 12 different functions/tools that will be used by the virtual assistant upon its reasoning of the user command. Those functions are Turning on the light, turning off the light, adjusting brightness, turning on and off the humidifier, Adjust the humidifier speed, turning on the air purifier, turning off the air purifier, Adjust air purifier speed, Turning on the smart fan, Turning off the smart fan, Adjust smart fan speed. Among the 12 functions, 4 of them, which are Adjust Brightness, Adjust Humidifier Speed, Adjust Air Purifier Speed, and Adjust Smart Fan Speed, will retrieve arguments (e.g., level of fan speed, etc.) from the user command. To demonstrate the variety of user requests, 10 different request prompts were used for each of the 12 functions. For the reliability metric, this study will ask the virtual assistant 10 times for the same prompt within each function. The confusion matrix for building operations with a virtual assistant for each function is shown in Figure 5. It should be noted that there are two additional columns for failed function call and Inaccurate argument retrieval, which aim to demonstrate the times when the AI systems can't understand the command of the user, error, or incorrect retrieval of argument. Additionally, to measure the task execution speed of the AI systems, this study will use tools like Llamacpp to measure the throughput and times needed to execute different tasks.

6.2 Evaluation of the AI Agent

To evaluate the AI agent's performance in automating smart building operations, two experimental setups are used: occupancy-based automation and threshold-based automation. For occupancy-

AI Systems	Task	Precision (%)	Recall (%)	F1 Score (%)	Accuracy (%)	Reliability (%)
AI Assistants	Smart appliance control task	95.91	92.75	94.17	92.75	95.45
AI Agents	Occupancy based automation	90.74	90.23	90.29	91	N/A
	Threshold based automation	88.58	88.16	88.25	90.25	N/A

Figure 8: Evaluation of the proposed AI systems.

based control, we define a predefined range of occupants (x_true) (e.g., 0-20 people) and corresponding smart appliance setpoints (y_true) (off, low, medium, high) as mentioned in section 5.2. The AI agent is tested with 200 randomized occupancy data points, and its predicted appliance adjustments ($\hat{y}$) are compared against ground truth values (y_true). If the AI's assigned setpoint deviates from the predefined range, the prediction is considered incorrect. The accuracy of the system is assessed using precision, recall, and F1-score. The confusion matrix for occupancy-based autonomous building operation with the AI agent for different scenarios is shown in Figure 6.

In addition, to evaluate the AI agent's performance in threshold-based control mode, the study implements predefined environmental control thresholds, including temperature (20°C-27°C), humidity (40%-100%), light intensity (50-150 lux), and carbon monoxide levels (0-50 ppm). These simplified threshold values are implemented primarily to demonstrate the functionality of the LLM-based automation system and its response mechanisms. This experiment involves feeding 400 environmental data points via REST API, where the AI agent continuously monitors real-time temperature, humidity, light intensity, and carbon monoxide levels. If the real-time data falls below or exceeds the predefined threshold, the AI will adjust the corresponding smart appliance by increasing or decreasing its performance to restore the environmental conditions to the comfort range. The AI's adjustments are then validated against predefined expected actions, which are whether to increase or decrease the performance of smart appliances. The confusion matrix for threshold-based autonomous building operation with the AI agent for different scenarios is shown in Figure 7. Accuracy is assessed using precision, recall, F1-score, and macro-averaged performance across all parameters to evaluate the AI's effectiveness in maintaining optimal building conditions. The evaluation dataset including testing prompts for the AI assistant and AI agents is available at [28].

7 Result and Discussion

The evaluation results in Figure 8 show the performance of the proposed virtual assistants and AI agents across different metrics. The virtual assistant for smart appliance control performed exceptionally well, achieving a precision of 95.91%, a recall of 92.75%, and an F1 score of 94.17%, demonstrating high accuracy and reliability in executing user commands. With an accuracy of 92.75% and a reliability score of 95.45%, it proved to be highly reliable in consistent task execution. For the AI agent, the occupancy-based automation system possesses a precision of 90.74%, a recall of 90.23%, and an F1 score of 90.29%, with an accuracy of 91%. These results indicate strong performance in adjusting smart appliances based on occupancy levels. The threshold-based automation system had slightly lower scores, with precision at 88.58%, recall at 88.16%, and an F1 score of 88.25%, achieving an accuracy of 90.25%.

Furthermore, the scalability of the proposed LLM-based AI systems is evaluated based on its throughput and ability to handle concurrent user requests, specifically measuring how many requests the AI can process simultaneously and how quickly the system can respond to user queries. In this experiment, LlamaBench [29], an open-source tool for benchmarking LLM, is used to assess the performance of the proposed AI-based agent and virtual assistant. The results indicated that execution time and throughput varied based on the specific task. For chat or text generation, the average throughput was 33.66 tokens per second. One token is approximately equivalent to 4 English characters, and 1,500 words correspond to around 2048 tokens [30]. Smart home control tasks took longer, with an average execution time of 5402.62 milliseconds per task and a throughput of 12.77 tokens per second. Concurrency user request is also an important indicator of the LLM model's scalability [31]. This study used Llamacpp for model deployment, which allows parallelization based on the model context length. For instance, a model with a context length of 8192 tokens can theoretically handle 16 parallel requests where each prompt has 256 tokens, and each response generates 256 tokens [32]. Although the Llama 3 model we used supports a context length of up to 128k tokens, we limited it to 8192 tokens due to limited computational resources. For real-world deployment, especially with a larger user base, we can improve the scalability by opting for models with larger context lengths and running them on machines with greater GPU RAM capacity.

8 Conclusion and Future Works

The proposed LLM-powered virtual assistant in this study allows users to interact with the building through voice and text interfaces for smart appliance control. The AI agent also powers the autonomous building operations by autonomously adjusting smart appliances, such as lighting and HVAC, based on occupancy and the baseline environmental comfort threshold to maintain optimal conditions for occupants. The virtual assistant and AI agent demonstrated strong performance with over 90% accuracy, recall, precision, F1, and reliability. In addition, the current trend towards smaller and more efficient language models, as evidenced by Microsoft's Phi-3, Meta's LLaMA 3.2, and Google's Gemma-2 model, indicates that powerful AI systems will be able to effectively deploy on low-cost edge devices such as Raspberry Pi while offering impressive performance. This development could significantly contribute to extending the reach of smart building systems to entire smart cities, enabling more distributed and responsive urban management.

REFERENCES

[1] D. Temel, “Designing Resilient and Autonomous Systems for Smart Infrastructure: Advancing Reliability, Efficiency, and Sustainability in Modern Networks,” *NFLSAI*, vol. 8, no. 1, p. 211, Jan. 2025, doi: 10.62802/091z1h59.

[2] G. Grazieschi, P. Gori, L. Lombardi, and F. Asdrubali, “Life cycle energy minimization of autonomous buildings,” *Journal of Building Engineering*, vol. 30, p. 101229, Jul. 2020, doi: 10.1016/j.jobe.2020.101229.

[3] K. Alanne and S. Sierla, “An overview of machine learning applications for smart buildings,” *Sustainable Cities and Society*, vol. 76, p. 103445, Jan. 2022, doi: 10.1016/j.scs.2021.103445.

[4] G. Franchini, G. Brumana, and A. Perdichizzi, “Monitored performance of the first energy+ autonomous building in Dubai,” *Energy and Buildings*, vol. 205, p. 109545, Dec. 2019, doi: 10.1016/j.enbuild.2019.109545.

[5] H. Zhang, A. B. Sediq, A. Afana, and M. Erol-Kantarci, “Generative AI-in-the-loop: Integrating LLMs and GPTs into the Next Generation Networks,” 2024, *arXiv*. doi: 10.48550/ARXIV.2406.04276.

[6] I. A. Scott and G. Zuccon, “The new paradigm in machine learning – foundation models, large language models and beyond: a primer for physicians,” *Internal Medicine Journal*, vol. 54, no. 5, pp. 705–715, May 2024, doi: 10.1111/imj.16393.

[7] M. McTear, S. Varghese Marokkie, and Y. Bi, “A Comparative Study of Chatbot Response Generation: Traditional Approaches Versus Large Language Models,” in *Knowledge Science, Engineering and Management*, vol. 14118, Z. Jin, Y. Jiang, R. A. Buchmann, Y. Bi, A.-M. Ghiran, and W. Ma, Eds., in Lecture Notes in Computer Science, vol. 14118. , Cham: Springer Nature Switzerland, 2023, pp. 70–79. doi: 10.1007/978-3-031-40286-9_7.

[8] G. S. Murugesan and S. A. Viswanathan, “Enhancing Human-Machine Interaction: A Study on Deployment of LLM and Gen AI Hybrid Models in Responsible Humanoids for Human Assistance,” in *2024 15th International Conference on Computing Communication and Networking Technologies (ICCCNT)*, Kamand, India: IEEE, Jun. 2024, pp. 1–6. doi: 10.1109/ICCCNT61001.2024.10724819.

[9] R. D. Manu, S. Kumar, S. Snehashish, and K. S. Rekha, “Smart Home Automation using IoT and Deep Learning,” vol. 06, no. 04, 2019.

[10] P. J. Rani, J. Bakthakumar, B. P. Kumaar, U. P. Kumaar, and S. Kumar, “Voice controlled home automation system using Natural Language Processing (NLP) and Internet of Things (IoT),” in *2017 Third International Conference on Science Technology Engineering & Management (ICONSTEM)*, Chennai, India: IEEE, Mar. 2017, pp. 368–373. doi: 10.1109/ICONSTEM.2017.8261311.

[11] E. Luger and A. Sellen, “‘Like Having a Really Bad PA’: The Gulf between User Expectation and Experience of Conversational Agents,” in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, San Jose California USA: ACM, May 2016, pp. 5286–5297. doi: 10.1145/2858036.2858288.

[12] D. Rivkin *et al.*, “AIoT Smart Home via Autonomous LLM Agents,” *IEEE Internet Things J.*, vol. 12, no. 3, pp. 2458–2472, Feb. 2025, doi: 10.1109/JIOT.2024.3471904.

[13] H. Yu, J. Hua, and C. Julien, “Analysis of IFTTT Recipes to Study How Humans Use Internet-of-Things (IoT) Devices,” in *Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems*, Coimbra Portugal: ACM, Nov. 2021, pp. 537–541. doi: 10.1145/3485730.3494115.

[14] “Automate without limits | Zapier.” Accessed: Apr. 14, 2025. [Online]. Available: https://zapier.com/

[15] H. Assistant, “Home Assistant,” Home Assistant. Accessed: Apr. 14, 2025. [Online]. Available: https://www.home-assistant.io/

[16] E. King, H. Yu, S. Lee, and C. Julien, “Sasha: Creative Goal-Oriented Reasoning in Smart Homes with Large Language Models,” *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 8, no. 1, pp. 1–38, Mar. 2024, doi: 10.1145/3643505.

[17] L. Wang *et al.*, “A survey on large language model based autonomous agents,” *Front. Comput. Sci.*, vol. 18, no. 6, p. 186345, Dec. 2024, doi: 10.1007/s11704-024-40231-1.

[18] J. Wei *et al.*, “Chain-of-Thought Prompting Elicits Reasoning in Large Language Models”.

[19] M. Winter, *Maximilian-Winter/llama-cpp-agent*. (Apr. 11, 2025). Python. Accessed: Apr. 14, 2025. [Online]. Available: https://github.com/Maximilian-Winter/llama-cpp-agent

[20] A. Saka *et al.*, “GPT models in construction industry: Opportunities, limitations, and a use case validation,” *Developments in the Built Environment*, vol. 17, p. 100300, Mar. 2024, doi: 10.1016/j.dibe.2023.100300.

[21] Hevner, March, Park, and Ram, “Design Science in Information Systems Research,” *MIS Quarterly*, vol. 28, no. 1, p. 75, 2004, doi: 10.2307/25148625.

[22] G. Jiang, Z. Ma, L. Zhang, and J. Chen, “EPlus-LLM: A large language model-based computing platform for automated building energy modeling,” *Applied Energy*, vol. 367, p. 123431, Aug. 2024, doi: 10.1016/j.apenergy.2024.123431.

[23] Meta, “Meta Llama 3,” Meta Llama. Accessed: May 22, 2024. [Online]. Available: https://llama.meta.com/llama3/

[24] G. Gerganov, *ggerganov/llama.cpp*. (Jul. 04, 2024). C++. Accessed: Jul. 04, 2024. [Online]. Available: https://github.com/ggerganov/llama.cpp

[25] Y. Zhao *et al.*, “Atom: Low-bit quantization for efficient and accurate llm serving,” *Proceedings of Machine Learning and Systems*, vol. 6, pp. 196–209, 2024.

[26] “reachsak/LLM_AI_Assistant_for_Human_Building_Interaction.” Accessed: Feb. 11, 2025. [Online]. Available: https://github.com/reachsak/LLM_AI_Assistant_for_Human_Building_Interaction

[27] R. Ly, *reachsak/LLM-AI-agent-for-Autonomous-Building-operation*. (Jan. 19, 2025). JavaScript. Accessed: Feb. 11, 2025. [Online]. Available: https://github.com/reachsak/LLM-AI-agent-for-Autonomous-Building-operation

[28] R. Ly, “Evaluation dataset,” Evaluation dataset for AI systems. Accessed: Apr. 13, 2025. [Online]. Available: https://reachsak.github.io/files/AI_systems_evaluation_dataset.zip

[29] “llamabench,” GitHub. Accessed: Oct. 22, 2024. [Online]. Available: https://github.com/ggerganov/llama.cpp/blob/master/examples/llama-bench/README.md

[30] OpenAI, “What are tokens and how to count them?” Accessed: Sep. 23, 2024. [Online]. Available: https://help.openai.com/en/articles/4936856-what-are-tokens-and-how-to-count-them

[31] Y. Yao *et al.*, “ScaleLLM: A Resource-Frugal LLM Serving Framework by Optimizing End-to-End Efficiency,” Sep. 10, 2024, *arXiv*: arXiv:2408.00008. Accessed: Sep. 27, 2024. [Online]. Available: http://arxiv.org/abs/2408.00008

[32] Y. Fu, “LLM Inference Sizing and Performance Guidance,” VMware Cloud Foundation (VCF) Blog. Accessed: Sep. 27, 2024. [Online]. Available: https://blogs.vmware.com/cloud-foundation/2024/09/25/llm-inference-sizing-and-performance-guidance/

Information Systems and e-Business Management (2025) 23:577–622
https://doi.org/10.1007/s10257-025-00699-1

ORIGINAL ARTICLE

Decentralized autonomous organization in built environments: applications, potential and limitations

Reachsak Ly[1] · Alireza Shojaei[1]

Received: 11 December 2023 / Revised: 13 November 2024 / Accepted: 3 January 2025 /
Published online: 26 January 2025

Abstracts
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,

✉ Alireza Shojaei
shojaei@vt.edu

Reachsak Ly
reachsak@vt.edu

[1] Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

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

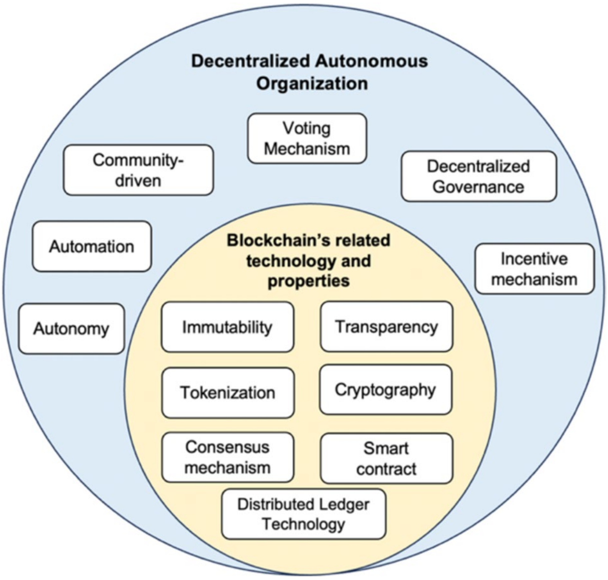
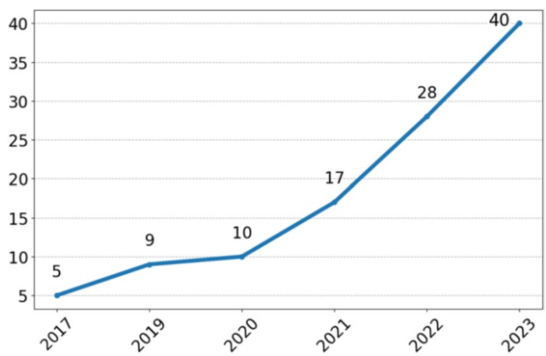


Fig. 1 The technical properties and concepts within a decentralized autonomous organization

built infrastructure, fostering better coordination and alignment with the collective interests and needs of the community.

Over the past few years, DAO has garnered increasing research attention within academia across diverse scholarly disciplines. Figure 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 (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;

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



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, Sect. 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

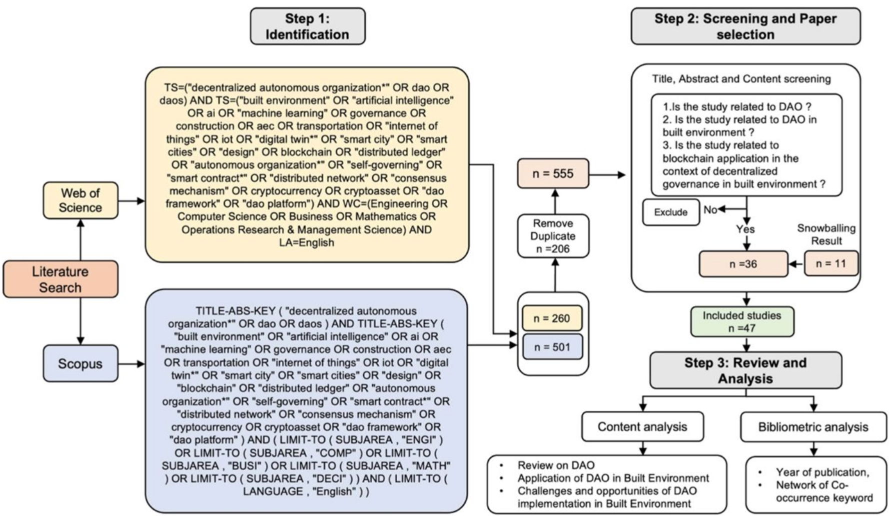


Fig. 3 Stages of the systematic literature review conducted in this study

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.

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.

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.

Table 1 Categorization of current DAO applications in the built environment

Research area	Number of studies	References
Design	2	(Dounas et al. 2022) (Dounas and Lombardi 2019)
Construction management	1	(Darabseh et al. 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)

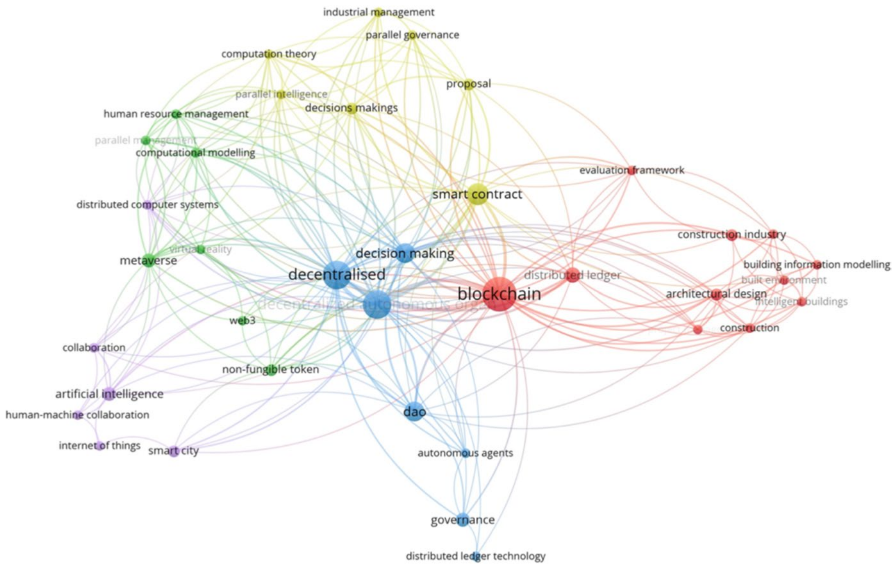


Fig. 4 A network of co-occurring keywords in the selected studies

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.

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

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

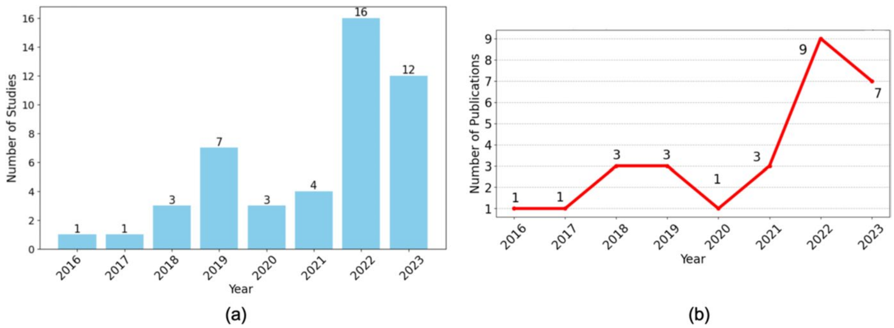


Fig. 5 **a** Year of publication of the 47 included studies (**b**) range of publication years for the 28 articles that either discuss DAO applications in the built environment or offer insights for future DAO use cases within this domain

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. 5a. 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 Fig. 5b. 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.

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). Figure 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. Figure 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

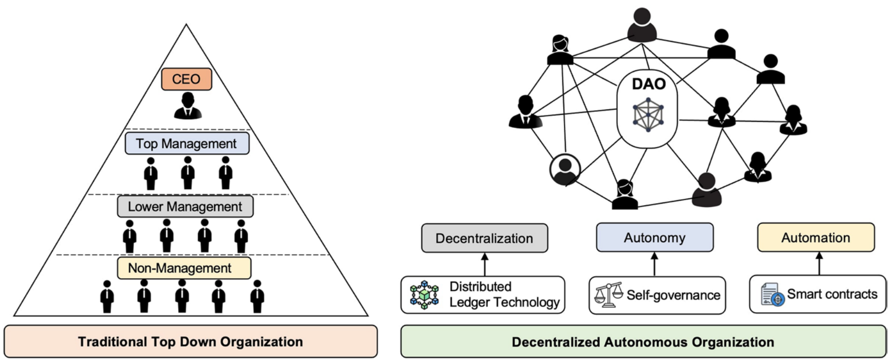


Fig. 6 The difference in structures between the traditional organization and decentralized autonomous organization

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

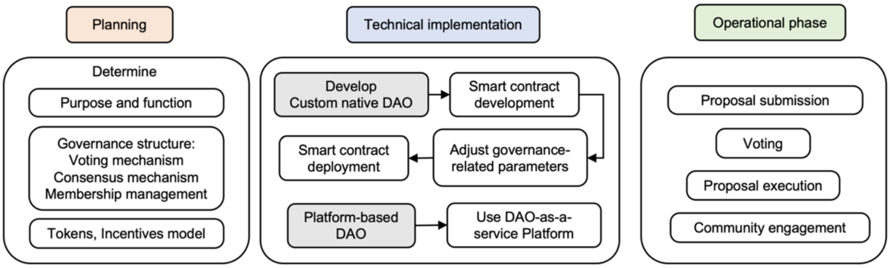


Fig. 7 Overview of key stages in DAO development

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.

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).

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).

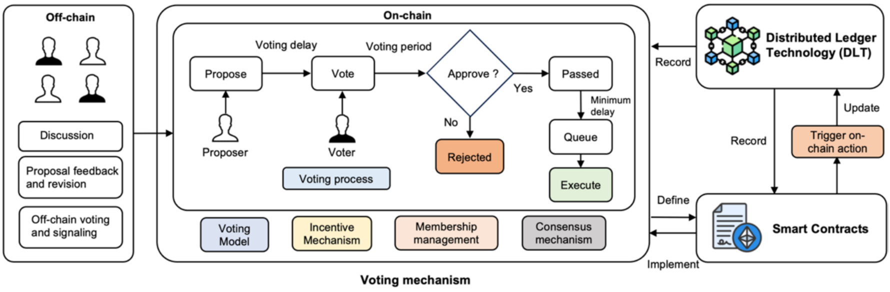


Fig. 8 Relationship between voting mechanism, smart contracts, and distributed ledger technology

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 predefined 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.

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

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

Table 4 (continued)

Voting Models	Characteristics	Strengths	Weaknesses
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

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, 2023), 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

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

Domain	References	Summary of findings	DAO framework	Tokenization model	Key methodology	Level of development
Design	(Dounas et al. 2022)	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 et al. 2023)	A governance DAO for collaborative decision-making in construction project with proof-of-concept implementation on platform-based DAO	Aragon platform	ERC20 tokens for transaction	Platform-based DAO	Proof of concept

Table 5 (continued)

Domain	References	Summary of findings	DAO framework	Tokenization model	Key methodology	Level of development
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

Table 5 (continued)

Domain	References	Summary of findings	DAO framework	Tokenization model	Key methodology	Level of development
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 management framework	N/A	NFT-based incentive tokens	Cyber-physical-social-systems, Metaverse, DAO, smart contract, federated intelligence	Theoretical framework

Table 5 (continued)

Domain	References	Summary of findings	DAO framework	Tokenization model	Key methodology	Level of development
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

Table 5 (continued)

Domain	References	Summary of findings	DAO framework	Tokenization model	Key methodology	Level of development
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 of self-governing meditation space	Ethereum	Use of tokens for payment and maintenance	Internet of things, sensors, DAO, smart contract	Prototype
	(Seidler et al. 2016)	A prototype of an Ethereum blockchain based, self-governing forest	Ethereum	Terra0 tokens as ownership	DAO, smart contract	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. (2022a, b) 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. (2022a, b) 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 et al. (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.

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

Table 6 Overview of the challenges and limitations of DAO implementation

Categories	Challenges	Description	References
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)

Table 6 (continued)

Categories	Challenges	Description	References
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)

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.

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. 2023). 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.

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. 9a). 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. 2023) (Fig. 9b). 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.

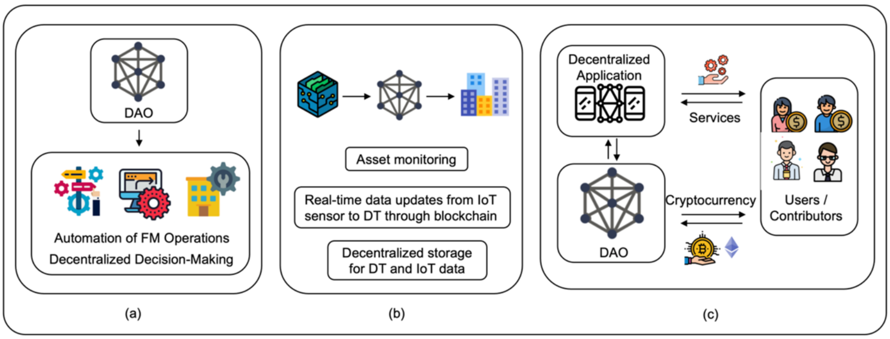


Fig. 9 Potential use cases of DAO in facility management

The integration of digital twins and DAO could also enable smart autonomous infrastructure to provide value and services to users through DApp (Fig. 9c). 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.

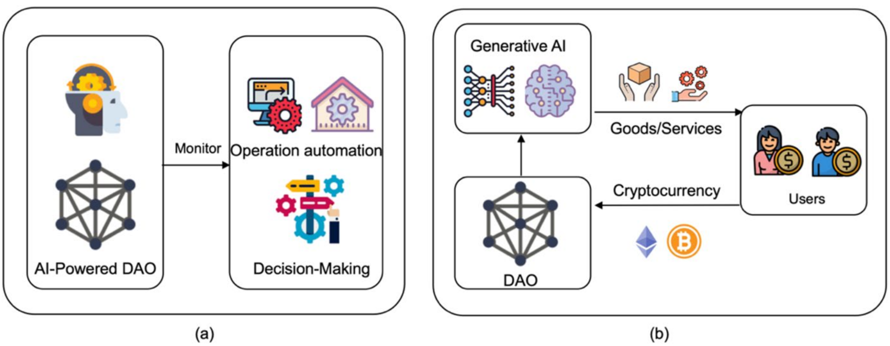


Fig. 10 Potential use cases of AI and DAO integration: **a** AI-powered DAO for decision-making and automation (**b**) generative AI and DAO integration

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. 10b). 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.

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.

Acknowledgements This research has received no external funding.

Authors' contributions Supervision: [XX]; Conceptualization: [XX, YY]; Writing—original draft preparation: [YY]; Writing—review and editing: [XX, YY]; Visualization: [YY]; Methodology: [XX, YY]; Project administration: [XX].

Funding No funding was received to assist with the preparation of this manuscript.

Data and materials availability 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.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent for publication Not applicable.

Ethics approval and consent to participate Not applicable.

References

Adewunmi YA, Nelson M, Chigbu UE et al (2023) A scoping review of community-based facilities Management for public services through social enterprises in developing communities. Facilities 41:868–889

Alexander K, Brown M (2006) Community-based facilities management. Facilities 24:250–268. https://doi.org/10.1108/02632770610666116

Antelmi A, Malandrino D, Scarano V (2019) Characterizing the behavioral evolution of twitter users and the truth behind the 90-9-1 Rule. In: companion proceedings of the 2019 world wide web conference. ACM, San Francisco USA, pp 1035–1038

Bellavitis C, Fisch C, Momtaz PP (2022) The rise of decentralized autonomous organizations (DAOs): a first empirical glimpse. Ventur Cap. https://doi.org/10.1080/13691066.2022.2116797

Benedict G, Sullivan C, Gill A (2022) Governance challenges of AI-enabled decentralized autonomous organizations: Toward a research agenda. ICIS 2022 Proceedings 1184

Bernovskis A, Stibe A, Sceulovs D et al (2023) Gamified DAOs as blockchain-based catalysts for prosocial and environmentally oriented cities. In: Younas M, Awan I, Grønli T-M (eds) Mobile web and intelligent information systems. Springer Nature Switzerland, Cham, pp 38–51

Cai W, Wang Z, Ernst JB et al (2018) Decentralized applications: the blockchain-empowered software system. IEEE Access 6:53019–53033
Cao L (2022) Decentralized AI: edge intelligence and smart blockchain, metaverse, Web3, and DeSci. IEEE Intell Syst 37:6–19. https://doi.org/10.1109/MIS.2022.3181504
Chang F-J, Fang R, Johar I (2022) Radicle Civics—Unconstituting Society. In: Sacred Civics, 1st edn. Routledge, London, pp 226–242. https://doi.org/10.4324/9781003199816
CityDAO (2021) CityDAO. https://www.citydao.io/. Accessed 27 Nov 2022
Copel N, Ater T (2017) DAV - Decentralized autonomous vehicles. https://dav.network/whitepaper.pdf. Accessed 27 Jul 2023
Cui L, Xie G, Qu Y et al (2018) Security and privacy in smart cities: challenges and opportunities. IEEE Access 6:46134–46145
Daneshgar F, Ameri Sianaki O, Guruwacharya P (2019) Blockchain: a research framework for data security and privacy. In: web, artificial intelligence and network applications: Proceedings of the workshops of the 33rd international conference on advanced information networking and applications (WAINA-2019) 33. Springer, pp 966–974
Daniel E, Tschorsch F (2022) IPFS and friends: a qualitative comparison of next generation peer-to-peer data networks. IEEE Commun Surv Tutorials 24:31–52
Darabseh M, Poças Martins J (2023) Transforming construction entities from traditional management to autonomous management using blockchain. In: Gomes Correia A, Azenha M, Cruz PJS et al (eds) Trends on construction in the digital era. Springer International Publishing, Cham, pp 111–121
Diallo N, Shi W, Xu L, et al (2018) eGov-DAO: a better government using blockchain based decentralized autonomous organization. In: 2018 international conference on eDemocracy & eGovernment (ICEDEG). IEEE, Ambato, pp 166–171
Ding W, Liang X, Hou J et al (2022) A novel approach for predictable governance of decentralized autonomous organizations based on parallel intelligence. IEEE Trans Syst Man Cybern, Syst. https://doi.org/10.1109/TSMC.2022.3224250
Ding Q, Liebau D, Wang Z, Xu W (2023) A survey on decentralized autonomous organizations (DAOs) and their governance. Available at SSRN 4378966
Ding Q, Xu W, Wang Z, Chuen DLK (2023b) Voting schemes in DAO governance. Forthcom Annu Rev Fintech. https://doi.org/10.2139/ssrn.4442470
Dounas T, Lombardi D (eds) (2022) Blockchain for construction. Springer Nature Singapore, Singapore
Dounas T, Lombardi D (2019) Blockchain grammars—designing with DAOs—the blockchain as a design platform for shape grammarists' decentralised collaboration. Wellington, New Zealand, pp 293–302
Dounas T, Voeller E, Prokop S, Vele J (2022) The architecture decentralised autonomous organisation—a stigmergic exploration in architectural collaboration. Ghent, Belgium, pp 567–576
Dounas T, Lombardi D, Vele J, Prokop S (2023) A crypto-twin framework for the aec industry: enabling digital twins with blockchain technologies. Archit Plan J 28(3):20. https://doi.org/10.54729/2789-8547.1215
DuPont Q (2017) Experiments in algorithmic governance: A history and ethnography of "The DAO," a failed decentralized autonomous organization. In: Bitcoin and beyond. Routledge, pp 157–177
Dwivedi V, Norta A, Wulf A et al (2021) A formal specification smart-contract language for legally binding decentralized autonomous organizations. IEEE Access 9:76069–76082. https://doi.org/10.1109/ACCESS.2021.3081926
Fan Y, Zhang L, Wang R, Imran MA (2023) Insight into voting in DAOs: conceptual analysis and a proposal for evaluation framework. IEEE Netw. https://doi.org/10.1109/MNET.137.2200561
Fan X, Li P, Zeng Y, Zhou X (2019) Implement liquid democracy on ethereum: a fast algorithm for realtime self-tally voting system. arXiv preprint arXiv:191108774
El Faqir Y, Arroyo J, Hassan S (2020) An overview of decentralized autonomous organizations on the blockchain. In: proceedings of the 16th international symposium on open collaboration. ACM, Virtual conference Spain, pp 1–8
Ferreira D, Li J, Nikolowa R (2023) Corporate capture of blockchain governance. Rev Financ Stud 36:1364–1407. https://doi.org/10.1093/rfs/hhac051
Finck M (2018) Blockchain regulation and governance in Europe, 1st edn. Cambridge University Press, Cambridge
Foschini L, Gavagna A, Martuscelli G, Montanari R (2020) Hyperledger fabric blockchain: chaincode performance analysis. In: ICC 2020 - 2020 IEEE international conference on communications (ICC). IEEE, Dublin, Ireland, pp 1–6

Fourie D, Poggenpoel W (2017) Public sector inefficiencies: are we addressing the root causes? S Afr J Account Res 31:169–180

Gong T, Tao X, Das M et al (2022) Blockchain-based e-tendering evaluation framework. IJADT. https://doi.org/10.54878/IJADT.131

Guidi B, Michienzi A (2022) Social games and blockchain: exploring the metaverse of decentraland. In: 2022 IEEE 42nd international conference on distributed computing systems workshops (ICDCSW). IEEE, Bologna, Italy, pp 199–204

Guo H, Yu X (2022) A survey on blockchain technology and its security. Blockchain: Res Appl 3:100067

Guo C, Dou Y, Bai T et al (2023) ArtVerse: a paradigm for parallel human-machine collaborative painting creation in metaverses. IEEE Trans Syst Man Cybern, Syst. https://doi.org/10.1109/TSMC.2022.3230406

Hardwick FS, Gioulis A, Akram RN, Markantonakis K (2018) E-voting with blockchain: An e-voting protocol with decentralisation and voter privacy. IEEE, pp 1561–1567

Harris F, McCaffer R, Baldwin A, Edum-Fotwe F (2021) Modern construction management. John Wiley & Sons, New Jersey

Hou J, Ding W, Liang X, et al (2021) A study on decentralized autonomous organizations based intelligent transportation system enabled by blockchain and smart contract. In: 2021 China automation congress (CAC). IEEE, Beijing, China, pp 967–971

Hunhevicz JJ, Wang H, Hess L, Hall DM (2021) no1s1 - a blockchain-based DAO prototype for autonomous space. pp 27–33

Hunhevicz JJ, Brasey P-A, Bonanomi MM, et al (2022) Applications of blockchain for the governance of integrated project delivery: a crypto commons approach. arXiv preprint arXiv:220707002

Hunhevicz JJ, Hall DM (2020) Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Adv Eng Inform 45:101094. https://doi.org/10.1016/j.aei.2020.101094

Kaal WA (2021) A decentralized autonomous organization (DAO) of DAOs. SSRN J. https://doi.org/10.2139/ssrn.3799320

Kahya A, Avyukt A, Ramachandran GS, Krishnamachari B (2021) Blockchain-enabled personalized incentives for sustainable behavior in smart cities. In: 2021 international conference on computer communications and networks (ICCCN). IEEE, Athens, Greece, pp 1–6

Khoshavi N, Tristani G, Sargolzaei A (2021) Blockchain applications to improve operation and security of transportation systems: a survey. Electronics 10:629

Leaman A, Bordass B (2001) Assessing building performance in use 4: the probe occupant surveys and their implications. Build Res Inf 29:129–143. https://doi.org/10.1080/09613210010008045

Li J, Greenwood D, Kassem M (2019) Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases. Autom Constr 102:288–307. https://doi.org/10.1016/j.autcon.2019.02.005

Li J, Qin R, Wang F-Y (2023) The future of management: DAO to smart organizations and intelligent operations. IEEE Trans Syst Man Cybern, Syst. https://doi.org/10.1109/TSMC.2022.3226748

Lin Y, Hu W, Chen X et al (2023) City 5.0: towards spatial symbiotic intelligence via DAOs and parallel systems. IEEE Trans Intell Veh 8:3767–3770. https://doi.org/10.1109/TIV.2023.3298903

Liu L, Zhou S, Huang H, Zheng Z (2021) From technology to society: an overview of blockchain-based DAO. IEEE Open J Comput Soc 2:204–215. https://doi.org/10.1109/OJCS.2021.3072661

Liu Z, Li Y, Min Q, Chang M (2022) User incentive mechanism in blockchain-based online community: an empirical study of steemit. Inf Manag. https://doi.org/10.1016/j.im.2022.103596

Ly R, Shojaei A, Naderi H (2024) DT-DAO: digital twin and blockchain-based DAO integration framework for smart building facility management. Construction research congress 2024. American Society of Civil Engineers, Des Moines, Iowa, pp 796–805

Ma L, Kaneko K, Sharma S, Sakurai K (2019) Reliable decentralized oracle with mechanisms for verification and disputation. In: 2019 seventh international symposium on computing and networking workshops (CANDARW). IEEE, pp 346–352

Malik H, Manzoor A, Ylianttila M, Liyanage M (2019) Performance analysis of blockchain based smart grids with Ethereum and Hyperledger implementations. In: 2019 IEEE international conference on advanced networks and telecommunications systems (ANTS). IEEE, pp 1–5

Mateus S, Sarkar S (2023) Can decentralized autonomous organizations (DAOs) revolutionize healthcare? California Management Review 65:

Mendoza F, Behrens HW (2020) Arbiter: improved smart city operations through decentralized autonomous organization. In: 2020 IEEE international symposium on technology and society (ISTAS). IEEE, Tempe, AZ, USA, pp 407–412
Michell KA (2010) A grounded theory approach to community-based facilities management: the context of Cape Town. University of Salford (United Kingdom), South Africa
Monteiro F, Correia M (2023) Decentralised autonomous organisations for public procurement. In: proceedings of the 27th international conference on evaluation and assessment in software engineering. ACM, Oulu Finland, pp 378–385
Oliveira TA, Oliver M, Ramalhinho H (2020) Challenges for connecting citizens and smart cities: ICT, e-governance and blockchain. Sustainability 12:2926
Page KL, Elmessiry A (2021) Global research decentralized autonomous organization (GR-DAO): a DAO of global researchers. In: computer science and information technology trends. academy and industry research collaboration center (AIRCC), pp 77–90
Petrolo R, Loscrì V, Mitton N (2017) Towards a smart city based on cloud of things, a survey on the smart city vision and paradigms. Trans Emerg Tel Tech 28:2931. https://doi.org/10.1002/ett.2931
Pierro GA, Tonelli R (2021) Analysis of source code duplication in ethreum smart contracts. In: 2021 IEEE international conference on software analysis, evolution and reengineering (SANER). IEEE, Honolulu, HI, USA, pp 701–707
Pierro GA, Tonelli R (2022) Can solana be the solution to the blockchain scalability problem? In: 2022 IEEE international conference on software analysis, evolution and reengineering (SANER). IEEE, pp 1219–1226
Potkany M, Vetrakova M, Babiakova M (2015) Facility management and its importance in the analysis of building life cycle. Procedia Econ Financ 26:202–208
Qin R, Ding W, Li J et al (2023) Web3-based decentralized autonomous organizations and operations: architectures, models, and mechanisms. IEEE Trans Syst Man Cybern, Syst. https://doi.org/10.1109/TSMC.2022.3228530
Rawat V, Dahiya N, Rai S, Arora A (2022) A blockchain-based decentralized framework for carbon accounting, trading and governance. In: 2022 8th international conference on computer technology applications. ACM, Kapfenberg Austria, pp 148–153
Revoredo T (2023) Artificial intelligence and DAOs: the perfect match? In: Medium. https://tatianarevoredo.medium.com/artificial-intelligence-and-daos-the-perfect-marriage-d84250d6bf3e. Accessed 19 Apr 2024
Rikken O, Janssen M, Kwee Z (2023) The ins and outs of decentralized autonomous organizations (DAOs) unraveling the definitions, characteristics, and emerging developments of DAOs. Blockchain: Res Appl. https://doi.org/10.1016/j.bcra.2023.100143
Saito Y, Rose JA (2023) Reputation-based decentralized autonomous organization for the non-profit sector: leveraging blockchain to enhance good governance. Front Blockchain 5:1083647
Santana C, Albareda L (2022) Blockchain and the emergence of decentralized autonomous organizations (DAOs): an integrative model and research agenda. Technol Forecast Soc Change 182:121806. https://doi.org/10.1016/j.techfore.2022.121806
Saurabh K, Rani N, Upadhyay P (2022) Towards blockchain led decentralized autonomous organization (DAO) business model innovations. BIJ. https://doi.org/10.1108/BIJ-10-2021-0606
Seidler P, Kolling P, Hampshire M (2016) Can an augmented forest own and utilise itself? White Paper
Senaratne S, Samaraweera A (2015) Construction project leadership across the team development process. Built Environ Proj Asset Manag 5:69–88. https://doi.org/10.1108/BEPAM-10-2012-0049
Setaki F, Van Timmeren A (2022) Disruptive technologies for a circular building industry. Build Environ 223:109394. https://doi.org/10.1016/j.buildenv.2022.109394
Shakow DJ (2018) The tao of the DAO: taxing an entity that lives on a blockchain. Tax Notes 160:18–23
Shojaei A, Ketabi R, Razkenari M et al (2021) Enabling a circular economy in the built environment sector through blockchain technology. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.126352
Singh S, Ashuri B (2019) Leveraging blockchain technology in AEC industry during design development phase. In: computing in civil engineering 2019. American Society of Civil Engineers, Atlanta, Georgia, pp 393–401
Singh MP, Chopra AK (2017) The internet of things and multiagent systems: decentralized intelligence in distributed computing. In: 2017 IEEE 37th international conference on distributed computing systems (ICDCS). IEEE, pp 1738–1747
Singh M, Kim S (2019) Blockchain technology for decentralized autonomous organizations. In: Advances in Computers. Elsevier, pp 115–140. https://doi.org/10.1016/bs.adcom.2019.06.001

Singularity DAO (2021) SingularityDAO. In: Singularity DAO. https://www.singularitydao.ai. Accessed 25 Dec 2022

Slavin A, Werbach K (2022) Decentralized autonomous organizations: beyond the hype. In: World Economic Forum. https://www.weforum.org/whitepapers/decentralized-autonomous-organizations-beyond-the-hype/. Accessed 27 Nov 2022

Sreckovic M, Windsperger J (2019) Decentralized autonomous organizations and network design in AEC: a conceptual framework. SSRN J. https://doi.org/10.2139/ssrn.3576474

Sreckovic M, Sibenik G, Breitfuß D, Preindl T (2020) Analysis of design phase processes with BIM for blockchain implementation. SSRN J. https://doi.org/10.2139/ssrn.3577529

Sulaiman R, Alamsyah A, Wulansari P (2022) Reshaping the future of recruitment through talent reputation and verifiable credentials using blockchain technology. In: 2022 10th international conference on information and communication technology (ICoICT). IEEE, Bandung, Indonesia, pp 316–321

Tao X, Liu Y, Wong PK-Y et al (2022) Confidentiality-minded framework for blockchain-based BIM design collaboration. Autom Constr 136:104172. https://doi.org/10.1016/j.autcon.2022.104172

Van Der Heijden J (2023) Construction 4.0 in a narrow and broad sense: a systematic and comprehensive literature review. Build Environ 244:110788. https://doi.org/10.1016/j.buildenv.2023.110788

Van Eck N, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. scientometrics 84:523–538

Wang S, Ding W, Li J et al (2019a) Decentralized autonomous organizations: concept, model, and applications. IEEE Trans Comput Soc Syst 6:870–878. https://doi.org/10.1109/TCSS.2019.2938190

Wang S, Ouyang L, Yuan Y et al (2019b) Blockchain-enabled smart contracts: architecture, applications, and future trends. IEEE Trans Syst Man Cybern, Syst 49:2266–2277. https://doi.org/10.1109/TSMC.2019.2895123

Wang S, Yuan Y, Wang X, et al (2018) An overview of smart contract: architecture, applications, and future trends. IEEE, pp 108–113

Wang Z, Chen X, Zhou X, et al (2021) An empirical study of solidity language features. In: 2021 IEEE 21st international conference on software quality, reliability and security companion (QRS-C). IEEE, Hainan, China, pp 698–707

Wang H, Hunhevicz J, Hall D (2022a) What if properties are owned by no one or everyone? foundation of blockchain enabled engineered ownership

Wang Q, Yu G, Sai Y, et al (2022b) An empirical study on snapshot DAOs. arXiv preprint arXiv:221115993

Wang G, Qin R, Li J, et al (2023) A novel DAO-based parallel enterprise management framework in Web3 Era. IEEE Trans Comput Soc Syst 1–10. https://doi.org/10.1109/TCSS.2023.3239059

Wohlin C (2014) Guidelines for snowballing in systematic literature studies and a replication in software engineering. pp 1–10

Woo J, Fatima R, Kibert CJ et al (2021) Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: a review of the literature. Build Environ 205:108199. https://doi.org/10.1016/j.buildenv.2021.108199

Xu Q, He Z, Li Z, Xiao M, Goh R, Li Y (2020) An effective blockchain-based, decentralized application for smart building system management. In: Real-Time Data Analytics for Large Scale Sensor Data. Elsevier, pp 157–181. https://doi.org/10.1016/B978-0-12-818014-3.00008-5

Yadlapalli AR, Mohite N, Pawar V, Sachdeva S (2019) Artificially intelligent decentralized autonomous organization. In: 2019 4th international conference on information systems and computer networks (ISCON). IEEE, Mathura, India, pp 667–671

Yang Z, Zhu C, Zhu Y, Li X (2023) Blockchain technology in building environmental sustainability: a systematic literature review and future perspectives. Build Environ 245:110970. https://doi.org/10.1016/j.buildenv.2023.110970

Ye Z, Yin M, Tang L, Jiang H (2018) Cup-of-water theory: a review on the interaction of BIM, IoT and blockchain during the whole building lifecycle. In: 34th international symposium on automation and robotics in construction. Taipei, Taiwan

Zhao C, Dai X, Lv Y et al (2022a) Decentralized autonomous operations and organizations in transverse: federated intelligence for smart mobility. IEEE Trans Syst Man Cybern, Syst. https://doi.org/10.1109/TSMC.2022.3228914

Zhao X, Ai P, Lai F et al (2022b) Task management in decentralized autonomous organization. J Ops Manag 68:649–674. https://doi.org/10.1002/joom.1179

Zhong B, Guo J, Zhang L et al (2022) A blockchain-based framework for on-site construction environmental monitoring: proof of concept. Build Environ 217:109064. https://doi.org/10.1016/j.buildenv.2022.109064

Zichichi M, Contu M, Ferretti S, D'Angelo G (2019) LikeStarter: a smart-contract based social DAO for crowdfunding. In: IEEE INFOCOM 2019—IEEE conference on computer communications workshops (INFOCOM WKSHPS). IEEE, Paris, France, pp 313–318

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Autonomous Building Cyber-Physical Systems Using Decentralized Autonomous Organizations, Digital Twins, and Large Language Model

Reachsak Ly,[1] Alireza Shojaei, Ph.D.[2]

[1] Ph.D. Student, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University. ORCID: https://orcid.org/0000-0003-0332-1312. Email: reachsak@vt.edu
[2] Assistant Professor, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University, (corresponding author) ORCID: https://orcid.org/0000-0003-3970-0541.
Email: shojaei@vt.edu

Abstract

Current autonomous building research primarily focuses on energy efficiency and automation. While traditional artificial intelligence has advanced autonomous building research, it often relies on predefined rules and struggles to adapt to complex, evolving building operations. Moreover, the centralized organizational structures of facilities management also hinder transparency in decision-making in the building operation management process, which limits the true building autonomy. Research on decentralized governing and adaptive building infrastructure, which could overcome these challenges, remains relatively unexplored. This paper addresses these limitations by introducing a novel Decentralized Autonomous Building Cyber-Physical System framework that integrates Decentralized Autonomous Organizations (DAOs), Large Language Models (LLMs), and digital twin to create a smart, self-managed, operational, and financially autonomous building infrastructure. This approach aims to enhance adaptability, enable decentralized decision-making, and achieve both operational and financial autonomy in building management. This study develops a full-stack decentralized application (Dapp) to facilitate decentralized governance of building infrastructure. An LLM-based artificial intelligence assistant is developed to provide intuitive human-building interaction for blockchain and building operation management-related tasks and enable autonomous building operation. The framework is validated through prototype implementation in a real-world building, with evaluations focusing on workability, cost, scalability, data security, privacy, and integrity. Six real-world scenarios were tested to evaluate the autonomous building system's workability, including building revenue and expense management, AI-assisted facility control, and autonomous adjustment of building systems. Results indicate that the prototype successfully executes these operations, confirming the framework's suitability for developing building infrastructure with decentralized governance and autonomous operation.

1. Introduction

Research on autonomous buildings has become a promising frontier in the field of smart and sustainable infrastructure. Autonomous buildings are characterized by their ability to operate independently through self-management, self-sufficiency, and intelligent operation. These buildings leverage a combination of advanced technologies to monitor, control, and automate the system's operation, reducing reliance on external resources and enhancing sustainability and efficiency. Existing research on autonomous buildings has primarily concentrated on achieving maximum energy efficiency, net-zero energy status, and ensuring energy self-sufficiency and off-grid performance. These objectives are undoubtedly crucial and have yielded significant advancements in the research on sustainable building operations. While energy autonomy [1] is crucial, it represents just one dimension of the overarching goal of achieving a comprehensive autonomous building infrastructure. To achieve operational autonomy within the building, researchers have further explored the integration of several advanced technologies, including building automation systems, artificial intelligence (AI), machine learning (ML), the Internet of

Things (IoT), and digital twins, to enhance building intelligence and autonomy in facilities management by enhancing various building operation and system such as HVAC, lighting, energy management, etc. [2], [3], [4].

Machine learning techniques and AI have played a pivotal role in enabling these advancements. Their capacity to analyze large volumes of data, recognize trends, and make well-informed choices has contributed significantly to improving energy efficiency, enhancing occupant comfort, and optimizing building performance. However, the functionality of this conventional machine learning model may rely on predefined rules or specific training data, which, in some circumstances, may not adequately capture the dynamic and complex nature of building operations. Furthermore, they often struggle to adapt to evolving circumstances or incorporate contextual information effectively. The advent of large language models (LLMs) offers a promising avenue to overcome these limitations and unlock a new realm of possibilities for autonomous building operations. LLMs exhibit remarkable capabilities in natural language processing, which could enable seamless human-machine interactions and intelligent decision-making processes. Unlike conventional AI models, LLMs possess a deep understanding of contextual information and can engage in human-like conversations, allowing for more intuitive and adaptive control of building systems. Moreover, LLMs have the potential to facilitate complex decision-making processes by integrating multiple data streams, analyzing scenarios from diverse perspectives, and providing well-reasoned recommendations and adjustments to the building system. Its human-like reasoning capabilities can open up new avenues for human-building interaction research and enhancement of the building infrastructure autonomy.

Furthermore, the rise of Web3 technologies with the emergence of distributed ledger technologies (DLT) [5] , such as blockchain technology [6] and decentralized autonomous organization (DAO), [7] has introduced new paradigms of decentralized governance and decentralized finance (DeFi) in the built environment, which hold significant potential for enhancing the overall autonomy of building systems [8]. Blockchain (BC) is a digital public ledger that has all its data documented and stored in a transparent and tamper-resistant manner in a decentralized network. In addition, DAO is a digital and community-driven entity running on a blockchain network that functions transparently and autonomously with democratic and collective decision-making capabilities among its members [9]. In addition to being energy self-sufficient, multiple research studies suggest that next-generation building infrastructure also needs to become both operationally and financially autonomous with the capability of decentralized self-governance and self-ownership to become fully autonomous. For instance, Chang and Joha [10] also introduced the concept of 'common infrastructure,' a social practice that emphasizes collaborative production, sharing, and maintenance of resources within building infrastructure. They proposed the idea of a civic, self-owned, and autonomous infrastructure with blockchain technology to promote inclusivity and reduce the need for direct ownership and control over the building infrastructure. Wang et al. [8] also proposed the engineered ownership concept by proposing a blockchain-based system with automation capabilities with distributed rights and power shared between autonomous agents in building infrastructure. Similarly, Hunhevicz et al. [11] have also contributed to the research on the self-governing of physical space by proposing the concept and prototypes of decentralized autonomous space (DAS) using DAO.

However, previous works on self-governing infrastructure have yet to incorporate advanced technologies such as digital twin and AI into their proposed decentralized systems. Specifically, the research on the integration of DLT with digital twins and LLMs in the context of physical infrastructure remains unexplored. By integrating the context-aware capabilities and human-like intelligence of LLM with the decentralized governance and self-ownership framework offered by DLT, researchers can potentially explore new frontiers in building autonomy research and pave the way for the creation of a decentralized and self-governed, intelligent, and sustainable, autonomous building infrastructure.

To address this knowledge gap, this paper introduces a novel decentralized autonomous building cyber-physical system (DAB-CPS) framework that integrates DAOs, LLMs, and a digital twin to create a smart and autonomous building infrastructure. The specific research objectives of this study are the following:

1) To design and develop a decentralized autonomous building cyber-physical system framework for collective and decentralized governance of building infrastructure with AI-enhanced building operation.
2) To explore the potential of financially autonomous physical space by designing a revenue generation model for building spaces through a DAO-based decentralized platform.
3) To assess the scope and capacity of AI virtual assistant and agent in enhancing the human building interaction and building operation automation by developing an LLM-based virtual assistant for building system control.
4) To investigate the capability of generative AI in the web3-based decentralized governance by integrating the LLM-based virtual assistant in the DAO-based decentralized platform to assist DAO members and users in executing blockchain transactions and participating in the DAO's governance processes.
5) To develop a full-stack decentralized application (Dapp) to facilitate the governance of the autonomous building infrastructure by the DAO members and enhance user interactions with the physical space.

The contributions of this study to the existing body of knowledge are as follows: (1) Presenting a novel AI and blockchain-integrated decentralized governance framework model within the context of autonomous building, paving the way for a new paradigm in smart building management and operations (2) Demonstrating the feasibility and benefits of large language models in enhancing human-building interaction, intelligent decision-making, and automation of building operations. (3) Developing a full-stack, open-source Dapp that serves as a template for other blockchain and AI-related applications in decentralized governance for physical infrastructure and autonomous building. (4) Demonstrating the practical prototype and evaluation of a decentralized framework for autonomous building in an actual physical building environment (5) Providing perspectives on the challenges and opportunities related to incorporating generative AI models, such as LLMs, into decentralized governance frameworks that contribute to the understanding of the interplay between AI and Web3 technologies in the built environment.

The rest of this paper is organized as follows: Section 2 presents a comprehensive background on the relevant concepts and studies related to the research. This section first covers the fundamentals of blockchain technology and DAO before reviewing the literature on DAO and artificial intelligence integration. This section also reviews the related studies on the application of LLMs in the construction industry, as well as discusses DAO application in the built environment. The research method of the study is presented in section 3, while section 4 describes the proposed decentralized autonomous building cyber-physical system (DAB-CPS) framework. Section 5 provides the implementation and validation of the developed system through a real case study. Then, a discussion on the findings, implications, and limitations of the research, as well as the evaluation of system usability and performance, are made in section 6. Finally, the conclusion is presented in Section 7.

2. Literature review

2.1. Overview of Decentralized Autonomous Organization

A decentralized autonomous organization (DAO) is a novel organizational structure built on blockchain technology, characterized by its community-driven governance, transparent operations, and autonomous execution of decisions. DAOs function as digital entities operating on a decentralized blockchain network, enabling collective decision-making processes among their members while adhering to predefined rules encoded in smart contracts [7]. Smart contracts are self-executing programs implemented on the blockchain that activate automatically when certain predefined conditions are satisfied [12]. This innovative approach to organizational governance fundamentally diverges from traditional centralized structures, introducing a paradigm shift towards decentralized and autonomous operations.

One of the earliest and most well-known implementations of DAO was "The DAO," which was launched on the Ethereum network in 2016. Although it was eventually hacked and shut down, it sparked significant interest and paved the way for further exploration and development of DAO applications. As of June 2024, DeepDao analytics [13] reports a total of 2,437 active DAOs with around 3.2 million active weekly users, which collectively manage approximately $30 billion worth of blockchain assets. These DAOs engage 3.2 million active users weekly. Among these organizations, 213 DAOs hold treasuries exceeding $1 million, 113 DAOs have assets over $10 million, and 36 DAOs manage funds surpassing $100 million.

DAOs are built upon three fundamental principles: decentralization, autonomy, and automation [7]. In contrast to hierarchical management systems, DAOs employ a decentralized network architecture, which eliminates the centralized governing body [14]. In addition, governance within a DAO occurs through a democratic process, where community members collectively participate and vote on proposals [15]. Approved proposals are then autonomously executed by the smart contracts, ensuring consistent and transparent implementation of the collective decisions. Furthermore, the immutable and transparent characteristics of blockchain technologies allow DAOs to automate organizational processes and transactions through predefined rules encoded in smart contracts, fostering trust and accountability [16].

The governance process within a DAO typically involves the submission of proposals by community members, followed by a voting process where token holders can cast their votes. Once the voting period concludes, the proposal is either accepted or rejected based on the predetermined voting rules and thresholds. Accepted proposals are then automatically executed by the smart contracts, ensuring transparency and adherence to the agreed-upon rules.

In recent years, DAOs have attracted growing research interest within industry and academia across various disciplines, including decentralized finance (DeFi) [17], healthcare [18], and education [19]. However, there have been DAO implementations for decentralized governance in the built environment, especially in the building infrastructure domain.

2.2. Integration of DAOs and artificial intelligence

The idea of integrating AI and DAOs for decentralized governance was proposed by McConaghy, [20] where he explored the potential of AI DAOs and their societal implications. The synergy of artificial intelligence (AI) and DAOs holds immense potential to revolutionize decision-making processes, solve governance-related challenges, and unlock new opportunities across various domains, including the built environment. Traditional DAOs operate based on predefined smart contract codes and voting mechanisms. However, by leveraging the ability of adaptive machine learning and feedback loops, AI-powered DAOs can learn, make decisions, and automate administrative tasks that are typically performed by humans [21].

Experts and researchers have explored various scenarios of AI and DAO integration to illustrate their potential symbiotic relationship and practical applications (Fig. 1). Revoredo [22] presents different AI DAO use cases such as managing blockchain treasuries and assets, leveraging swarm intelligence for meta-governance, smart contracts automation, assisting DAO governance, and AI-generated content or services for DAO. One notable example is Singularity DAO, which leverages AI to facilitate asset management and investment decisions based on user behavior analysis [23]. In the realm of smart transportation, scholars suggest the use of intelligent agent networks to coordinate and optimize autonomous mobility systems through collaborative decision-making [24]. Furthermore, within the domain of smart cities, researchers have also proposed the integration of DAOs and parallel systems to facilitate the deployment of AI applications [25], by fusing the physical and virtual environments with spatial symbiotic intelligence, an integrated and collaborative DAO-AI decision-making system could be created to address the diverse needs of city residents more effectively [26]. Moreover, generative AI has been successfully integrated with DAOs to create self-sustaining digital organizations whose revenue is generated by AI-generated content. For instance, the works by Yadlapalli et al. [27] harnessed the potential of combining AI and DAOs by creating a digital, self-governing organization that sustains itself through the revenue generated from selling digital art automatically created by a Generative Adversarial Network (GAN). Similarly, Guo et al. [28] integrated artificial intelligence and DAOs to build a human-machine collaborative painting system for artistic content creation, further demonstrating the synergies between these two technologies. However, despite these advancements, there are a few research gaps that need to be addressed. First, most previous research has primarily focused on using AI to power DAO-related products and services through content generation or service provision. None have effectively utilized AI as a tool for assisting the DAO governance process. The few studies that have explored this area have only proposed conceptual frameworks but have yet to conduct empirical implementation. Furthermore, the integration of advanced AI models like LLMs with DAOs has yet to be explored. This presents a unique opportunity to investigate how LLMs can enhance DAO governance, decision-making processes, and overall efficiency. Addressing these gaps could pave the way for more sophisticated, intelligent, and autonomous decentralized systems.

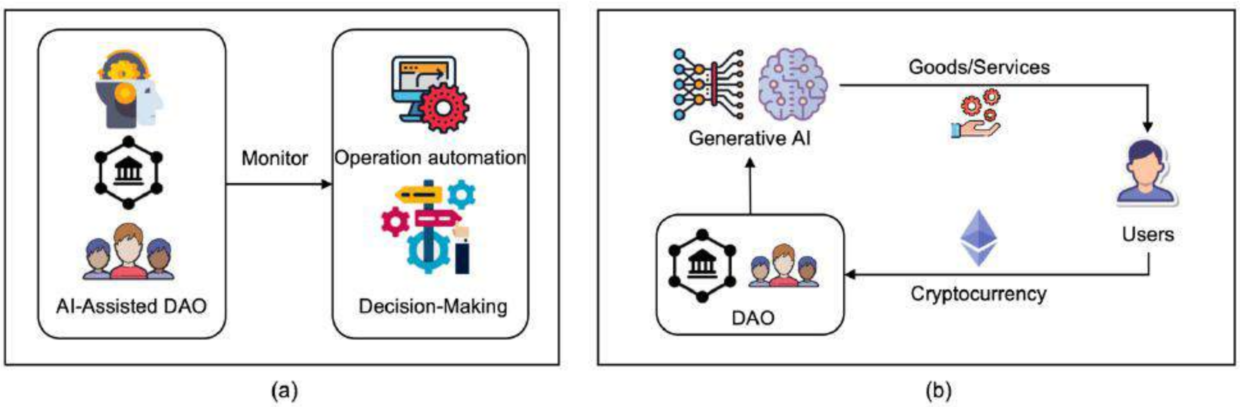


Fig 1. Integration of DAO and AI

2.3. Application of Large language model in construction industry

Large language models have emerged as a major advancement in the field of natural language processing (NLP) by revolutionizing the way humans interact with computer systems. These models are trained on large amounts of data, which allows them to comprehend and generate human-like language with remarkable fluency and coherence. Among the most prominent LLMs, OpenAI's ChatGPT has garnered significant attention due to its impeccable performance in information extraction and text summarization. These models leverage transformer-based architectures that are capable of learning patterns of natural language, which allow the generation of contextually relevant and coherent text by providing prompts that combine task instructions with selected contextual examples. A primary benefit of GPT models is their ability to generate language that closely resembles text written by humans. This has opened up a wide range of applications, such as chatbots and natural language communication, where these models can provide accurate and human-like responses to open-ended queries.

The capability and application of LLM have gained significant attention from researchers in the construction domain in the past few years. As a result, several studies have been conducted to explore the application of LLM in various stages of the construction project lifecycle, including project planning, construction, operations, and maintenance. For instance, in the project planning phase, a study by Prieto et al. [29] examines the use of LLM in construction schedule generation based on the project scopes and requirements. The findings show that the LLM developed a structured schedule that adopts a logical framework to meet the specified scope requirements. Within the construction phase, researchers have also explored the use of LLM in the construction robotics domain. You et al. [30] introduced RoboGPT, a novel system that utilizes the reasoning abilities of ChatGPT for automating sequence planning in robot-assisted assembly for construction tasks. Experimental evaluations and case studies demonstrated that RoboGPT-enabled robots could manage complicated construction operations and adapt to real-time changes. Additionally, LLM has also been used in the construction safety domain. Chen et al. [31] proposed a construction safety query system, which combines image captioning with a visual question-answering capability on head-mounted AR devices by leveraging vision language models such as ChatGPT 4. The system allows construction workers to query safety-related information by capturing images and asking questions through natural language interaction, thereby improving safety inspection, compliance checking, and progress monitoring in construction sites. In another study, Uddin et al. [32] examined the impact of integrating ChatGPT into the construction education curriculum. The investigation involved measuring students' hazard recognition abilities before and after introducing ChatGPT as an educational tool. The results showed significant improvements in hazard recognition, suggesting the potential benefits of integrating LLMs into construction safety education and training. Furthermore, LLM has also been used by researchers to facilitate efficient information search. For instance, Zheng and Fischer [33] introduced an AI-powered virtual assistant system that integrates ChatGPT for supporting natural language-based building information models (BIMs) search. This system allows users to query BIM databases using natural language, extract relevant information, and receive responses along with 3D visualizations.

While previous research has investigated the integration of GPT models in various domains of construction, the application of LLMs in the context of smart building infrastructure remains relatively unexplored. The advanced reasoning capabilities and natural language processing power of LLMs hold significant potential for enhancing automation and intelligent decision-making for smart building operations, as well as facilitating intuitive interaction between occupants and facility management operations. Furthermore, it is important to note that the existing research on the application of LLMs in the construction domain has primarily utilized commercialized GPT models, such as OpenAI's ChatGPT. Saka et al. [34] highlights some key concerns regarding data privacy, cost scalability, and confidentiality issues related to the usage of these models. The use of these cloud-based GPT models requires sensitive data to be transmitted to external servers for processing, potentially exposing it to unauthorized access or data breaches. Another significant challenge lies in the cost and scalability aspects of these commercial LLM services. As an example, users must pay a monthly subscription fee of $20 to access the ChatGPT web interface, which also comes with certain usage limitations. Similarly, the developed applications that use the GPT models API also face recurring charges based on their level of usage. These cost considerations may hinder the broader adoption and scalability of such applications within the construction industry. Therefore, there is a need to explore alternative solutions, such as utilizing local and open-source LLMs that can improve inference speed while addressing data privacy concerns, as the data remains localized within the device or system.

2.4. Decentralized autonomous organization and self-governing entity.

In recent years, various studies and prototypes have highlighted the potential of utilizing DAO in the development of web3-inspired autonomous systems and entities. McConaghy [35] is among the earliest to propose the concept of a web3-based self-governing and self-sustaining entity. He envisions a future where the integration of AI with blockchain and DAO creates smart and decentralized self-operated physical world objects such as self-own cars and self-own infrastructure such as highway roads and power grids, etc. Additionally, Wang et al. [8] also developed the concept of engineering ownership, which proposed the idea of a blockchain-based system with automation capabilities with distributed ownership and power shared between autonomous human or machine agents in the building infrastructure domain. Furthermore, in their works, Chang and Joha [10] also introduced the concept of civic and autonomous infrastructure to enhance inclusivity and eliminate the need for centralized ownership and control. They highlight the need to shift from centralized intermediaries, such as traditional financial institutions, to decentralized networks that promote shared governance. This shift is critical for developing infrastructures that are not only self-managed but also self-owned, operating without reliance on any centralized authority by leveraging distributed ledger technology.

Studies on the application of DAO governance have shown that human and machine agents can collaboratively create a decentralized organizational system that operates autonomously with self-ownership and without centralized control. DAO-powered entities encompass a range of applications, including a self-sustaining, generative AI-powered digital organization [27], [28], decentralized space [11] to an on-chain, and community-governed city [36]. One of the earliest concepts of the web3-based self-governing and self-sustaining entity was first introduced by Seidler et al. [37] in 2016, where they proposed the idea of a self-governing forest that can intelligently exploit its resources by selling its logging license with blockchain's smart contract automation process. In addition, the CityDAO project [36] aims to build a future blockchain-based city by leveraging land tokenization and decentralized governance. Users can purchase certificates to gain citizenship of the land through blockchain tokens to become CityDAO citizens and participate in the governance of the land, such as its policies, regulations, and future developments through the DAO governance.

In the context of building infrastructure, Ye et al. [38] have presented a DAO-enabled autonomous building maintenance system where the building operates independently according to predefined rules in smart contracts. The authors gave an exemplary use case where the embedded sensors detect equipment failures and report the issue to the DAO. The DAO then executes the appropriate responses, such as notifying the maintenance team and procuring replacement parts based on the programmed smart contract rules. The research on autonomous entities was further advanced in 2022 with the introduction of the No1s1 project, [11] where the authors have developed a prototype of a self-governing meditation space based on blockchain technology. This application demonstrates how DAO can be operated on a physical infrastructure, highlighting the potential for self-operating and self-sustaining physical spaces through smart contract-driven autonomy. However, the prototype lacks the integration of artificial intelligence, which could potentially enhance the autonomy adaptability, decision-making capabilities, and overall intelligence in managing and operating the autonomous systems. Furthermore, Dounas et al. [39] proposed a digital twin and blockchain-integrated system for the AEC industry. This framework also focuses on the utilization of DAO for collaboration between humans and computing agents in future physical infrastructure. Ly et al. [40] further advanced this concept by developing another framework that integrates digital twin and DAO applications to enable data-driven and decentralized governance in smart building facilities management. However, there is a lack of comprehensive empirical investigations into the practical application of this concept in the actual building environment. Therefore, there is a need for further investigation into the integration of AI, digital twins, and DAO alongside its empirical studies within the realm of autonomous building infrastructure.

3. Research Methodology

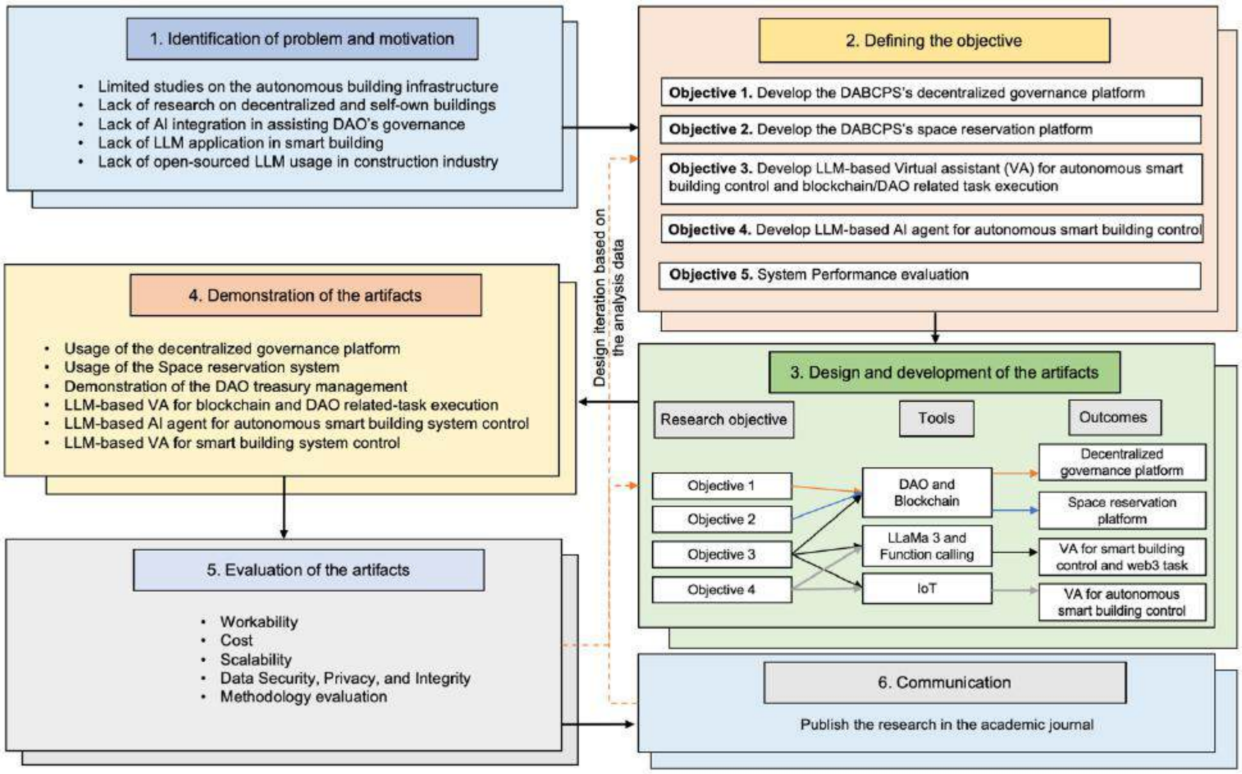


Fig. 2. Design Science Research-driven research flow

The development of the decentralized autonomous building cyber-physical system (DAB-CPS) adopted the Design Science Research (DSR) methodology, a rigorous problem-solving paradigm that emphasizes the iterative process of creating and evaluating innovative artifacts to solve identified problems in real-world contexts [41]. The DSR methodology has been widely adopted by researchers in developing blockchain-based solutions. For instance, Xu et al. [42] utilized the DSR approach to develop a blockchain-based framework aimed at facilitating decentralized carbon management, particularly in the certification of construction materials and products. Similarly, Cheng et al. [43] used DSR to create a blockchain framework for construction cost management, while Elghaish et al. [44] utilized the same methodology for the development of an AI virtual assistant for managing BIM data. The DSR process involves six different stages: (1) Problem identification and motivation, (2) Objective definition, (3) Design and development of the artifact, (4) demonstration of the artifact, (5) evaluation of the artifact, and (6) communicating the results [45]. Fig. 2 presents the development process of the decentralized autonomous building cyber-physical system with the six stages of DSR as follows:
(1) Problem identification and motivation. The literature review conducted in Section 2 reveals several research gaps, including limited studies on autonomous building infrastructure, lack of research on decentralized governance of building operation and self-owned buildings, lack of AI integration in assisting DAO governance, and the lack of open-source LLM application in the construction industry especially in the smart building domain.
(2) Objective definition. To address these knowledge gaps, this paper aims to design and develop a decentralized autonomous building cyber-physical system (DAB-CPS) framework that integrates decentralized autonomous organizations and large language models to create a smart and autonomous building infrastructure with AI-enhanced building operation and system control

and financially autonomous physical spaces with distributed governance mechanism through DAO-based decentralized governance platform.
(3) Design and development. The main goal of this study, the development of DAB-CPS, will be achieved through the following objectives. (i) To develop the DAO decentralized governance platform for the operational and treasury management of the physical space (ii) To develop the physical space reservation platform for the users (iii) To create the LLM-based Virtual Assistant (VA) for autonomous smart building control and blockchain or DAO related task execution (iv) Create the LLM-based AI agent for autonomous smart building control, and conduct system performance evaluation (v) To conduct system performance evaluation. Each of these objectives will be discussed in further detail in section 4.
(4) Demonstration. The developed system mentioned above will be deployed in the actual physical building space to create a prototype of the DAB-CPS framework. Different scenarios of the system capabilities will be demonstrated, including the management of the decentralized governance platform, usage of the space reservation system, and the demo of the AI virtual assistant for blockchain and DAO-related-task execution, as well as the AI agent for smart building system control.
(5) Evaluation. A real case study in a smart building will be provided to simulate the proposed system in a realistic setting. The evaluations of the DAB-CPS framework are presented in Section 5.
(6) Communication. The design and development methodology of the proposed DAB-CPS system and prototype, as well as the evaluation results, will be published in international academic journals.

4. Proposed DAB-CPS framework
4.1. Framework overview

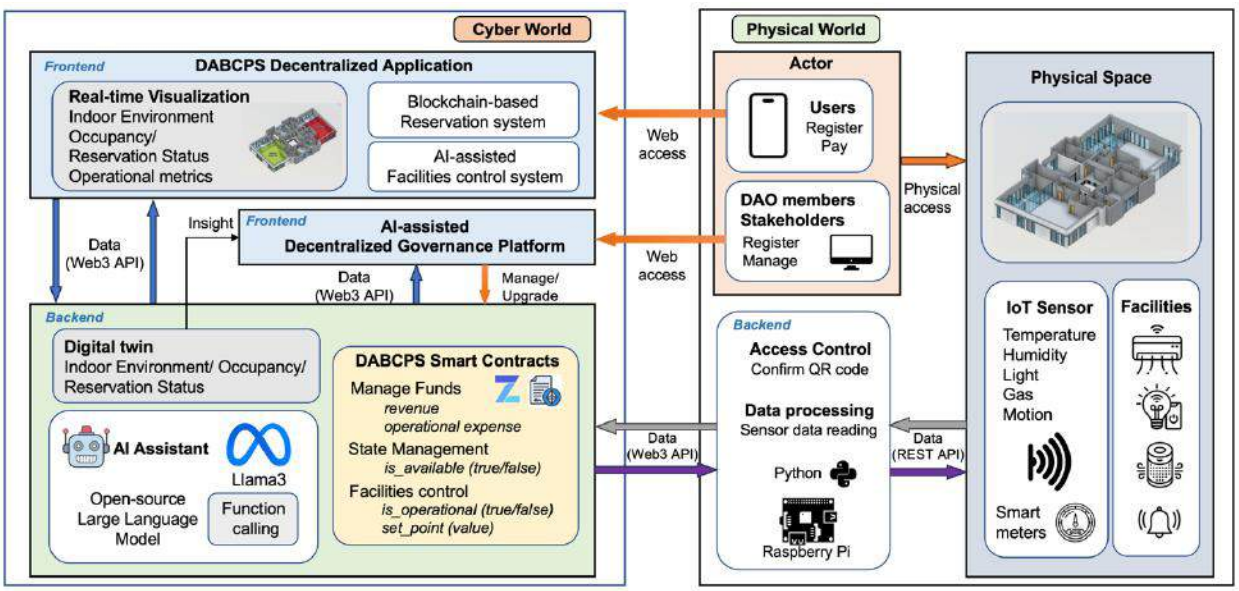


Fig. 3. Proposed Decentralized Autonomous Building Cyber-Physical System (Orange arrow: Human interaction on the CPS, Grey arrow: Data from Physical to Cyber system, purple arrow: Response from Cyber to Physical system)

In this study, we propose the concept of a decentralized autonomous building cyber-physical system (DAB-CPS), which is referred to as a web3 and AI-enabled, community-governed building infrastructure that functions autonomously with blockchain-based self-management protocols. The proposed framework aims to create a self-governing, autonomous building infrastructure leveraging blockchain technology, DAOs, and LLMs model-powered building automation systems. The DAB-CPS framework will be demonstrated through the development of a decentralized rental space. This decentralized space will be designed to earn blockchain's cryptocurrency or tokens (revenue) in exchange for renting/leasing itself to the users/occupants. The DAO's governance platform will be created to oversee the space's functional operation and financial aspect, including managing its revenue and necessary operational expenses (e.g., maintenance fee, electricity usage, etc.) with DAO treasury and blockchain-based transactions to sustain the system operation.

The architecture of this framework and the relationship between different components is also shown in Fig. 3. As depicted, the DAB-CPS framework is divided into two main domains: the Cyber world and the Physical world. The framework's cyber elements comprise different technologies, including blockchain, DAO, AI virtual assistant, and digital twins, while the physical element of the framework includes IoT devices, sensors, physical space, equipment, and human actors. In the physical world, the IoT device and sensors continuously monitor environmental conditions, while Raspberry Pi serves as the intermediary between the physical sensors and the cyber system by processing data and transmitting it to the cyber component. These sensor data are then used for digital twin visualization before feeding into the LLM-based AI agent for autonomous building operations management. The threshold values and automation logic of the building facilities are encoded in the blockchain smart contracts, which are managed by the decentralized governance platform. The AI virtual assistant also enhances user interactions with the physical space and supports DAO members in their governance activities.

The orange arrows in Fig. 3 represent human interactions with the cyber and physical system, showing how users and DAO members interact with the frontend applications and physical space. The Grey arrows indicate data flow from the Physical World to the Cyber World, including the sensor data transmission via Web3 and REST API. Purple arrows show the system's responses from the Cyber World to the Physical World, such as controlling facilities based on the command and decision from the DAO stakeholders and AI agents. Lastly, the blue arrow demonstrated the communication between the frontend and backend components of the Dapp. In addition, as illustrated in Fig. 4, the technical stacks of the DAB-CPS architecture are comprised of six layers. The user layers represent the human actors interacting with the system, which includes both DAO members who participate in governance and regular occupants who use the physical space. The main component of the application layers is the full stack Dapp, which contains key components from different layers, including the decentralized governance platform, space reservations portal, digital building twin visualization portal, and the AI-assistant portal. A Dapp with an interactive graphical user interface will be developed to provide access for the users to rental/booking services, facility control, and live digital twin visualization of the space, as well as offer the stakeholder an interactive platform for the collective governance of the physical space. Furthermore, the blockchain layer serves as the foundation of decentralized and trustless operations of the systems by encompassing the DAO-based decentralized governance platform and the blockchain-based space reservation portal. The decentralized governance platform will enable stakeholders (DAO members) to collectively manage the building operation and policy through DAO's decentralized governance mechanism, such as proposal submission, token-based voting, treasury management, and more. Furthermore, the space reservation portal allows users to reserve and cancel the space through blockchain transactions.

Moreover, the artificial intelligence layer leverages LLMs to enhance system capabilities. It includes smart assistance for decentralized governance, blockchain transactions, human-building interaction through a virtual assistant, and LLM-based autonomous building facilities automation. Furthermore, the physical infrastructure layer comprises the tangible components of the system, including the physical infrastructure, building systems and facilities, IoT edge devices, and environmental sensors, which are mainly responsible for data collection and operation of the physical space. In addition, the Data Transmission and Visualization Layer handles the processing and visualizing of the data collected from the physical layer. Its main component is the digital building twin portal, which gives the user real-time visualization of physical space conditions, including indoor environment, occupancy, and reservation status. The following sections will discuss each of these components in further detail.

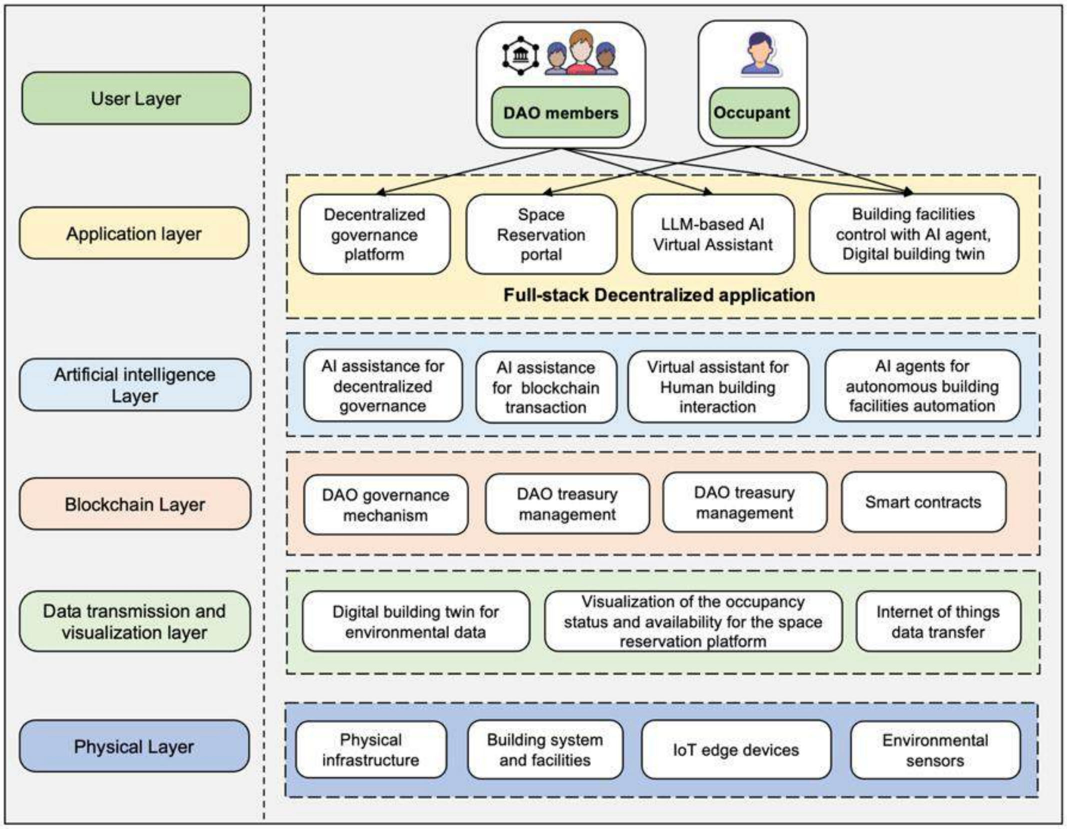


Fig. 4. Technical stacks of the Decentralized Autonomous Building Cyber-Physical System

4.2. Decentralized governance platform

The primary component of the proposed DAB-CPS framework is the decentralized governance platform, which serves as the central decision-making and operational hub of the physical space. Fig. 5 illustrates the architecture framework of the platform's framework, including its DAO-based governance mechanism and main functionality. The main objective of this decentralized governance platform is to facilitate transparent, secure, and decentralized governance processes among key stakeholders to collectively manage the physical space and building infrastructure, including facilities management tasks such as building facilities automation logic, operation, and maintenance issues as well as financial related matter such as income, budget allocations, expense for the physical space with DAO treasury and blockchain-based transactions, ultimately enabling a self-sustaining, nonprofit-seeking operation. Depending on the ownership structure of the physical space (public or private), DAO members can be comprised of various stakeholders, including building owners, facility managers, maintenance team, or broader occupant demographics who will be responsible for data-driven and collective governance of the DAO physical space by collectively propose and vote on different matters such as funding allocation, space operational settings, maintenance schedules, etc.

Voting mechanisms are essential to the operation of the decentralized governance platform. Upon the initial deployment of the DAO on the blockchain network, a predetermined quantity of governance tokens is minted and allocated to members based on their specific roles and responsibilities within the organization. Key members will receive a larger allocation of governance tokens, which grants them more voting power and governance rights compared to regular members. The governance tokens used in this study are based on the ERC-20 standard [46] as they provide token fungibility and transferability among DAO members, which facilitate the fractionalized ownership of the DAO system and the delegation of voting power. The platform will implement a token-based quorum voting mechanism [47], where the voting power will be proportionate to the number of tokens held by the DAO members. The DAO's governance process encompasses several key stages, including proposal submission, vote casting, proposal queuing, and execution. These procedures are governed by predefined conditions embedded within the DAO's smart contract, established during its initial deployment. These conditions include voter eligibility criteria, available voting options, duration of voting periods, implementation of voting delays, and quorum requirements. Upon the submission of a proposal for on-chain voting, a mandatory delay period is initiated. This interval allows voters to thoroughly examine the proposal, engage in discussions, and formulate informed decisions before casting their votes. Once the active voting period starts, eligible members can securely sign and cast their votes, with results transparently recorded on the blockchain. If a proposal achieves the required threshold, a minimum delay period is enforced before smart contract execution. This pause provides an opportunity for members to contest decisions or retract support if necessary, ensuring thoughtful consideration and mitigating hasty actions. Following this delay, the smart contract autonomously triggers the corresponding actions and updates the blockchain ledger. These actions may encompass fund transfers, contract modifications, or the initiation of any governance activities such as access control, incentivization, and more.

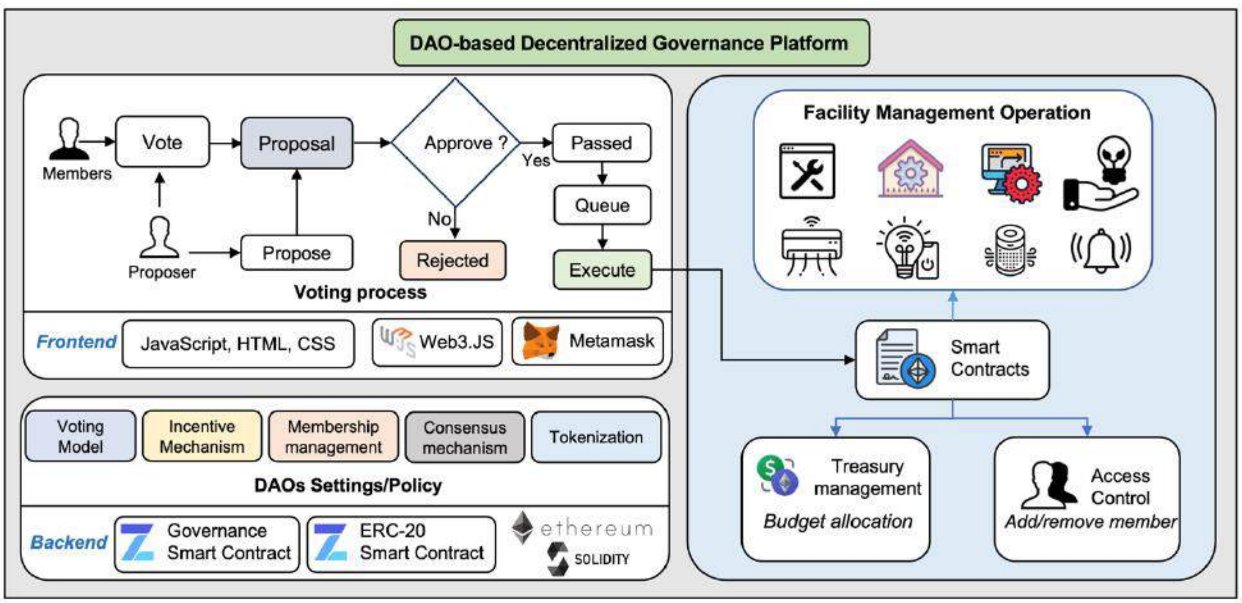


Fig. 5. The framework of the decentralized governance platform.

4.3. Space reservation portal

The Space Reservation Portal functions as a vital component of the decentralized autonomous building system, serving as the primary income source for the proposed DAB-CPS system. The portal provides an intuitive, web-based interface that allows users to easily navigate available time slots, make reservations, and manage their bookings. Users' booking and cancellation will be facilitated by the blockchain's smart contracts. This ensures that all transactions are immutable, traceable, and executed automatically without intermediaries. When a user makes a booking, the associated funds are automatically transferred to the DAO's treasury through smart contracts.

4.4. AI virtual assistant portal

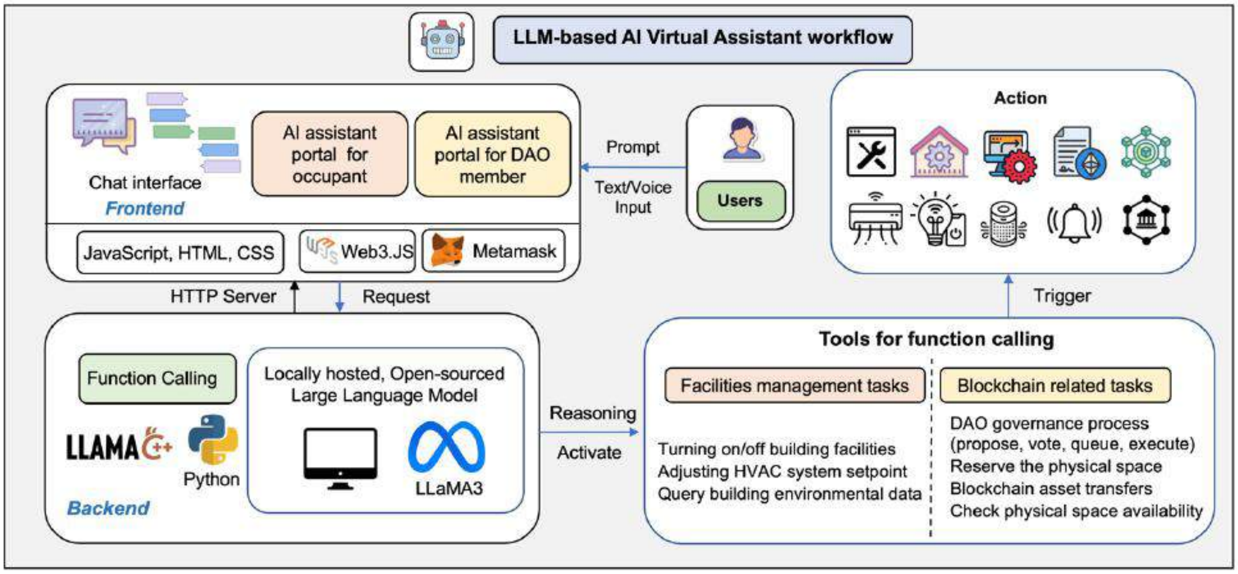


Fig. 6. Workflow of the Virtual Assistant

The AI Virtual Assistant portal aims to facilitate the human-building interaction aspect within the proposed DAB-CPS framework. This portal aims to provide smart and personalized assistance to both the DAO members and regular users for interaction with the physical building facilities and the Dapp components such as the decentralized governance platform and space reservation portal. For regular users, the AI virtual assistant serves as an interface for interacting with the physical space. Users can communicate with the AI virtual assistant through text and voice input to control various building facilities, adjust setpoints for the specific building smart facilities, or turn systems on or off as needed. The assistant also provides real-time information on indoor environmental conditions by accessing live sensor data reading from the IoT device. Additionally, it integrates with the blockchain-based reservation system, allowing users to check room availability and book spaces directly through the AI interface. The AI virtual assistant also facilitates the governance tasks of the DAO members and administrators of the physical space. The AI virtual assistant also supports the DAO members or owners in their interactions with the blockchain. DAO members can instruct the AI virtual assistant to vote on their behalf by calling the appropriate smart contract functions for executing transactions, including voting, queuing and exacting proposals, and transfer of blockchain assets and tokens. It can also facilitate the creation and submission of new DAO proposals, thereby streamlining the governance workflow.

Central to the AI virtual assistant is a locally hosted, open-source LLM and its function calling capabilities, specifically the LLaMA3 model by Meta [48]. The use of local and open-source LLM is driven by several factors, including enhanced data privacy, and reduced operational costs. By keeping all interactions and data processing within the local infrastructure, the system also ensures independence from third-party entities and maintains strict control over sensitive information. The AI virtual assistant Portal workflow is illustrated in Fig. 6, which demonstrates the integration of frontend and backend components. Users interact with the system through a web-based chat interface. The submitted prompts by the user are transferred to the backend and processed by the local LLM model. Upon receiving a query, the LLMs model leverages its reasoning and function-calling capabilities to understand the user's request and activates the appropriate predefined tools for either facilities management tasks or blockchain-related operations before executing the corresponding tasks. In this study, the quantization of the LLM is performed using the Llama.cpp library [49]. Quantization is an essential operation for the reduction of the model's size and computational requirements, which is particularly important for deploying the AI virtual assistant on local hardware [50].

4.5. Digital building twin

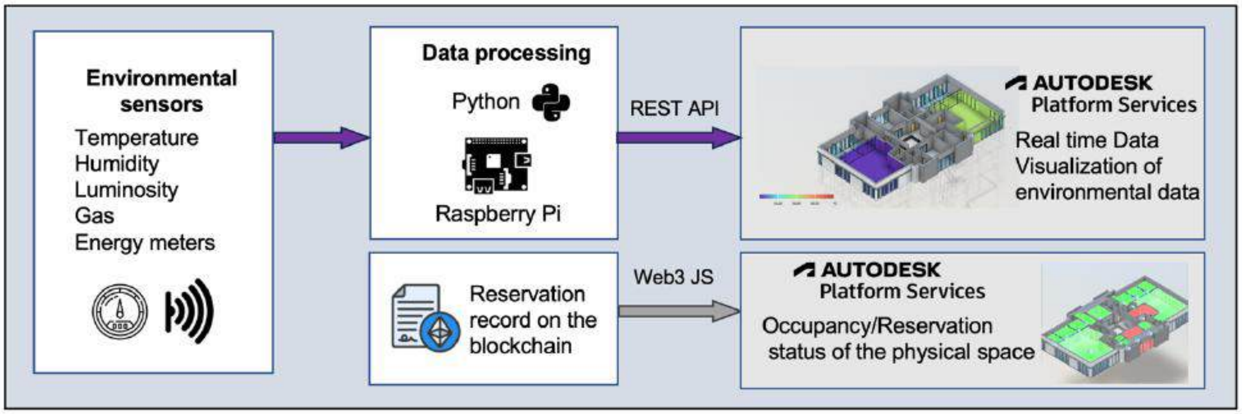


Fig. 7 Workflow of the Virtual Assistant

The digital building twin offers a comprehensive virtual representation of the physical structure within the proposed DAB-CPS framework. This advanced digital replica enables real-time monitoring of various building performance metrics, including energy usage, environmental data, and space availability. The twin's architecture incorporates both static and dynamic data components, with the static elements derived from a detailed Building Information Modeling (BIM) model. There are two different digital twin visualizations available in this study (Fig. 7). The first digital twin visualization aims to provide stakeholders with valuable insights into the building's environmental condition and corresponding energy performance, which facilitates data-driven decisions for the physical space facilities management strategies. The real-time and historical environmental data such as humidity level, temperature, light intensity, carbon monoxide gas, and energy usage information are collected with and processed by edge devices before being transmitted to the first digital twin platform. Furthermore, the second digital twin platform focuses on the dynamic representation of the physical space's availability and reservation status.

4.6. LLM-based autonomous building operation.

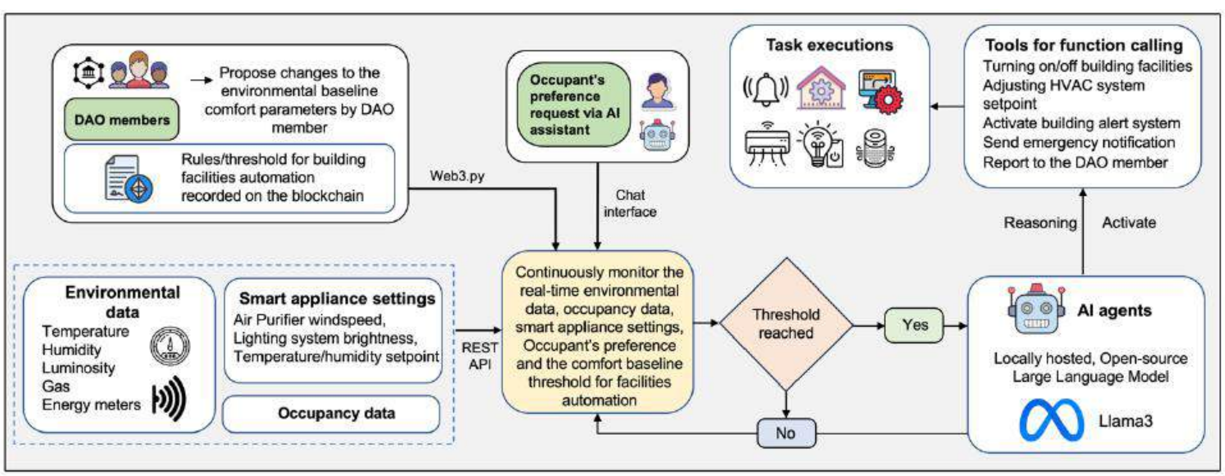


Fig. 8. Summary of the LLM-based AI agent for autonomous building operation.

In addition to the AI virtual assistant in the previous section, the DAB-CPS framework also leverages LLMs and function callings as an AI agent to oversee the autonomous building operation and facilities management. The proposed LLM-based autonomous building operation framework leverages the integration of IoT devices and sensors, smart building facilities such as the HVAC and lighting system, LLMs, and blockchain technologies to create decentralized and automated control of building systems (Fig. 8).

An array of environmental sensors and IoT Devices will be used to collect environmental data such as temperature, humidity, luminosity, carbon monoxide gas levels, as well as the energy usage information and occupancy level within the physical space. Raspberry Pi devices are used to process these data and feed them into the AI agent through REST API. In addition, the threshold parameters used for the automated smart building facilities operation (e.g., max or min temperature, humidity, etc.) will be extracted from the blockchain smart contracts, ensuring secure and transparent operations. These threshold values are the baseline comfort parameters for ensuring optimal comfort and indoor environmental quality and are defined by DAO members, who serve as administrators for the physical spaces. These thresholds are recorded on the blockchain for transparency and immutability and form the basis for the AI's decision-making process. During the operation, the LLM-based AI agent will continuously compare real-time sensor data from the physical space against these predefined thresholds on the blockchain. When the environmental data values exceed these thresholds, the AI agent utilizes its function-calling capabilities to control various building systems, including smart lighting and HVAC systems. These operations involve adjusting setpoints, activating or deactivating devices, or triggering alerts to maintain optimal building conditions.

In addition to the rule-based automation, the LLM-based AI agent is also designed to perform contextual decision-making, which allows for more sophisticated and dynamic system control. The proposed AI agent can interpret multiple variables simultaneously, such as the current settings of smart appliances and the occupancy levels within the building. In this study, the occupancy data will be periodically analyzed, and the AI agent will adjust the performance of building systems (e.g., HVAC performance or lighting intensity) based on occupancy level to dynamically optimize energy consumption. In addition to occupancy-based adjustments, the AI agent can also process natural language inputs from users, such as feedback or specific requests, and dynamically modify its autonomous control logic in response. This enables the system to accommodate immediate individual preferences or situational changes. The proposed AI agent provides a level of flexibility and adaptability that surpasses traditional automation systems, making the building's operational framework not only more efficient but also more responsive to dynamic environmental and user-driven changes.

5. Proof of concept: Implementation and validation of the prototype

In this section, a case study with the developed prototypes is used to validate the viability and functionality of the DAB-CPS framework. The code for the technical implementation of the DA-CPS prototypes is available under an open-source license [51]. The tools, coding languages, and development environments employed for each module of the DAB-CPS prototypes are summarized in Table 1.

Table 1. Tools used for prototype development.

Tasks	Programming language (packages)	Development environment
Frontend web pages development	React JS	Visual Studio Code
Smart contract development	Solidity	Brownie
Digital building twin	JavaScript (Autodesk API)	Visual Studio Code
IoT sensors and smart home device	Python	Visual Studio Code
Interaction between Dapp and smart contract	JavaScript (web3.js API)	Visual Studio Code
AI agent's function calling	Python (llama-cpp-agent)	Visual Studio Code

Large language models deployment	C++ (llamacpp)	Visual Studio Code
Large language models Inference	Python (llamacpp-python)	Visual Studio Code

5.1. Development of the Dapp backend

5.1.1. Smart contract design and development

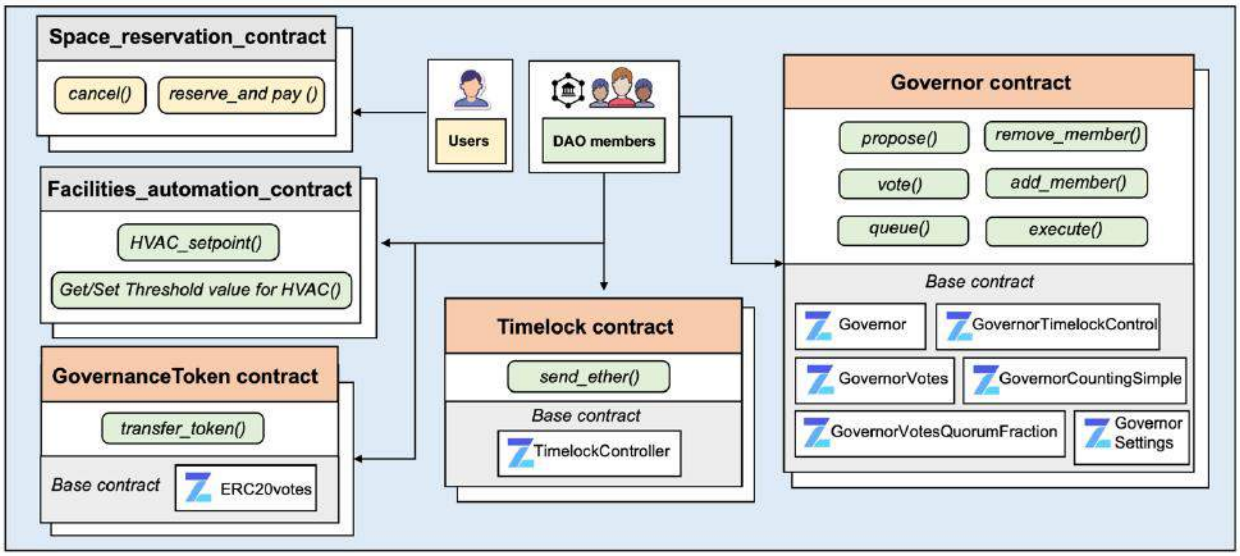


Fig. 9. Design of the decentralized governance platform's smart contracts

This section details the design and development of smart contracts for the backend of the proposed DAB-CPS framework, including Dapp components such as a decentralized governance platform, space reservation system, and the automation logic of building facilities operation. The five smart contracts in this prototype, the DAO Governor contract, Governance Token contract, Timelock contract, space reservation contract, and facilities automation contract, were written in the Solidity programming languages [52] and compiled using Brownie library, a python-based development environment that allows developers to write, test, and deploy Ethereum smart contracts. Given the collaborative aspect of the governance platform, a public/permissionless blockchain network is chosen for the design and development of this DAO application. Ethereum blockchain [53] is chosen in this study as it provides a diverse set of tools for DAO development. For research purposes, Ethereum's test network, Sepolia, will be used as it provides all the necessary functions of Ethereum without any fees. The design of the five smart contracts and the relationship between their function and the roles of actors in the proposed framework are illustrated in Fig. 9. The decentralized governance platform is structured around three primary smart contracts: the DAO Governor contract, the Time Lock contract, and the Governance Tokens contract. This study utilized the base smart contracts from the OpenZepplin library [54] , including the DAO governor contracts and ERC-20 contracts, as it provides secured and audited codes with community-standardized contracts for DAO development.

The DAO Governor contract Is primarily responsible for the core governance processes within the decentralized governance platform. It manages proposal submissions, voting procedures, and the execution of approved decisions. It handles the votes counting mechanism and determines the outcome of proposals based on established quorum and majority requirements. The DAO Governor contract in this study is built upon several OpenZepplin base contracts. For example, the Governor base contract provides essential functions for proposal creation and execution. The GovernorTimelockControl contract adds a security layer by introducing a delay in proposal execution. The GovernorVotes contract ensures voting power is based on the ERC-20 governance tokens [46]. GovernorCountingSimple implements a straightforward vote-counting mechanism, while GovernorVotesQuorumFraction enforces a quorum based on a fraction of the total token supply. Additionally, GovernorSettings allows for the configuration of governance parameters such as voting delays and periods. The DAO Governor contract works closely with the Timelock contract to schedule the execution of approved proposals and interfaces with the Governance Tokens contract to verify member voting power for proposals.

In addition, the Governance Token contract manages the distribution and administration of the platform's fungible tokens, which represent voting power within the DAO-based governance framework. This contract handles the minting of new governance tokens upon deployment. It functions as the medium for both governance and transactional activities within the system. The Governance Tokens contract inherits from the ERC20Votes base contract, which extends the standard ERC20 token with voting and delegation capabilities. This enables token holders to vote directly or transfer their voting power to other DAO members. In this platform, it facilitates the delegation of voting power by allowing the allocation and transfer of tokens between members. This process is handled by the transfer_token function within this contract. The Governor Token contract also interfaces with the DAO Governor contract to determine voting weights and eligibility for proposal submissions.

Additionally, the Timelock contract serves as a security measure, enforcing governance decisions by introducing a mandatory delay between the approval of a proposal and its execution. This contract is extended from the TimelockController base contract from the OpenZepplin library. It queues approved proposals for a specified delay period and executes them only after this period has elapsed. This ensures that all stakeholders have adequate time to review approved decisions and make any changes if necessary. In contrast to the Governance Token contract, which controls fungible tokens, the Timelock contract manages the DAO organization’s monetary assets, such as Ethereum cryptocurrency. One key function within the Timelock contract is send_ether, which facilitates monetary transactions between the DAO organization and external contract addresses.

In addition, the space reservation contract contains two important functions, reserve () and cancel (), which allow the users to reserve the physical space and make corresponding cancellations on the space reservation portal. Once the user reserves the space, the rental fee will be automatically transferred to the Timelock contract of the decentralized governance platform. Finally, the facilities automation contract contains the set and get function for the threshold variables. The set threshold variable function can be called by the DAO member from the decentralized governance platform to define the threshold parameters for the smart building facilities operation. The get threshold variable function will be called through web3 JS by the LLM-based AI agent for comparison against the real-time environmental data.

In addition, upon development, the three DAO contracts (Governor contracts, Governance Token contracts, and Timelock contracts) were deployed to the Ethereum Sepolia test network. It is also crucial to highlight that, by default, the user who initially deployed the governance token contract is the owner of all that governance token contract, which contradicts the notion of decentralized governance where no individual is supposed to be solely in control in the DAO’s treasury. To address this problem, this study deployed these three contracts simultaneously at once in a single Python script. The initial DAO member can also be determined by the initial allocation of ERC-20 tokens within the Governance token and a certain user address within the first deployment of the contract. By doing so, the ownership of the Governance Token contract and Timelock contract, which are crucial for the management of DAO’s ERC-20 token and Ethereum cryptocurrency assets, will be successfully transferred to the Governor contacts right after the initial deployment of DAO. Therefore, future governance actions such as monetary and token assets will be monitored by the Governor’s contracts, which are controlled by all DAO members instead of a single user or authority. The “onlyDAOmember” modifier is used in proposed smart contracts to enforce access control and security to important functions within DAO. Regular users or non-DAO members can only access the space reservation contract. The five smart contracts developed in this study are presented in Fig. 10.

Fig. 10. Summary of smart contract within the DAB-CPS prototypes. (a)Space reservation contract (b)Building automation contract (c)Timelock controller contract (d) DAO Governor contract (e) Governance token contract

5.1.2. Digital building twin

Fig. 11. Myers-Lawson School of Construction's Bishop-Favrao Hall and its BIM model

As previously mentioned in section 4.5, the DAB-CPS framework incorporates two distinct digital building twins of a single physical building. The first digital building twin aims to provide a visualization of the environmental condition and energy usage within the building, while the second digital building twin seeks to provide the reservation status of the physical space. This study chooses Bishop-Favrao Hall, home to the Department of Building Construction at Virginia Tech, as the location for the case study to implement and evaluate both digital twins and the DAB-CPS prototype. The BIM model of Bishop-Favrao Hall was developed using Autodesk Revit 2024 (Fig. 11). The environmental data for the first digital twin is collected using a network of sensors managed by a Raspberry Pi 4B single-board computer. The system interfaces with a series of environmental sensors and IoT devices to continuously monitor and collect real-time data. Key sensors used in this setup include (1) DHT11 Humidity and Temperature Sensor (2) Light Intensity Sensor (3) MQ-2 Gas Sensor and (4) Groove Smart Plug for Energy Metering. These sensors' data are read and processed on the Raspberry Pi 4B using Python libraries such as Adafruit_DHT (for the DHT11) and Rpi.GPIO, and Adafruit_MQTT. Once the environmental data is collected and processed on the Raspberry Pi 4B, it is transmitted to the first digital twin platform via a REST API, which is facilitated by Python's Flask library. The data is sent in JSON format, which includes the sensor readings for temperature, humidity, light levels, air quality, and energy consumption. For the digital twin development, the Autodesk Platform Service's Model Derivative API is utilized to integrate the dynamic environmental data into the BIM model. It allows for the real-time visualization of sensor data onto the digital building model, which allows DAO members to monitor the real-time conditions of the building. Fig. 12 presents the summary of the digital twin development workflow.

Moreover, the second digital twin platform focuses on dynamically representing the physical space's availability and reservation status. The dynamic data for this building twin is the reservation status of various spaces within the building. When a room or space is booked, the reservation is recorded on the Ethereum blockchain through a dedicated space reservation smart contract. This digital twin utilizes the Web3.js library to retrieve booking information for each space and continuously updates the vacancy status in real time. This information is transmitted to the digital twin system through the REST Web3.js library, ensuring accurate, real-time reflection of space utilization across the building.

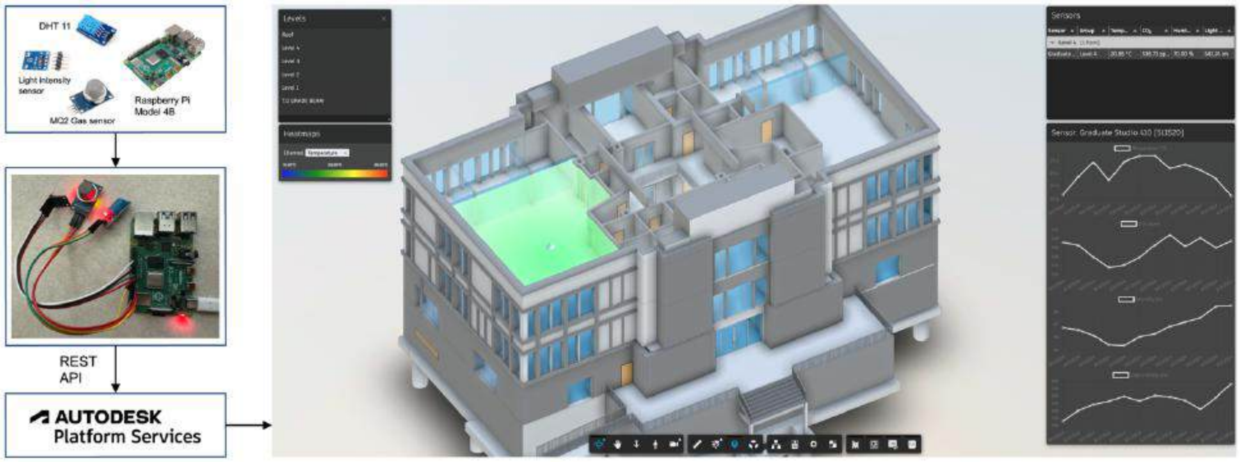


Fig. 12. Workflow of digital building twin development.

5.1.3. Deployment of the AI agent and virtual assistant module

The proposed AI agent and virtual assistant in this study is powered by LLaMA 3 8b, an open-source LLM with eight billion parameters developed by Meta [55]. The number of parameters of a model directly affects the accuracy, responsiveness, and functionality of the AI system. The model with a high number of parameters tends to provide better output quality, improving both the general language understanding and the precision of function calling, which is a critical feature in this AI system. The workstation used for the LLaMA4 model deployment in this study is an Apple MacBook Pro with an M1 Max chip with 32GB of RAM. To run the LLaMA 3 model efficiently, this study employs a quantized version of the model using the llama.cpp library. Llama.cpp is a tool that allows the execution of quantized LLMs on local hardware with support for different types of GPU. One key advantage of this tool is its ability to reduce the size of the model through quantization, which involves representing the model's weights in lower precision formats. This enables running complex models on devices with less computational power without severely compromising performance. The 8-bit quantized model of LLaMA 3 8b is used in this study.

Function calling is one of the core features of the proposed AI virtual assistant. In this context, function calling refers to the AI's ability to analyze user requests, extract key information, and invoke predefined tools or functions to perform tasks. This study leverages llama-cpp-agent, a Python-based package, to implement the function-calling capabilities of the proposed AI virtual assistant. In this study, various Python functions and tools were developed for the AI virtual assistant to handle both blockchain-related tasks and facilities management operations. These include turning building facilities on or off, adjusting the setpoints of HVAC systems, querying environmental data, sending emergency alerts, and managing decentralized governance processes such as proposing, voting, queuing, and executing DAO proposals. Additionally, the AI virtual assistant supports functions like reserving physical spaces, checking space availability, transferring blockchain assets, and signing blockchain transactions.

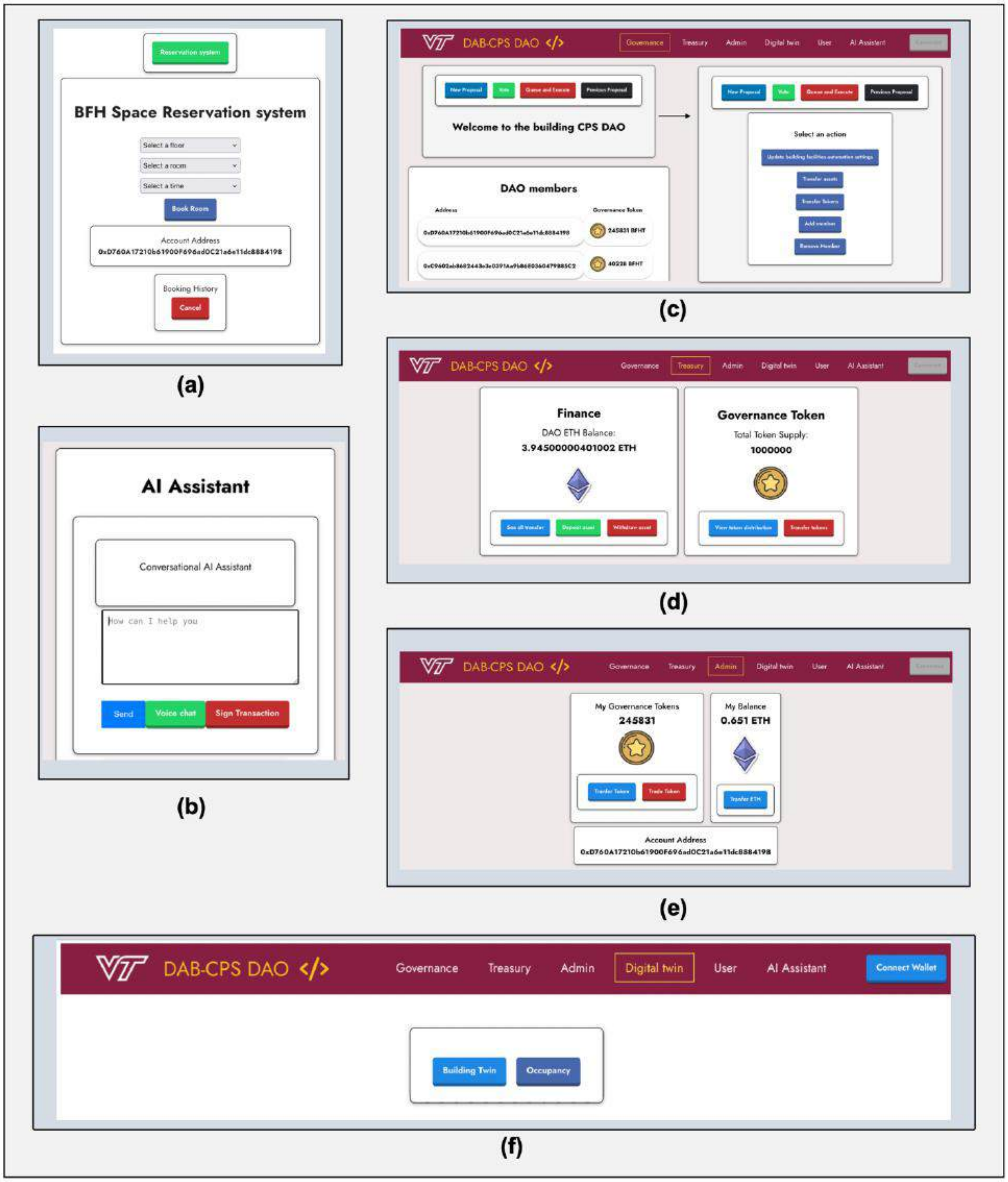


Fig. 13. Front-End of the DA BCPS Dapp: (a) Space reservation portal (b) AI assistance portal (c) Governance Portal (d) DAO Treasury tab (e) DAO Administrator tab (f) Digital twin tab.

5.2. Development of the Dapp Frontend

The front end of the Dapp for the proposed DAB-CPS prototype was developed using React JS due to its flexibility, modular structure, and compatibility with web3 JS, which facilitates the interaction between the Ethereum blockchain and the web application. This frontend offers an intuitive interface for both regular users and DAO members to interact with the physical space and the blockchain system. Additionally, MetaMask was integrated into the application to link the users' Ethereum wallets and accounts to the Dapp to facilitate blockchain-related transactions. As illustrated in Fig. 13, the Dapp is comprised of six main tabs: Governance, Treasury, Admin, Digital Twin, User, and AI assistant. The Governance tab allows DAO members to propose and vote to implement different building operation-related governance actions, such as adding or removing members, transferring governance tokens or cryptocurrency, and updating lighting, HVAC, and facilities automation settings. The Treasury tab displays the governance and monetary assets of the entire DAO, including governance tokens and Ethereum cryptocurrency. DAO members can propose and vote to transfer these assets from the DAO organization to specific addresses. The admin tab provides information on the governance and monetary assets of individual DAO members. Similar to the Treasury tab, DAO members can transfer their assets to other addresses through this section. The Digital Twin tab displays the two digital twins described earlier: one representing the environmental conditions and energy usage of the building, and the other showing the reservation status of the physical spaces within the building. In the User tab, regular users can access the space reservation system to book rooms and times. Finally, The AI virtual assistant tab enables both users and DAO members to interact with the AI virtual assistant. To enhance accessibility, the AI virtual assistant also integrates the Web Speech API from node JS [56], which provides speech-to-text functionality for the React JS app, allowing users to input queries or commands through voice interaction. This feature supports a more intuitive interface, enabling seamless communication between users and the AI virtual assistant.

5.3. Physical space and related equipment

The physical space used for this study's DAB-CPS prototype testing is meeting room at Myers Lawson school of construction. While the room is equipped with a native HVAC system and integrated lighting, it is not available on demand for public use for direct access to control these systems. To simulate the required environmental management capabilities for the study, a range of smart home devices has been installed to facilitate access control from AI virtual assistant and decentralized system on the air quality, humidity, lighting, and fan speed within the physical space (Fig. 14). To simulate air quality control within the space, this study uses a smart air purifier device, Xiaomi Smart Air Purifier 4 Compact, which is equipped with multiple fan speed configurations. This allows adjustments to airflow and purification settings within the room by the AI virtual assistant and the autonomous AI agent. Next, a smart humidifier, the Govee Smart Humidifier H7141, is used to facilitate the adjustment of humidity levels within the room. The Xiaomi Mi Smart Standing Fan 2 is also integrated into the system by offering multiple fan speeds for personalized airflow control. This device allows the AI agent to demonstrate its ability to regulate air circulation within the space, simulating traditional HVAC systems. For lighting control, this study used a smart bulb, Yeelight Smart Light Bulbs W3 as it offers adjustable brightness levels, which mimic the control of indoor lighting conditions. These smart devices were selected for their flexibility and compatibility with the research objectives, specifically, the availability of APIs and open-source tools for smart home control.

Fig. 14. Physical spaces and equipment used in the experiment. (a)Physical space (b) smart home appliance

5.4. Implementation

This section describes the implementation of DAB-CPS prototypes in the physical space to verify their feasibility. While the proposed DAB-CPS prototype has been fully developed with all the software and necessary environmental sensors and hardware components, the testing of user interaction still requires the involvement of key building stakeholders, including facility managers, building operators, and other decision-makers. However, since the technologies used in the DAB-CPS prototypes such as blockchain have not yet achieved mainstream adoption in the construction industry, the involving stakeholders' testing would require significant time for coordination and specialized technical expertise. Given these constraints, a scenario-based evaluation approach was adopted to simulate the user interaction aspect of the system. This approach allows the system's functionality, performance, and efficiency to be tested across various controlled scenarios without requiring the immediate participation of real stakeholders. Scenario-based validation has been widely used in different blockchain-related studies [57], [58], [59] and provides a feasible, effective method to demonstrate the viability of the technology in different practical contexts. In this study, the validation process was structured around several key scenarios, including user reservation on the space reservation portal, income and expense management by the DAO entity, proposal voting by DAO members, and AI virtual assistant demonstration for blockchain-related tasks and facility management tasks. The following sections will provide more details on each of the scenarios and its validation process.

5.4.1. Implementation Preparation

For the implementation of the DAB-CPS prototype and Dapp, a scenario was designed to include five distinct stakeholder roles: four facility managers and one occupant. Each of these roles was assigned an Ethereum account funded with 1 Sepolia testnet Ethereum token to participate in the blockchain operations. One of the users was designated to deploy the DAO smart contract, which included the governance contract, token contract, and Timelock contract. In this setup, the governance token, named BFHTokens, was minted in a total supply of 1,000,000 tokens. At the time of deployment, three out of the five accounts were allocated 10,000 BFHTokens each, which granting them as DAO members status. The remaining two accounts were designated for other purposes: one would be a regular user responsible for making space reservations, while the other would be added as a DAO member through a vote by the existing members. The smart devices in the physical space were configured with specific environmental setpoints to simulate real-time control and demonstrate the capabilities of the DAB-CPS system. The baseline comfort parameters were set within the following ranges: room temperature between 20°C (min) and 27°C (max), illuminance intensity between 50 lux (min) and 150 lux (max), relative humidity between 40% (min) and 100% (max), and carbon monoxide concentration between 400 ppm (min) and 1000 ppm (max). To further assess the energy consumption within the physical space, all equipment was connected to two smart plugs equipped with energy meters. These meters tracked the energy usage of the devices throughout the experiment, which was conducted over a seven-day period from September 14 to September 21, 2024. To simulate one month's worth of energy data within this two-day window, the measured energy consumption was multiplied by a factor of 4. This calculation was necessary to simulate the frequency of events like utilities expense payouts, where the DAO would distribute funds based on energy consumption data.

The interaction between facility managers and occupants with Dapp is illustrated through ten steps, which are labeled alphabetically from (a) to (j) in Fig. 15. Steps (a), (b), and (c) are related to pre-implementation activities such as roles assignments, account funding, and smart contract deployment. Steps (d) and (e) are related to occupant interaction with the reservation system and digital twin. Step (f) to (j) demonstrate the DAO member governance process for blockchain and facilities management-related tasks.

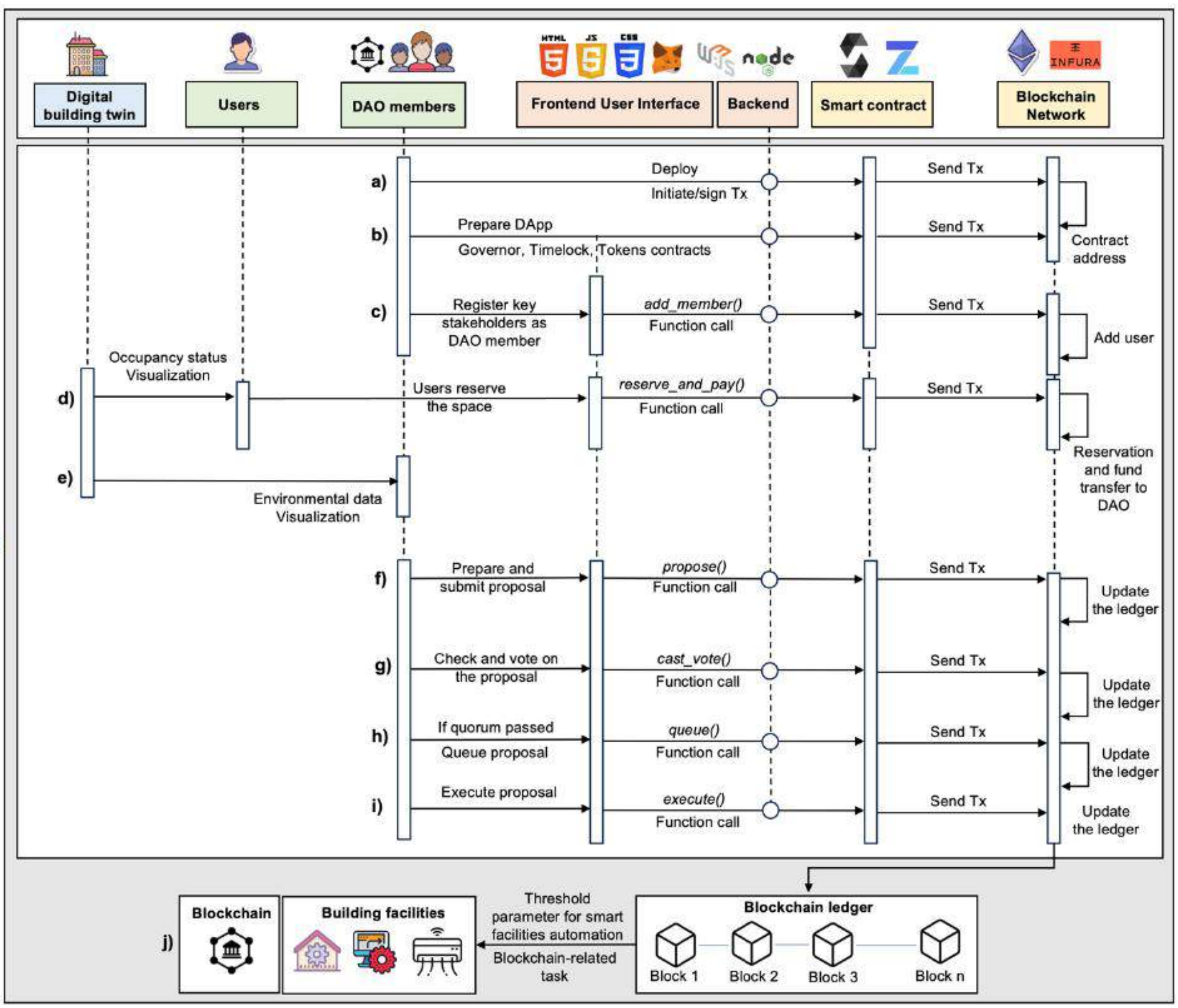


Fig.15. Sequence diagram of implementing the Dapp.

5.4.2. Scenario 1: User reservation on the space reservation portal

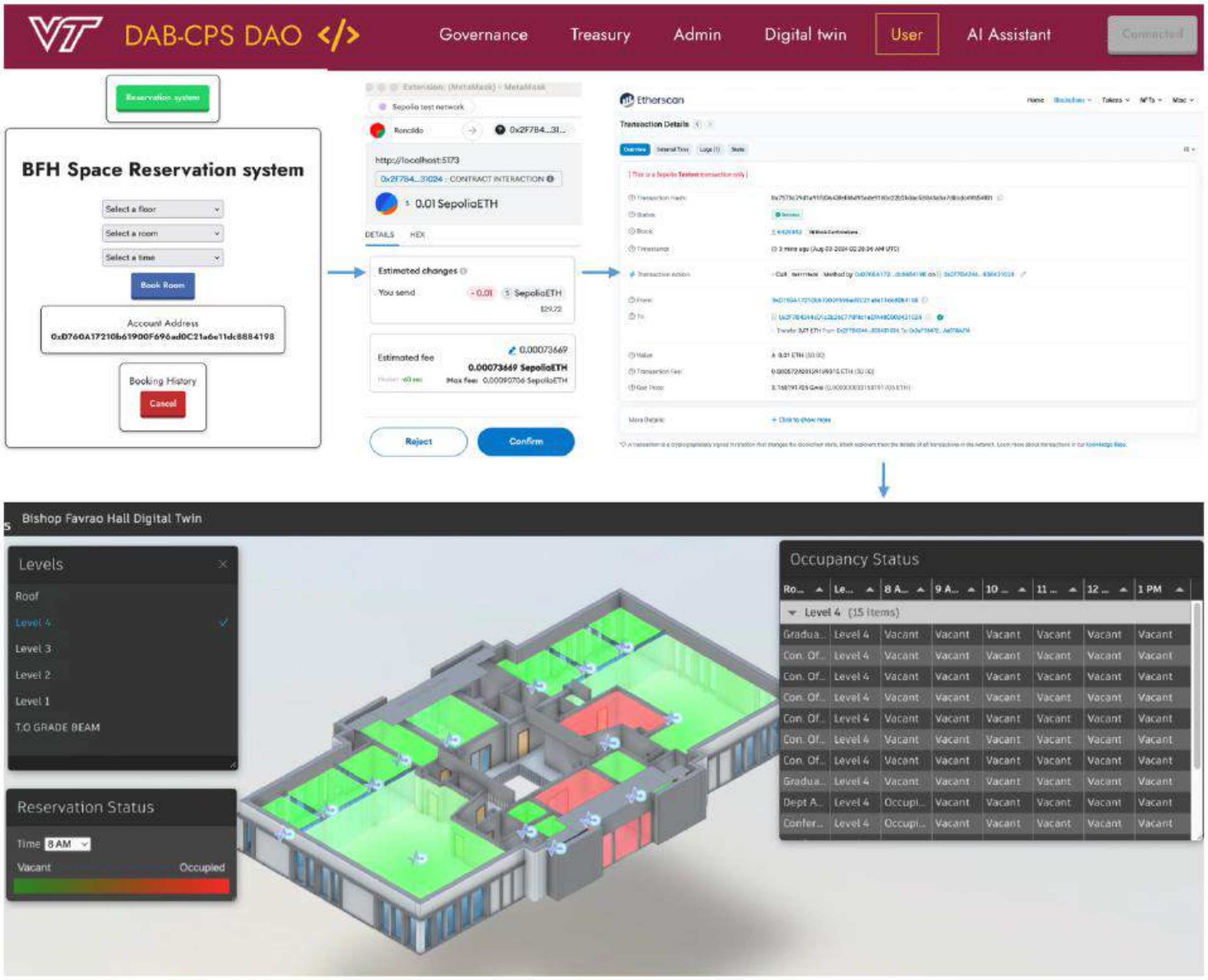


Fig. 16. Roadmap for reserving the physical space on the Dapp.

In this scenario, the main objective is to validate the user reservation process within the DAB-CPS system, demonstrating the interaction between end-users and the Dapp for booking physical spaces. As shown in Fig. 16, the user can access the decentralized space reservation portal on their phone or computer. To initiate the reservation process, users link their Ethereum wallet to the Dapp frontend via MetaMask, select a location, and specify the desired time for the reservation before booking and signing the transaction. The user pays a fee of 0.001 Ethereum for the reservation. After the booking transaction is processed, the successful booking is displayed on the portal. In addition, the space is marked as "occupied" and represented visually by a red heatmap on the building's digital twin, indicating that the room is no longer available. Additionally, the booking fees are transferred to the DAO's address, contributing to its revenue. This scenario validates the ability of users to make space reservations while simultaneously generating income for the DAO, confirming that the system functions as intended in real-world conditions.

5.4.3. Scenario 2: DAO Expenditure management

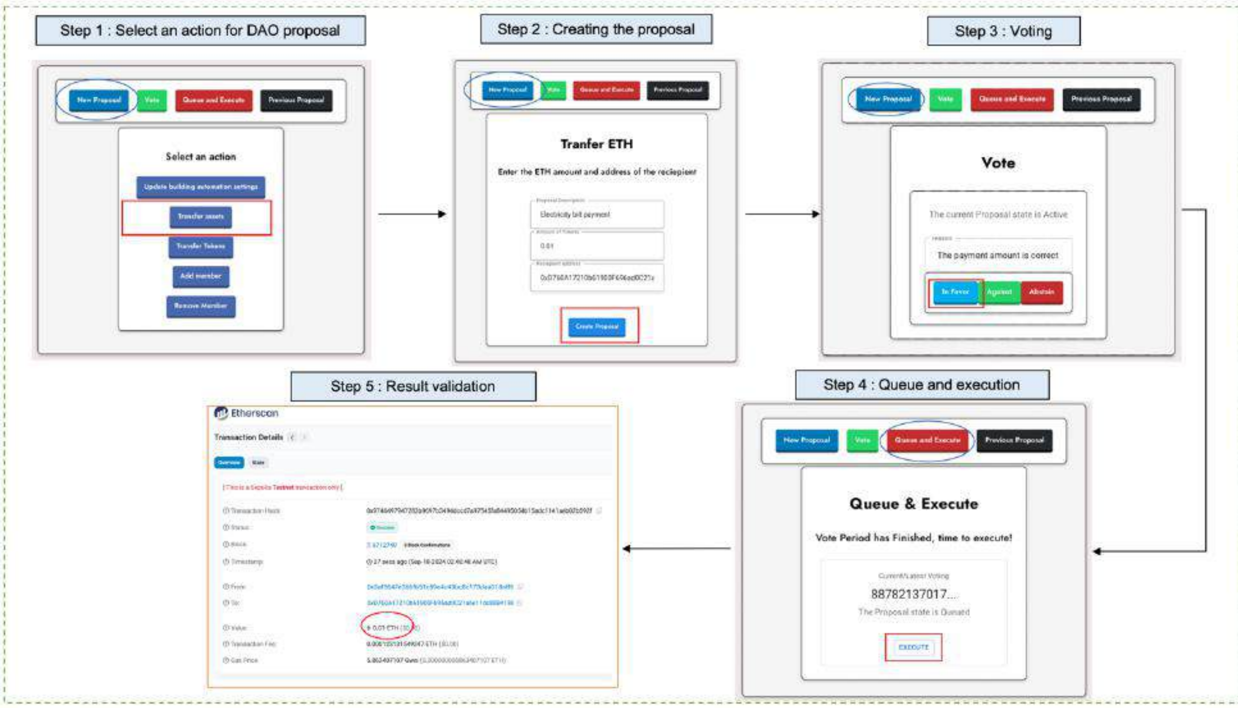


Fig. 17. The roadmap for the DAO governance process for expense management

The second scenario focuses on the validation of DAO-managed expenses, specifically demonstrating how DAO members can coordinate to manage and pay expenses related to the decentralized space. This scenario simulates the payment of electricity bills for energy usage within the space. The total energy consumption for the month is obtained via the Govee smart app, which measures energy use through connected smart plugs with energy meters. For research purposes, the electricity rate is set according to the current rate in Blacksburg, Virginia, and the total energy cost is calculated based on this rate. The equivalent cost in Ethereum is then derived by converting the dollar amount to Ethereum tokens. Next, a DAO member initiates a proposal to pay the calculated energy bill in Ethereum to the electricity provider's Ethereum address. As shown in Fig. 17, all DAO members participate in the voting process to approve or reject the expense. Once the proposal is passed, the payment transaction is executed on the blockchain. As illustrated, the Ethereum transaction can be tracked and verified through Etherscan, showing the successful transfer of the equivalent Ethereum to the electricity provider’s wallet. This scenario validates the capability of the DAO to manage and approve expenses in a decentralized manner, demonstrating the system’s ability to autonomously handle essential operational costs through collective decision-making.

5.4.4. Scenario 3: DAO Governance for updating building system operational threshold.

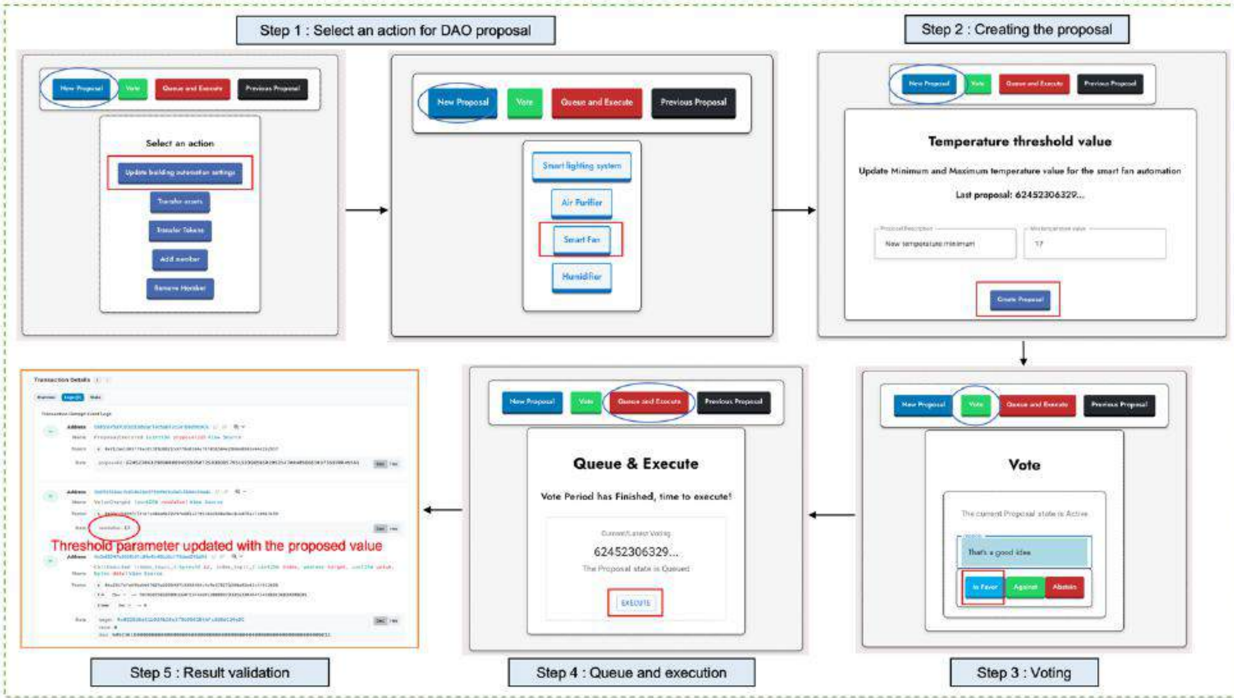


Fig. 18. The roadmap for the DAO governance process for setting operational thresholds for smart appliances.

This scenario also aims to evaluate the decentralized governance aspect of the DAB-CPS system by demonstrating the DAO's capacity to set operational thresholds for smart appliances of the physical space, such as adjusting baseline environmental comfort variables value including minimum and maximum temperature, humidity, luminance, carbon monoxide concentration level, which dictate the environmental conditions for optimal user comfort. As depicted in step 1 and step 2 in Fig. 18, a DAO member initiated a proposal to modify the minimum temperature threshold to 17 degrees Celsius. In step 3, DAO members participated in the voting process, where they could either approve or reject the proposed changes. Upon successful voting and proposal approval, DAO members queued and executed the proposal to write the new threshold values into the blockchain's smart contract (step 4). As can be seen in step 5, the updated parameters were successfully recorded on the blockchain. Finally, the DAB-CPS prototypes with its AI agent subsequently adopted these new values to autonomously control the environmental conditions in the space. Therefore, this scenario validated the DAO's ability to democratically set operational thresholds for space devices, confirming that the DAB-CPS system can effectively integrate decentralized decision-making into its autonomous building management processes.

5.4.5. Scenario 4: AI virtual assistant for Blockchain-Related Tasks Execution

This scenario aims to evaluate the integration of AI virtual assistant in facilitating blockchain-related tasks for DAO members and users within the DAB-CPS prototype. For validation purposes, this experiment tests the use of an AI virtual assistant to assist the Ethereum token transfers. In this scenario, the selected task involves the transfer of 0.01 Ether to the address

“0x3aF5647E366fb51C89e4c43Bc8C173dAa018AFf6”. As demonstrated in Fig. 19, the user issued a command to the AI virtual assistant to transfer Ether. The prompt is then transmitted to the backend, where it is processed by a locally hosted LLMs. Upon receiving the user’s query, the AI employs its function-calling and contextual understanding capabilities to interpret the request, extract useful information such as user address and amount of ether, and activate the "send Ether" function, which is pre-programmed in the list of its executable tools. The AI virtual assistant then called the Ethereum transfer function on the blockchain smart contract and prompted the front-end interface to request the user or DAO member’s signature to confirm the transaction. After the successful transaction, an amount of 0.01 Ether has been sent to the address “0x3aF5647E366fb51C89e4c43Bc8C173dAa018AFf6,” as requested.

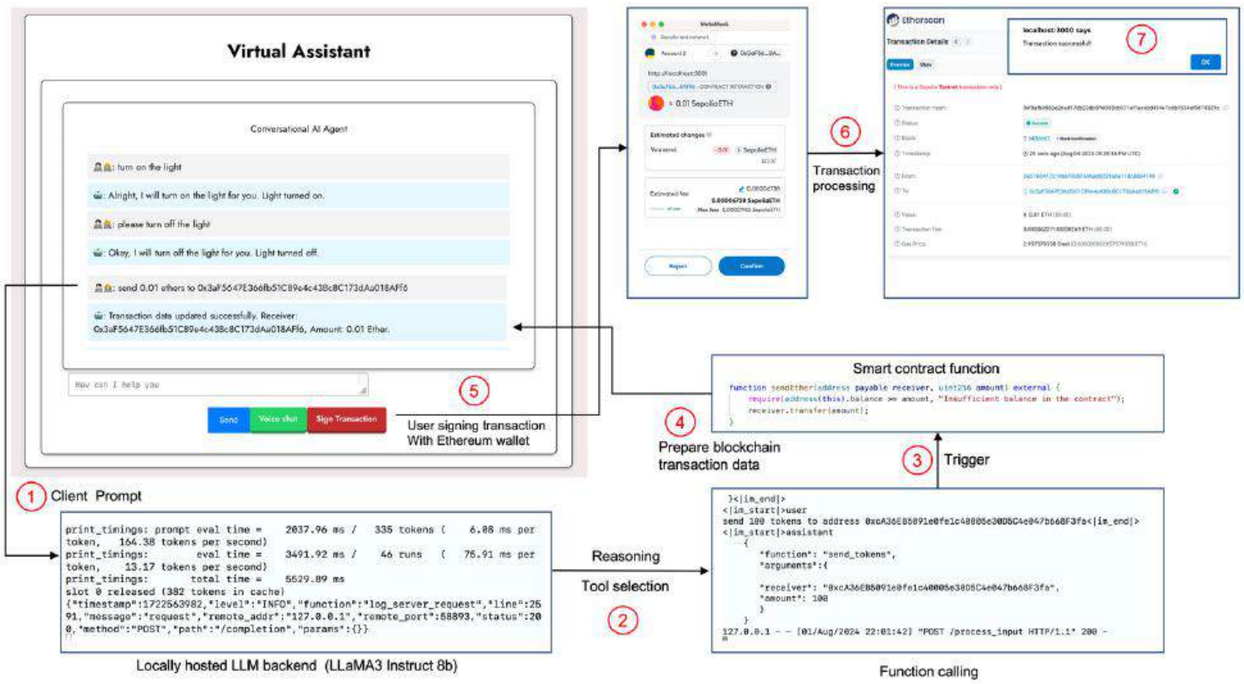


Fig. 19. Blockchain task execution using LLM-based AI virtual assistant.

5.4.6. Scenario 5: AI-Assisted Control of Smart Devices

This scenario aims to validate the LLM-based AI assistant’s ability to control smart home devices within the DAB-CPS prototype. For this demonstration, the control of a smart light bulb was selected. Users can interact with the AI virtual assistant to issue voice commands such as turning the light on or off. Like the previous scenarios, the user’s prompts are transmitted to the backend, where they are processed by the locally hosted LLMs. Upon receiving the request, the AI uses its function-calling capabilities to understand and act upon the user's instructions. It then activates a Python script that interfaces with the device's API, enabling it to control the smart light bulb as requested. In addition, instead of the simple on/off commands, users can also provide the context or hint, such as stating that the room is "too dark" or "too bright." The AI virtual assistant, leveraging its context-awareness capabilities, can autonomously adjust the brightness level of the light bulb, which can be seen in Fig. 20. This dynamic interaction demonstrates the enhanced functionality of the LLM-powered AI virtual assistant, distinguishing it from traditional AI virtual assistant that lack such nuanced environmental awareness.

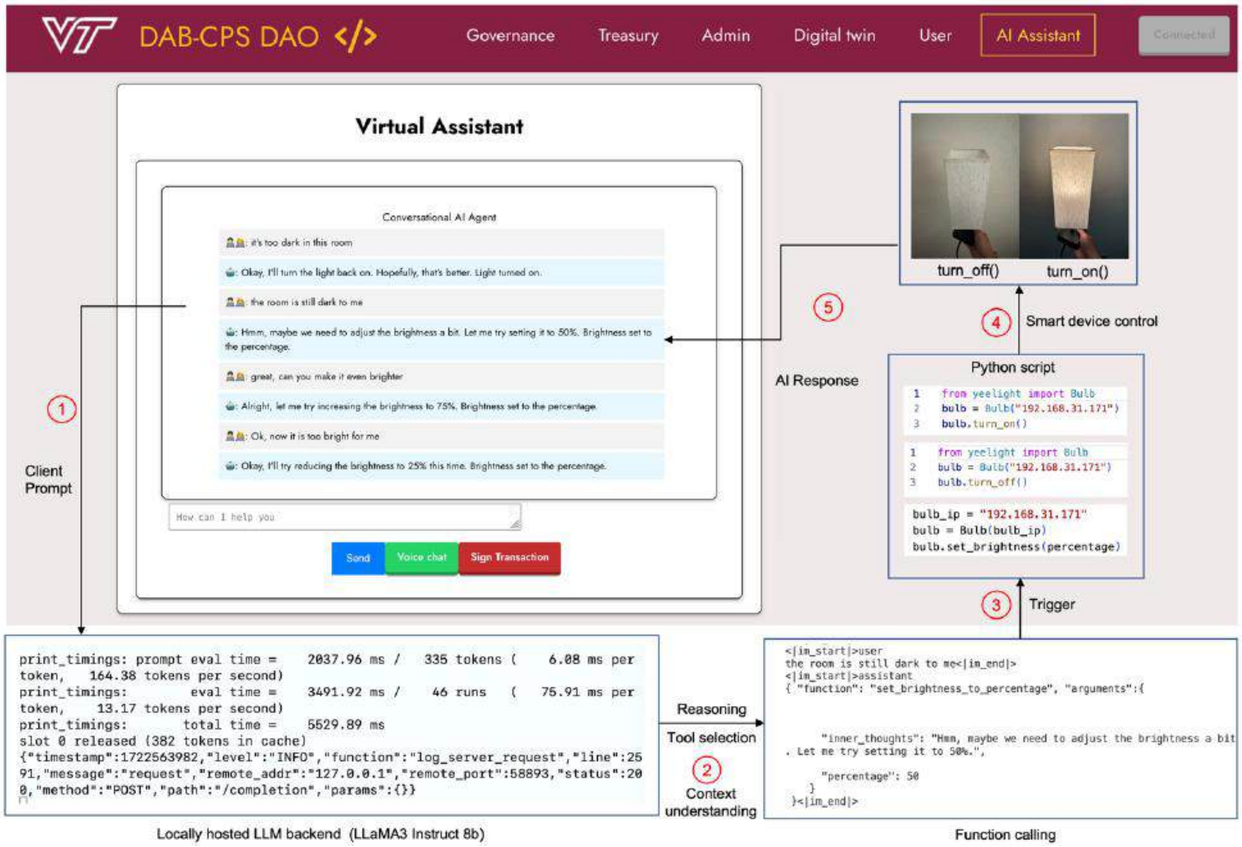


Fig. 20. Workflow of the smart appliance control using LLM-based AI virtual assistant.

5.4.7. Scenario 6: Autonomous building operation with LLM-based AI agent

This section aims to validate the role of the AI agent in managing smart devices for autonomous building operations through two distinct scenarios: automatic appliance control based on occupancy and autonomous adjustments according to environmental data. In the first case, we examine how the AI system adjusts appliance settings in response to occupancy changes. The detection of occupancy is a well-researched area that has been conducted through different methods, including surveillance cameras, machine learning, and sensor technologies. Therefore, the occupancy detection itself is not within the scope of this study. This experiment uses the simulated occupancy data (randomly selected between 1 and 10) and is updated every 10 minutes to test the AI agent's ability to autonomously control devices such as a smart fan and air purifier. For demonstration, this study defines low occupancy as fewer than five individuals, while high occupancy is defined as more than five individuals. As demonstrated in Fig. 21, the AI agent continuously monitors the fan and air purifier settings and occupancy data through RESTful API. Depending on the occupancy levels, the AI agent modifies the performance of the devices accordingly. If no occupants are detected, the AI agent will turn off all devices. In the case of low occupancy, it reduces the performance to a lower setting, while in high occupancy scenarios, it increases the devices' performance to meet the demand. Initially, both smart fan and air purifier were set to low performance at level 1. During the experiment, the simulated occupancy was ten individuals, which led the AI agent to perform the contextual reasoning and raise the performance settings of the fan and air purifier to level 3 and level 7, respectively, to ensure environmental comfort in the physical space.

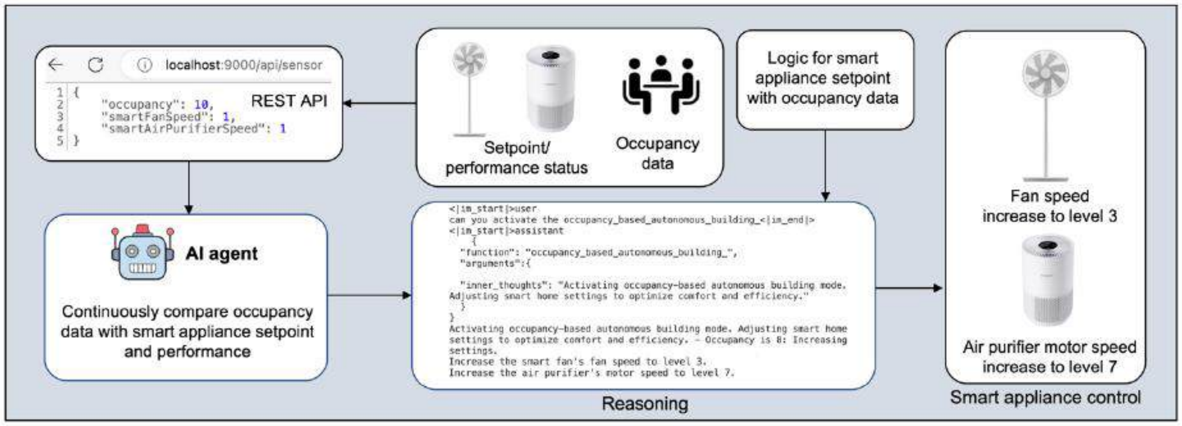


Fig. 21. Occupancy-based autonomous smart appliance control using LLM-based AI agent.

The second case aims to validate the AI agent's ability to autonomously adjust smart appliances based on baseline environmental comfort parameters retrieved from blockchain smart contracts and real-time environmental conditions, such as temperature, humidity, luminance, and carbon monoxide levels. In this scenario, the smart appliance setpoints were initially configured at their lowest levels. As shown in Fig. 22, the AI retrieved the baseline comfort parameters via web3.py, which included temperature (20°C min, 27°C max), illuminance (50-150 lux), humidity (40-100%), and carbon monoxide concentration (400-1000 ppm). The real-time room conditions—28°C temperature, 45% humidity, 34 lux, and 752 ppm carbon monoxide level—were obtained through REST API. Upon processing this data, the AI agent determined that the temperature and luminance were outside the comfort range and automatically adjusted the smart fan to speed level 3 and the smart light to 90% brightness while leaving other appliance settings unchanged. This experiment demonstrates the AI's ability to autonomously regulate the indoor environment by adjusting smart devices based on real-time data and predefined comfort thresholds. In addition, the smart appliance control by user preference is demonstrated in the previous section.

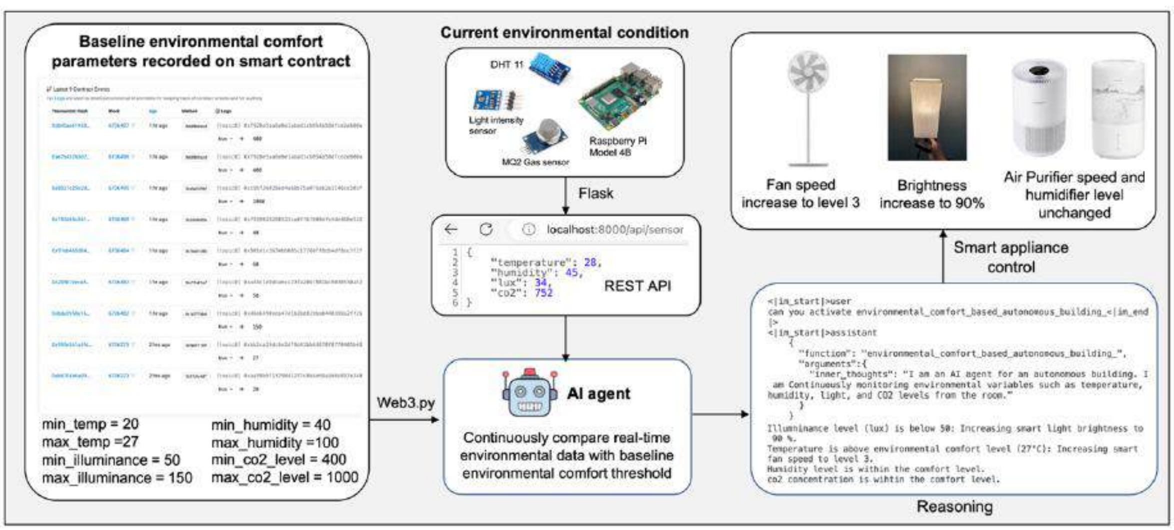


Fig. 22. Autonomous smart appliance control using environmental comfort threshold and LLM-based AI agent.

6. Results, evaluation, and discussion

The DAB-CPS prototype was subjected to a two-week experimental testing phase. By the end of the period, a total of 9 space bookings were successfully made through the decentralized space reservation system, generating a total revenue of 0.09 ETH for DA BCPS's DAO. On the decentralized governance platform, eight proposals are being submitted for voting. These proposals included actions such as adding and removing members, paying utility bills, sending governance tokens, and adjusting environmental parameter thresholds for smart space management. Of these, five proposals were successfully passed, while three proposals failed due to insufficient support from the DAO members, where governance token backing did not surpass the 50% threshold. This demonstrates that the voting mechanism functioned as intended by enforcing democratic decision-making in the decentralized governance process. During this period, the smart plug energy meters documented a total electricity consumption of 22.73 kilowatt-hours (kWh) for the smart appliance usage. Given the current electricity rate of $0.169475 per kWh, the calculated total electricity cost amounts to USD 3.85, which is equivalent to 0.0016 ETH. Based on this data, DAO members have initiated a proposal and subsequent voting process to authorize the transfer of 0.0016 ETH for the electricity bill payment. Additionally, throughout the period, the AI virtual assistant processed a total of 35 requests, which included 21 requests for smart home device control and 14 requests to execute blockchain-related tasks. The AI agent is also capable of autonomously adjusting smart appliances based on given comfort threshold and occupancy data to maintain optimal comfort. Table 2 presents the criteria used to evaluate the workability of the DAB-CPS system prototypes, all of which were successfully achieved. The system demonstrated its capability across multiple key areas, including user reservation of physical spaces, digital twin visualization environmental conditions and reservation status, and the effective execution of decentralized governance processes through DAO member proposals and voting. Additionally, the AI virtual assistant proved successful in both smart building control and blockchain-related task execution.

Table 2. Workability test result

No.	Criteria	Result
1	User interaction with the physical space reservation portal	Achieved
2	Digital building twin for environmental condition and reservation status	Achieved
3	DAO members interaction with the decentralized governance platform (proposing/voting/queuing and executing the proposal)	Achieved
4	AI virtual assistant for smart building system control	Achieved
5	AI virtual assistant for blockchain related task execution	Achieved
6	AI agent for autonomous building operation	Achieved

6.1. Cost analysis

Transaction on the Ethereum network requires a gas fee to compensate for the computational power needed to process the transaction on the network. The cost analysis of the DAB-CPS system evaluates the gas consumption and transaction fees for various blockchain operations performed during the experiment, including smart contract deployments, governance actions, space reservations, and AI-assistant-related tasks. These fees are expressed in Ether (ETH) and converted to USD to illustrate the financial implications of each transaction. Gas fees are measured in units of gas, with the total transaction cost calculated by multiplying the gas used by the gas price. The key operations listed in Table 3 incurred different transaction fees. For example, the deployment of core smart contracts like Governor, Timelock, and Tokens consumed significant gas, costing around 0.051903 ETH in total (~122.38 USD). Other operations, such as

DAO member registration, space reservations, governance/Ethereum tokens transfer, as well as governance proposals submission, voting, queuing, and execution, had costs ranging from 0.000110 ETH (~0.26 USD) to 0.001052ETH (~2.47 USD) per transaction. It's crucial to recognize that these costs depend on the particular blockchain network selected for Dapp implementation, and transaction costs may differ when applied to a Mainnet network. The fees were calculated during testing on the Sepolia testnet and are summarized in the final column of Table 3.

Table 3. The transaction cost of the proposed decentralized governance platform.

Operations	Smart contract	Gas	Transaction fee (ETH)	Transaction fee (USD)
Contract deployment	DAO Governor	3,880,388	0.003880	9.15
Contract deployment	Timelock controller	1,909,795	0.001909	4.50
Contract deployment	GovernanceToken	1,971,098	0.001971	4.65
Contract deployment	Facilities automation	488,638	0.011985	28.26
Contract deployment	Space reservation	1,662,788	0.032158	75.82
Adding DAO member	DAO Governor	73,610	0.000110	0.26
Space Reservation payment	Space reservation	181,123	0.003839	9.05
Proposal submission	DAO Governor	108,168	0.000199	0.47
Voting on proposal	DAO Governor	93,186	0.000169	0.40
Queuing proposal	DAO Governor	123,769	0.000235	0.38
Executing the Proposal	DAO Governor	132,563	0.000238	0.56
Governance Tokens transfer	GovernanceToken	72,954	0.000139	0.3286
Ethereum tokens transfer	Timelock controller	21,055	0.001052	2.479

6.2. Scalability

The scalability of the developed DAB-CPS prototype is evaluated by assessing both its underlying blockchain infrastructure and the LLM-based AI system. On the blockchain side, the system scalability is influenced by the limitations of the Ethereum blockchain, specifically its proof-of-stake consensus mechanism, which can limit the transaction throughput. Every transaction within the Ethereum network must receive validation from all participating nodes before being added to the blockchain. As transaction volumes rise, more nodes will be necessary to ensure network efficiency. However, with the expansion of the network, the processes required to reach a consensus also escalate, potentially resulting in delays and increased gas fees [60]. This challenge is common within the Ethereum blockchain-based systems, where throughput is limited to around 30 transactions per second [61]. However, in the proposed DAB-CPS, users interact with the decentralized governance platform by proposing ideas, voting on them, and executing approved proposals where each of these actions triggers specific smart contract functions. While this can introduce a significant number of transactions, the decentralized nature of governance helps distribute activity over time. It is quite improbable that all DAO members will simultaneously submit proposals, vote, or execute actions, which in turn reduce the likelihood of bottlenecks. Likewise, it is less likely that all users will attempt to book rooms simultaneously. These factors help mitigate potential scalability concerns in our experimental setup, which currently can process a manageable number of transactions without issue. However, if the system were to be adopted in a real-world scenario with a larger number of users, migrating to a more scalable blockchain solution like Polygon, which can process over 65,000 transactions per second [62], could be a practical solution.

Furthermore, the scalability of the proposed LLM-based AI system is evaluated based on its throughput and ability to handle concurrent user requests, specifically measuring how many requests the AI can process simultaneously and how quickly the system can respond to user queries. In our experiment, we used LlamaBench, an open-source tool for benchmarking LLM, to assess the performance of the proposed AI-based agent and virtual assistant. The results indicated that execution time and throughput varied based on the specific task. For chat or text generation, the average throughput was 33.66 tokens per second. One token is approximately equivalent to 4 English characters, and 1,500 words correspond to around 2048 tokens [63]. Smart home control tasks require longer processing time, with an average execution time of 5402.62 milliseconds per task and a throughput of 12.77 tokens per second. Blockchain-related tasks had the highest execution time, averaging 8714.91 milliseconds per task, with a throughput of 12.52 tokens per second. Text generation typically requires less computational effort compared to smart home or blockchain tasks, where the model must perform more intricate operations, resulting in longer execution times. However, the overall performance remains within acceptable limits, with even the most complex blockchain tasks completed in under 9 seconds and simpler tasks executed in as little as 5 seconds.

Concurrency user request is also an important indicator of the LLM model's scalability [64]. In this study, we used Llamacpp for model deployment, which allows parallelization based on the model context length. For instance, a LLAMA 3 8B model with a context window is 4096 tokens deployed on a machine with one 48G L40/L40s GPU that can handle up to 16 concurrent requests [65]. Although the Llama 3 model we used supports a context length of up to 128k tokens, we limited it to 4096 tokens due to limited computational resources. For real-world deployment, especially with a larger user base, we can improve the scalability by opting for models with larger context lengths and running them on machines with greater GPU RAM capacity.

6.3. Data Security, Privacy, and Integrity

One of the primary concerns in permissionless blockchain systems is preserving users' confidentiality. The DAB-CPS system addresses this by leveraging Ethereum's pseudonymous structure, where user identities are protected through public-key cryptography [66]. This ensures that all actions, including voting, submitting proposals, and reserving spaces, are linked to pseudonymous public keys rather than personal information. Although transactions are publicly visible on the blockchain, the identities of participants remain anonymous and secure. In addition, all participants, including DAO members, building occupants, or system users, sign transactions using private keys. This guarantees that only authorized individuals can validate and execute the transactions. The combination of public-key cryptography and digital signatures enhances security, making stored records immutable and tamper-proof once recorded on the blockchain. This strengthens user privacy, ensuring that personal data remains protected.

Another important aspect of the system's security is the accessibility of transaction data. In the DAB-CPS system, governance proposals and user votes are intentionally made public to promote transparency. The number of governance tokens held by each DAO member is also publicly accessible, fostering accountability and trust within the community. This transparency encourages active participation, as members can verify actions and engage in governance based on reliable information. Additionally, the system ensures the availability of this data permanently, thereby maintaining data integrity and preserving trust throughout the governance process.

6.4. Methodology evaluation

Hevner et al. [41] present seven guidelines for evaluating methodological rigor and relevance in Design Science Research (DSR). The findings in Table 4 illustrate that the development process of the DAB-CPS framework and prototype is scientific.

Table 4. Evaluation of the methodology in accordance with DSR guidelines.

Guideline	Description

Design as an Artefact	This paper proposed the decentralized autonomous building cyber-physical system (DAB-CPS) framework and develop the corresponding prototype using different technical component including DAO and LLM-based AI agent and virtual assistant
Problem Relevance	The research addresses relevant problems and knowledge gaps identified through a literature review, including limited studies on autonomous building infrastructure, lack of research on decentralized governance of building operation, and the lack of open-source LLM application as well as DAO and AI integration in the smart building domain.
Design Evaluation	The methodology includes both quantitative and qualitative evaluations of the DAB-CPS framework including analysis on the system cost and scalability, methodology evaluation, as well as data security, privacy, and integrity. The system workability is also validated with six different scenarios. The results indicate that the prototype's performance meets acceptable standards.
Research Contributions	The research contributions can be summarized as follows: - Novel DAO and AI-based decentralized governance model for smart, operational, and financially autonomous infrastructure - Full-stack, open-source Dapp template for decentralized governance. - Integration of DAO and LLM-based AI system and digital building twin - Implementation and evaluation of the DAB-CPS prototype in the real-world settings.
Research Rigor	The research follows a structured DSR methodology with six clearly defined stages, from problem identification to communication of results. The prototype of the proposed DAB-CPS framework is validated and evaluated in real physical building to demonstrate its feasibility
Design as a Search Process	This study explored existing literature and industry practices to identify knowledge gaps in autonomous building research. The innovative DAB-CPS framework and prototype was develop using state of the art AI, digital twin and blockchain technologies.
Communication of Research	The implementation code base DAB-CPS prototype is publicly shared. Additionally, the research findings, prototypes design, development methodology, and evaluation results will be published in international academic journals.

6.5. Limitations

The DAB-CPS framework presents a novel approach to future smart and autonomous building infrastructures. However, despite its advantages, the framework is not without limitations. This section outlines key constraints related to the proposed system and its proof-of-concept implementation.

A primary constraint is the inherent volatility of the Ethereum cryptocurrency used for transactions within the system. This volatility introduces financial instability, complicating both the physical reservations and utility/expense payments for users and DAO members. This can lead to discrepancies between expected and actual costs, potentially deterring users from widespread adoption. To address this issue, future iterations of the framework could explore the integration of stablecoins, such as USDT or USDC [67], which offer more stable decentralized payment options by being pegged to reserve assets like the U.S. Dollar. Additionally, the reliance on smart appliances and smart plugs for energy meters instead of a fully integrated smart building automation system represents a limitation of the current implementation. Despite this constraint, these devices were suitable for the research objectives and effectively demonstrated the capabilities of the DAB-CPS framework in simulating a range of building operation management functionalities. Another significant limitation lies in the technical constraints preventing AI virtual assistants from directly executing blockchain-related tasks. For security reasons, the current system avoids the direct embedding of private keys onto the AI virtual assistant and necessitates manual signing and confirmation of transactions for each user request, which, to some extent, reduces the overall efficiency and increases system complexity. Future research should focus on developing a personalized AI system capable of automated blockchain task execution without security concerns. This could potentially involve the integration of zero-knowledge proofs [68] with the LLM, which could allow users to prove their identity to the AI system without revealing their private keys, thereby maintaining security while enabling more automated interactions.

6.6. Future outlooks

As per the authors' knowledge, this study represents the initial attempt to develop an integrative framework and prototype for autonomous building infrastructure that synergizes artificial intelligence, digital twin, and distributed ledger technology. The author believes that the DAB-CPS framework and its associated prototypes not only have the potential to significantly advance the current state of research and knowledge in autonomous buildings but could also contribute to future research on automation in smart communities and cities.

The framework's potential applications are not limited to building infrastructure. The decentralized governance platform could also be customized to govern civil infrastructure, where entire systems could be democratically controlled by DAO members and autonomously operated. This could revolutionize how we manage and interact with urban environments, from transportation networks to utility systems, fostering a new era of citizen participation and efficient resource management. In addition, LLMs play a crucial role in the proposed AI system, which is the backbone of this study. The current trend towards smaller and more efficient language models, as evidenced by Microsoft's Phi-3 [69], Meta's LLaMA 3.2 model [70] , and Google's Gemma-2 model [71], indicates that powerful AI systems will be able to effectively deploy on low-cost edge devices such as Raspberry Pi while offering impressive performance. This development could significantly advance research in smart cities and infrastructure by having advanced AI systems to be more accessible and have widespread deployment across urban environments. Furthermore, LLMs with multi-modal capabilities present an exciting opportunity for enhancing smart building functionalities. These advanced AI systems are capable of processing visual, auditory, and textual data, which could revolutionize tasks such as surveillance, emergency response, and safety detection. The contextual awareness of these models could significantly advance research in autonomous buildings, leading to more sophisticated and responsive urban environments.

7. Conclusion

This paper presents a novel Decentralized Autonomous Building Cyber-Physical System (DAB-CPS), an innovative, integrative framework for smart buildings, which is comprised of web3-based governance, artificial intelligence, digital building twin, facilities management, and building automation systems. The framework aims to serve as a blueprint for a self-governing, autonomous building infrastructure by leveraging blockchain technology, DAOs, and LLMs-powered building automation systems. The DAB-CPS framework is designed to create a financially self-sustaining building infrastructure capable of autonomously managing its operations, including generating revenue for its operational expense, allowing the building to self-sustain and self-managed in a decentralized manner.

The DAB-CPS framework comprises several key components. The decentralized governance platform, powered by DAO's governance, facilitates transparent decision-making and resource management. The space reservation system allows users to reserve physical space autonomously using blockchain technology. The digital twin component provides real-time visualization of both the reservation statuses and environmental conditions such as temperature, humidity, and occupancy. The large language-powered AI systems allow users to interact with the building through voice and text interfaces for blockchain and facility management-related tasks such as smart appliance control and blockchain transactions. The AI agent also powers the autonomous building operations by autonomously adjusting smart appliances such as lighting and HVAC based on occupancy and the baseline environmental comfort threshold to maintain optimal conditions for occupants. The resource and code implementation for these components is available on a GitHub repository under an open-source license, allowing for further development and application of this framework beyond autonomous building management.
In this study, the prototype of the DAB-CPS framework was conducted in a real-world building to validate its practical application. Evaluations of the system included analyses of cost efficiency, scalability of the AI and governance system, as well as data security, privacy, and system integrity. The workability of the DAB-CPS system was validated through six different scenarios, including user interactions with the space reservation portal, income and expense management handled by the DAO entity, proposal voting conducted by DAO members for building-related decisions, and the AI virtual assistant's performance in carrying out blockchain-related tasks and facility management operations, such as controlling smart appliances based on environmental data. The results from these evaluations demonstrated that the developed prototype system completed these operations and can potentially serve as the viable framework for autonomous building operation and management in building infrastructure.

CRediT authorship contribution statement

Reachsak Ly: Writing – review & editing, Writing – original draft, Visualization, Conceptualization.
Alireza Shojaei: Project administration, Supervision, Conceptualization, Methodology.

Declaration of Generative AI and AI-assisted technologies in the writing process.

During the preparation of this work, the author(s) used OpenAI GPT4 to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the research presented in this paper.

Data availability

The code is publicly available in a GitHub repository under an open-source license.

References

[1] R. McKenna, E. Merkel, and W. Fichtner, "Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects," *Applied Energy*, vol. 189, pp. 800–815, Mar. 2017, doi: 10.1016/j.apenergy.2016.03.062.
[2] K. Mason and S. Grijalva, "A review of reinforcement learning for autonomous building energy management," *Computers & Electrical Engineering*, vol. 78, pp. 300–312, 2019.
[3] T. Nilsson, A. Crabtree, J. Fischer, and B. Koleva, "Breaching the future: understanding human challenges of autonomous systems for the home," *Pers Ubiquit Comput*, vol. 23, no. 2, pp. 287–307, Apr. 2019, doi: 10.1007/s00779-019-01210-7.

[4] Z. Peng, X. Li, and F. Yan, “An adaptive deep learning model for smart home autonomous system,” in *2020 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS)*, IEEE, 2020, pp. 707–710.
[5] A. Sunyaev and A. Sunyaev, “Distributed ledger technology,” *Internet computing: Principles of distributed systems and emerging internet-based technologies*, pp. 265–299, 2020.
[6] S. Perera, S. Nanayakkara, M. N. N. Rodrigo, S. Senaratne, and R. Weinand, “Blockchain technology: Is it hype or real in the construction industry?,” *Journal of Industrial Information Integration*, 2020, doi: 10.1016/j.jii.2020.100125.
[7] S. Wang, W. Ding, J. Li, Y. Yuan, L. Ouyang, and F.-Y. Wang, “Decentralized Autonomous Organizations: Concept, Model, and Applications,” *IEEE Trans. Comput. Soc. Syst.*, vol. 6, no. 5, pp. 870–878, Oct. 2019, doi: 10.1109/TCSS.2019.2938190.
[8] H. Wang, J. Hunhevicz, and D. Hall, “What if properties are owned by no one or everyone? foundation of blockchain enabled engineered ownership,” presented at the 2022 European Conference on Computing in Construction, Jul. 2022. doi: 10.35490/EC3.2022.213.
[9] M. Singh and S. Kim, “Blockchain technology for decentralized autonomous organizations,” in *Advances in Computers*, vol. 115, Elsevier, 2019, pp. 115–140. doi: 10.1016/bs.adcom.2019.06.001.
[10] F.-J. “Fang-R. Chang and I. Johar, “Radicle Civics—Unconstituting Society,” in *Sacred Civics*, 1st ed., London: Routledge, 2022, pp. 226–242. doi: 10.4324/9781003199816-22.
[11] J. J. Hunhevicz, H. Wang, L. Hess, and D. M. Hall, “no1s1 - a blockchain-based DAO prototype for autonomous space,” presented at the 2021 European Conference on Computing in Construction, Jul. 2021, pp. 27–33. doi: 10.35490/EC3.2021.185.
[12] S. Wang, Y. Yuan, X. Wang, J. Li, R. Qin, and F.-Y. Wang, “An overview of smart contract: architecture, applications, and future trends,” presented at the 2018 IEEE Intelligent Vehicles Symposium (IV), IEEE, 2018, pp. 108–113.
[13] DeepDAO, “DAO Statistics,” DeepDAO. Accessed: Jun. 11, 2024. [Online]. Available: https://deepdao.io/organizations
[14] H. Altaleb and R. Zoltan, “Decentralized autonomous organizations review, importance, and applications,” in *2022 IEEE 26th International Conference on Intelligent Engineering Systems (INES)*, Georgioupolis Chania, Greece: IEEE, Aug. 2022, pp. 000121–000126. doi: 10.1109/INES56734.2022.9922656.
[15] C. Santana and L. Albareda, “Blockchain and the emergence of Decentralized Autonomous Organizations (DAOs): An integrative model and research agenda,” *Technol. Forecasting Social Change*, vol. 182, p. 121806, Sep. 2022, doi: 10.1016/j.techfore.2022.121806.
[16] O. Rikken, M. Janssen, and Z. Kwee, “The ins and outs of decentralized autonomous organizations (DAOs) unraveling the definitions, characteristics, and emerging developments of DAOs,” *Blockchain: Res. Appl.*, p. 100143, Jun. 2023, doi: 10.1016/j.bcra.2023.100143.
[17] M. Zichichi, M. Contu, S. Ferretti, and G. D’Angelo, “LikeStarter: a Smart-contract based Social DAO for Crowdfunding,” in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, Paris, France: IEEE, Apr. 2019, pp. 313–318. doi: 10.1109/INFCOMW.2019.8845133.
[18] S. Mateus and S. Sarkar, “Can Decentralized Autonomous Organizations (DAOs) Revolutionize Healthcare?,” *California Management Review*, vol. 65, no. 1, Jan. 2023.
[19] K. L. Page and A. Elmessiry, “Global Research Decentralized Autonomous Organization (GR-DAO): A DAO of Global Researchers,” in *Computer Science and Information Technology Trends*, Academy and Industry Research Collaboration Center (AIRCC), Oct. 2021, pp. 77–90. doi: 10.5121/csit.2021.111708.

[20] T. McConaghy, “AI DAOs, and Three Paths to Get There,” Medium. Accessed: Jun. 10, 2024. [Online]. Available: https://medium.com/@trentmc0/ai-daos-and-three-paths-to-get-there-cfa0a4cc37b8
[21] G. Benedict, C. Sullivan, and A. Gill, “Governance Challenges of AI-enabled Decentralized Autonomous Organizations: Toward a Research Agenda,” *ICIS 2022 Proceedings*, p. 1184, 2022.
[22] T. Revoredo, “Artificial Intelligence and DAOs: the perfect match?,” Medium. Accessed: Apr. 19, 2024. [Online]. Available: https://tatianarevoredo.medium.com/artificial-intelligence-and-daos-the-perfect-marriage-d84250d6bf3e
[23] Singularity DAO, “SingularityDAO,” Singularity DAO. Accessed: Dec. 25, 2022. [Online]. Available: https://www.singularitydao.ai
[24] C. Zhao, X. Dai, Y. Lv, J. Niu, and Y. Lin, “Decentralized Autonomous Operations and Organizations in TransVerse: Federated Intelligence for Smart Mobility,” *IEEE Trans. Syst. Man Cybern, Syst.*, pp. 1–11, 2022, doi: 10.1109/TSMC.2022.3228914.
[25] Y. Lin, W. Hu, X. Chen, S. Li, and F.-Y. Wang, “City 5.0: Towards Spatial Symbiotic Intelligence via DAOs and Parallel Systems,” *IEEE Trans. Intell. Veh.*, vol. 8, no. 7, pp. 3767–3770, Jul. 2023, doi: 10.1109/TIV.2023.3298903.
[26] W. Ding *et al.*, “A Novel Approach for Predictable Governance of Decentralized Autonomous Organizations Based on Parallel Intelligence,” *IEEE Trans. Syst. Man Cybern, Syst.*, pp. 1–12, 2022, doi: 10.1109/TSMC.2022.3224250.
[27] A. R. Yadlapalli, N. Mohite, V. Pawar, and S. Sachdeva, “Artificially Intelligent Decentralized Autonomous Organization,” in *2019 4th International Conference on Information Systems and Computer Networks (ISCON)*, Mathura, India: IEEE, Nov. 2019, pp. 667–671. doi: 10.1109/ISCON47742.2019.9036152.
[28] C. Guo, Y. Dou, T. Bai, X. Dai, C. Wang, and Y. Wen, “ArtVerse: A Paradigm for Parallel Human–Machine Collaborative Painting Creation in Metaverses,” *IEEE Trans. Syst. Man Cybern, Syst.*, pp. 1–9, 2023, doi: 10.1109/TSMC.2022.3230406.
[29] S. A. Prieto, E. T. Mengiste, and B. García De Soto, “Investigating the Use of ChatGPT for the Scheduling of Construction Projects,” *Buildings*, vol. 13, no. 4, p. 857, Mar. 2023, doi: 10.3390/buildings13040857.
[30] H. You, Y. Ye, T. Zhou, Q. Zhu, and J. Du, “Robot-Enabled Construction Assembly with Automated Sequence Planning Based on ChatGPT: RoboGPT,” *Buildings*, vol. 13, no. 7, p. 1772, Jul. 2023, doi: 10.3390/buildings13071772.
[31] H. Chen *et al.*, “Augmented reality, deep learning and vision-language query system for construction worker safety,” *Automation in Construction*, vol. 157, p. 105158, Jan. 2024, doi: 10.1016/j.autcon.2023.105158.
[32] S. M. J. Uddin, A. Albert, A. Ovid, and A. Alsharef, “Leveraging ChatGPT to Aid Construction Hazard Recognition and Support Safety Education and Training,” *Sustainability*, vol. 15, no. 9, p. 7121, Apr. 2023, doi: 10.3390/su15097121.
[33] J. Zheng and M. Fischer, “Dynamic prompt-based virtual assistant framework for BIM information search,” *Automation in Construction*, vol. 155, p. 105067, Nov. 2023, doi: 10.1016/j.autcon.2023.105067.
[34] A. Saka *et al.*, “GPT models in construction industry: Opportunities, limitations, and a use case validation,” *Developments in the Built Environment*, vol. 17, p. 100300, Mar. 2024, doi: 10.1016/j.dibe.2023.100300.
[35] T. McConaghy, “Nature 2.0,” Medium. Accessed: Jun. 10, 2024. [Online]. Available: https://blog.oceanprotocol.com/nature-2-0-27bdf8238071
[36] CityDAO, “CityDAO.” Accessed: Nov. 27, 2022. [Online]. Available: https://www.citydao.io/
[37] P. Seidler, P. Kolling, and M. Hampshire, “terra0.” Accessed: Jul. 27, 2023. [Online]. Available: https://terra0.org/assets/pdf/terra0_white_paper_2016.pdf

[38] Z. Ye, M. Yin, L. Tang, and H. Jiang, “Cup-of-Water Theory: A Review on the Interaction of BIM, IoT and Blockchain During the Whole Building Lifecycle,” in *34th International Symposium on Automation and Robotics in Construction*, Taipei, Taiwan, Jul. 2018. doi: 10.22260/ISARC2018/0066.
[39] T. Dounas, D. Lombardi, J. Vele, and S. Prokop, “A crypto-twin framework for the aec industry: enabling digital twins with blockchain technologies.,” *Architecture and planning journal*, vol. 28, no. 3, 2022.
[40] R. Ly, A. Shojaei, and H. Naderi, “DT-DAO: Digital Twin and Blockchain-Based DAO Integration Framework for Smart Building Facility Management,” in *Construction Research Congress 2024*, Des Moines, Iowa: American Society of Civil Engineers, Mar. 2024, pp. 796–805. doi: 10.1061/9780784485262.081.
[41] Hevner, March, Park, and Ram, “Design Science in Information Systems Research,” *MIS Quarterly*, vol. 28, no. 1, p. 75, 2004, doi: 10.2307/25148625.
[42] Y. Xu *et al.*, “A blockchain-based framework for carbon management towards construction material and product certification,” *Advanced Engineering Informatics*, vol. 61, p. 102242, Aug. 2024, doi: 10.1016/j.aei.2023.102242.
[43] J. C. P. Cheng, H. Liu, V. J. L. Gan, M. Das, X. Tao, and S. Zhou, “Construction cost management using blockchain and encryption,” *Automation in Construction*, vol. 152, p. 104841, Aug. 2023, doi: 10.1016/j.autcon.2023.104841.
[44] F. Elghaish, J. K. Chauhan, S. Matarneh, F. Pour Rahimian, and M. R. Hosseini, “Artificial intelligence-based voice assistant for BIM data management,” *Automation in Construction*, vol. 140, p. 104320, Aug. 2022, doi: 10.1016/j.autcon.2022.104320.
[45] G. L. Geerts, “A design science research methodology and its application to accounting information systems research,” *International Journal of Accounting Information Systems*, vol. 12, no. 2, pp. 142–151, Jun. 2011, doi: 10.1016/j.accinf.2011.02.004.
[46] P. Cuffe, “The role of the erc-20 token standard in a financial revolution: the case of initial coin offerings,” in *IEC-IEEE-KATS Academic Challenge*, IEC-IEEE-KATS, 2018.
[47] Y. Fan, L. Zhang, R. Wang, and M. A. Imran, “Insight into Voting in DAOs: Conceptual Analysis and A Proposal for Evaluation Framework,” *IEEE Network*, pp. 1–8, 2023, doi: 10.1109/MNET.137.2200561.
[48] W. Huang *et al.*, “How Good Are Low-bit Quantized LLaMA3 Models? An Empirical Study,” *arXiv preprint arXiv:2404.14047*, 2024.
[49] G. Gerganov, *ggerganov/llama.cpp*. (Jul. 04, 2024). C++. Accessed: Jul. 04, 2024. [Online]. Available: https://github.com/ggerganov/llama.cpp
[50] Y. Zhao *et al.*, “Atom: Low-bit quantization for efficient and accurate llm serving,” *Proceedings of Machine Learning and Systems*, vol. 6, pp. 196–209, 2024.
[51] R. Ly, *reachsak/DA-BCPS*. (Sep. 08, 2024). Accessed: Sep. 27, 2024. [Online]. Available: https://github.com/reachsak/DA-BCPS
[52] C. Dannen and C. Dannen, “Solidity programming,” *Introducing Ethereum and Solidity: Foundations of Cryptocurrency and Blockchain Programming for Beginners*, pp. 69–88, 2017.
[53] “Ethereum Blockchain Whitepaper,” ethereum.org. Accessed: Mar. 14, 2024. [Online]. Available: https://ethereum.org/en/whitepaper/
[54] “OpenZepplin Governance.” Accessed: Mar. 13, 2024. [Online]. Available: https://docs.openzeppelin.com/contracts/4.x/api/governance
[55] A. Dubey *et al.*, “The Llama 3 Herd of Models,” Aug. 15, 2024, *arXiv*: arXiv:2407.21783. Accessed: Sep. 16, 2024. [Online]. Available: http://arxiv.org/abs/2407.21783
[56] P. V. K. V. Prasad, N. V. Krishna, and T. P. Jacob, “AI CHATBOT using Web Speech API and Node.Js,” in *2022 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS)*, Erode, India: IEEE, Apr. 2022, pp. 360–362. doi: 10.1109/ICSCDS53736.2022.9760803.

[57] X. Tao *et al.*, “Enhancing BIM security in emergency construction projects using lightweight blockchain-as-a-service,” *Automation in Construction*, vol. 150, p. 104846, Jun. 2023, doi: 10.1016/j.autcon.2023.104846.

[58] H. Naderi, A. Shojaei, and R. Ly, “Autonomous construction safety incentive mechanism using blockchain-enabled tokens and vision-based techniques,” *Automation in Construction*, vol. 153, p. 104959, Sep. 2023, doi: 10.1016/j.autcon.2023.104959.

[59] X. Tao, M. Das, Y. Liu, and J. C. P. Cheng, “Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design,” *Automation in Construction*, vol. 130, p. 103851, Oct. 2021, doi: 10.1016/j.autcon.2021.103851.

[60] A. Chauhan, O. P. Malviya, M. Verma, and T. S. Mor, “Blockchain and scalability,” presented at the 2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C), IEEE, 2018, pp. 122–128.

[61] A. Abrol, “Solana vs Polygon vs Ethereum - Blockchain Council.” Accessed: Sep. 27, 2024. [Online]. Available: https://www.blockchain-council.org/blockchain/solana-vs-polygon-vs-ethereum/

[62] S. Bhujel and Y. Rahulamathavan, “A Survey: Security, Transparency, and Scalability Issues of NFT’s and Its Marketplaces,” *Sensors*, vol. 22, no. 22, p. 8833, Nov. 2022, doi: 10.3390/s22228833.

[63] OpenAI, “What are tokens and how to count them?” Accessed: Sep. 23, 2024. [Online]. Available: https://help.openai.com/en/articles/4936856-what-are-tokens-and-how-to-count-them

[64] Y. Yao *et al.*, “ScaleLLM: A Resource-Frugal LLM Serving Framework by Optimizing End-to-End Efficiency,” Sep. 10, 2024, *arXiv*: arXiv:2408.00008. Accessed: Sep. 27, 2024. [Online]. Available: http://arxiv.org/abs/2408.00008

[65] Y. Fu, “LLM Inference Sizing and Performance Guidance,” VMware Cloud Foundation (VCF) Blog. Accessed: Sep. 27, 2024. [Online]. Available: https://blogs.vmware.com/cloud-foundation/2024/09/25/llm-inference-sizing-and-performance-guidance/

[66] W. Wang *et al.*, “A Survey on Consensus Mechanisms and Mining Strategy Management in Blockchain Networks,” *IEEE Access*, vol. 7, pp. 22328–22370, 2019, doi: 10.1109/ACCESS.2019.2896108.

[67] B. N. Thanh, T. N. V. Hong, H. Pham, T. N. Cong, and T. P. T. Anh, “Are the stabilities of stablecoins connected?,” *Journal of Industrial and Business Economics*, vol. 50, no. 3, pp. 515–525, 2023.

[68] X. Yang and W. Li, “A zero-knowledge-proof-based digital identity management scheme in blockchain,” *Computers & Security*, vol. 99, p. 102050, Dec. 2020, doi: 10.1016/j.cose.2020.102050.

[69] M. Abdin *et al.*, “Phi-3 Technical Report: A Highly Capable Language Model Locally on Your Phone,” Aug. 30, 2024, *arXiv*: arXiv:2404.14219. Accessed: Sep. 27, 2024. [Online]. Available: http://arxiv.org/abs/2404.14219

[70] Meta, “Llama 3.2: Revolutionizing edge AI and vision with open, customizable models,” Meta AI. Accessed: Sep. 27, 2024. [Online]. Available: https://ai.meta.com/blog/llama-3-2-connect-2024-vision-edge-mobile-devices/

[71] Gemma Team *et al.*, “Gemma 2: Improving Open Language Models at a Practical Size,” Aug. 02, 2024, *arXiv*: arXiv:2408.00118. Accessed: Sep. 27, 2024. [Online]. Available: http://arxiv.org/abs/2408.00118

DT-DAO: Digital Twin and Blockchain-Based DAO Integration Framework for Smart Building Facility Management

Reachsak Ly[1]; Alireza Shojaei, Ph.D.[2]; and Hossein Naderi[3]

[1]Ph.D. Student, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ. ORCID: https://orcid.org/0000-0003-0332-1312. Email: reachsak@vt.edu
[2]Assistant Professor, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ. (corresponding author). ORCID: https://orcid.org/0000-0003-3970-0541.
Email: shojaei@vt.edu
[3]Ph.D. Student, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ. ORCID: https://orcid.org/0000-0002-6625-1326. Email: hnaderi@vt.edu

ABSTRACT

Digital Twin (DT) technology provides a comprehensive virtual representation and dynamic mirror of the physical infrastructure, which is invaluable for Facility Management (FM) applications. However, its operations and sensitive data are managed by the centralized infrastructure, which is relatively vulnerable to being compromised. To address these problems, this paper proposes DT-DAO, a conceptual blockchain-based framework integrating Digital Twin (DT) and Decentralized Autonomous Organization (DAO). Given the immutable nature of blockchain technology, the DT-DAO framework can strengthen the security and resilience of the DT. Moreover, taking advantage of the DAO's decentralized governance mechanism, task automation capabilities, and the real-time sensory data retrieved from the physical assets, DT-DAO can also be used to create an autonomous physical asset (e.g., smart buildings, infrastructure) that can have its operations run automatically and autonomously as predefined in the smart contract. In addition, this paper also provides potential use cases of DT-DAO in smart building FM.

INTRODUCTION

A digital twin (DT) is denoted as a virtual duplicate of a tangible entity that receives continuous updates with live information obtained from different sources including sensors and tracking systems (Sacks et al. 2020). One particular area where the DT is extensively used in the Architecture, Engineering, Construction, and Operation (AECO) industry is facility management (FM) of built infrastructure. In smart built infrastructure, such as smart buildings, different techniques can be used in conjunction with DT to monitor and maximize building performance, minimize energy usage, improve occupant comfort, and reduce costs (Puķīte and Geipele 2017). Automation is another fundamental feature of a smart building that can be achieved by a combination of technologies such as building management systems, sensors, actuators, and the Internet of Things (IoT) (Havard et al. 2018). The digital representation of the building, data from of physical building's condition, and the automation of operations within the buildings are interconnected. Building condition and operation-related data can be collected via IoT sensors or other data acquisition techniques, which will be later analyzed by other advanced technology (e.g., machine learning) before being used for updating the DT and triggering the automation of specific tasks within a building (Ye et al. 2018).

However, the existing communication protocols for IoT devices and data storage are mainly based on the centralized system which is exposed to cyber threats. Morenas et al. (2020) describe the potential loophole within the traditional building automation services and IoT communication protocols such as MQTT, KNX, BACnet, and Zigbee. The collected IoT data can be susceptible to data breaches, tempering, forgery, and cyber-attacks such as spoofing, information eavesdropping, and denial of service attacks (Sharma and Park 2018). Similarly, DT technology is also vulnerable to several security threats which could lead to disruption of the operation, resulting in productivity loss. In addition, DT -related and collected sensor data are stored on a centralized database which is vulnerable to data loss caused by system failure or data breaches caused by cyber-attacks (Alcaraz and Lopez 2022).

Over the years, several research works have focused on leveraging blockchain technology as a potential solution to address these problems. For instance, multiple studies have proposed the use of blockchain in the application of distributed access control for IoT devices to reduce the centralized nature of the access management (Novo 2018; Zyskind et al. 2015). In another study, the authors implemented the blockchain-based IoT communication method and provide a comparison to the traditional IoT communication protocol (Fakhri and Mutijarsa 2018). In addition, Hasan et al. (2022) proposed a framework for IoT data streaming by using the Ethereum blockchain and the Interplanetary files system (IPFS). Different studies have also investigated the integration of DT and blockchain technology in the construction industry. For instance, EtherTwin aims to facilitate the secure storage of DT data with blockchain by integrating the Ethereum blockchain and the distributed hash table (DHT) Swarm to provide a decentralized solution for participants from different DT lifecycles to create, modify, upload, and store DT related document (Putz et al. 2021). Additionally, in this study (Lee et al. 2021), the authors developed a DT and blockchain-based, decentralized information-sharing framework and compliance checking application in a construction project with the use of GPS sensor data. Ye et al. (2018) have introduced the concept of an autonomous building maintenance system where the building is expected to self-operate with the encoded rules in smart contracts. The concept of an autonomous entity was further developed with the No1s1 project (Hunhevicz et al. 2021) whereas the authors have developed a prototype of a self-governing meditation space based on blockchain technology. However, these works have yet to incorporate DT into their systems. Dounas et al. (2022) proposed the concept of DT and blockchain integrated system for the AEC industry which is quite broad and lacks specificity for building FM domain.

The aforementioned research works have all recognized the significance of IoT data security, decentralized storage of IoT sensors and DT-related data, and the potential benefits of blockchain and DT integrations in the AEC industry. However, the existing implementations haven't accommodated the capabilities of decentralized and autonomous task automation, and secure real-time data transmission within the DT and blockchain-integrated system in FM. This is the gap that our proposed framework seeks to address. DT-DAO aims to incorporate IoT, DT, and blockchain technology to enable real-time monitoring of assets, autonomous automation, and decentralized governance capabilities of operational tasks in FM of the physical building twin. By using smart contracts and decentralized oracles networks, real-time IoT sensory data will be collected and stored in decentralized storage before feeding into the DT in real time from the blockchain. Automated response or task automation in FM can be configured based on these sensory data values and custom thresholds in the deployed smart contract. Also, DAO offers a novel, distributed governance mechanism which will allow stakeholders to perform decision-making and management of those tasks in a decentralized manner.

BACKGROUND

Digital Twins. DT can be described as a synchronized and constantly updating digital replica of physical assets or systems (Borth et al. 2019). The definitions of DT depend on its applications in different industry contexts. In the field of construction, DT can be referred to as the digital copy of a physical infrastructure created by using digital technologies, such as 3D modeling, data analytics, and simulation. DT contains both static and dynamic data about its corresponding physical asset in different project phases including its design, construction, and operation and maintenance. Applications of DT in built infrastructure include construction project simulation, infrastructure performance and assets monitoring, energy management, predictive maintenance, and FM (Opoku et al. 2021).

Blockchain technology. Blockchain (BC) is a digital public ledger that has all its data documented and stored in a transparent, secure, tamper-evident, and tamper-resistant manner in the decentralized network. In a blockchain database information is organized into blocks which are interconnected to form a chain. Fundamental elements of Blockchain technology (BTC) encompass distributed ledger technology (DLT), consensus mechanism, and cryptography-related technology such as asymmetric key cryptography, cryptographic hash function, and Merkle tree (Tasca and Thanabalasingham 2017). The fundamental objective of blockchain technology and DLT is to facilitate interactions between users without requiring mutual trust or the involvement of any centralized authority. Cryptography technologies are employed in blockchain to maintain the security, integrity, and immutability of the ledger. Also, the consensus mechanism serves to guarantee the agreement between all nodes on the current states of the system thereby maintaining the network's integrity and immutability. In addition, to extend the utility of blockchain beyond the financial industry to other sectors, additional applications such as tokens, smart contracts, and decentralized autonomous organizations have also been introduced.

***Smart contract*.** Smart contracts are computer-programmed agreements with their rules incorporated in an If/Then format, commonly known as the 'code-is-law' rules (Lessig 2000). Smart contract leverages the infrastructure and characteristics of blockchain to expand its use cases beyond cryptocurrency transactions by offering self-enforcing and secure task execution capabilities based on a decentralized consensus. Smart contracts can leverage real-world data for automatic execution or trigger certain actions on the blockchain. This information or third-party data is referred to as oracle (Al-Breiki et al. 2020), a bridge for connecting the outside world and blockchain. This data can include anything, from weather data, and cryptocurrency exchange information to the Internet of Things sensor data.

Decentralized autonomous organization (DAO). DAO is a digit entity running on a blockchain network with its fundamental operations adhered to rules written in smart contract code. DAO is a community-based body that operates transparently and autonomously without any central authority. The three fundamental characteristics of DAO are decentralization, autonomy, and automation (Wang et al. 2019). The main objective of DAO is to decentralize the organization's and entities' traditional management systems by providing more distributed and democratic decision-making mechanisms and transparent access to any operational activities and records. This can facilitate DAO members or stakeholders in working toward common goals and interests. There has been a handful of DAO implementations in built environments including, transportation, smart governance, design, smart cities, etc.

PROPOSED FRAMEWORK

DT-DAO framework. This section presents the proposed structure of the DT-DAO framework. As illustrated in Figure 1, the proposed framework is constructed by six different layers, namely, physical, basic technology, governance, treasury management, smart contract, and the application layer.

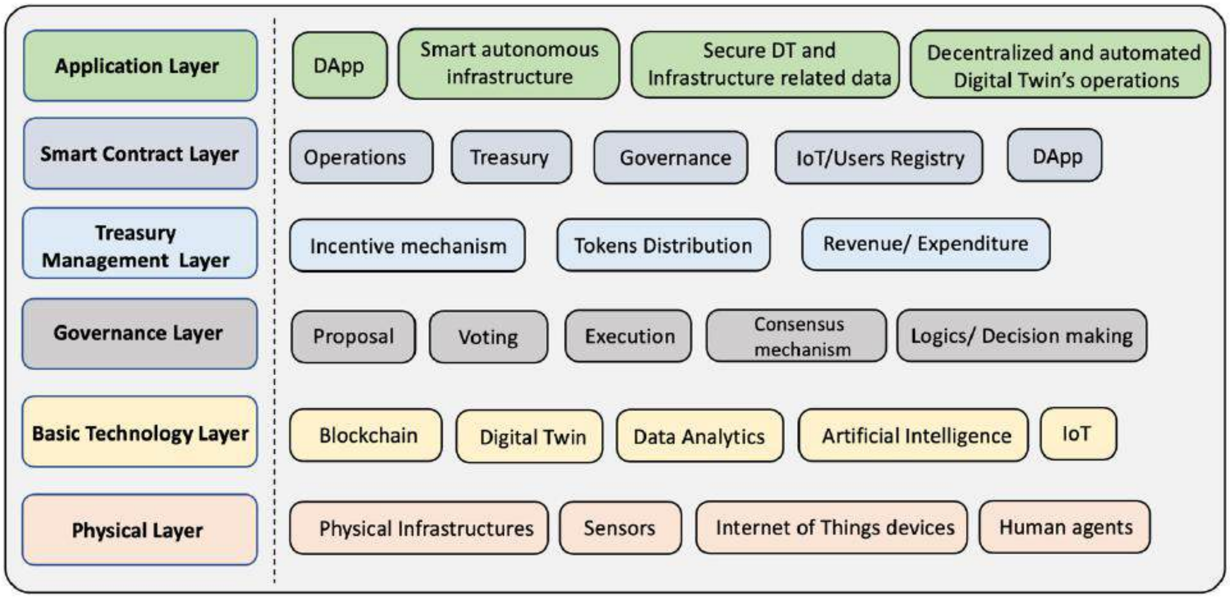


Figure 1. Organization Framework of DT-DAO.

Operation-wise, the DT-DAO framework is composed of three main modules, the physical world component and the on-chain and off-chain operation component in the cyber world. The interaction between different components within the DT-DAO framework is shown in Figure 2. The physical world includes human components such as users, administrators, and stakeholders, and their respective physical entities including smart buildings and other infrastructures. The cyber aspect of the framework comprises the on-chain and off-chain operations. The off-chain operation mainly represents the digital twinning process of the physical infrastructure, starting from data acquisition, and data/model integration, to the DT service layer and the data representing the condition of the corresponding physical twin. The on-chain operation aspect includes the DAO modules, data storage components, data transmission mechanisms, and other blockchain-related smart contracts and operations. The details of the six distinct layers and the interconnectivity between various components within them are discussed below.

Physical layer. The physical layer encapsulates the related physical entities aspect of the framework which includes physical assets (e.g., smart buildings), participating humans (users, physical asset's owner, stakeholders, occupants, administrative staff, etc.), and the data acquisition hardware such as Internet of thing's devices, sensors, reality capture technologies and other data collecting equipment. There are two different groups of participating human agents in this layer, user and administrative personnel. The former, as the name suggested, utilizes the services and decentralized application provided by the DT and DAO framework while the latter manages both the operations of the physical twin and DT using DAO's governing mechanism.

Further details on this are discussed in the governance layer section. Depending on the nature and types of the physical assets (residential building, educational building, campus building, etc.), the users and administrator and the corresponding services provided also vary accordingly.

Data acquisition is one of the fundamental tasks in this layer as well as in creating DT. The common source for data collection includes sensors (e.g., temperature, humidity, pressure, motion, light, gas sensors, etc.), Internet of Things devices, Computer-Aided Design (e.g., BIM models), contactless information collection methods (e.g., RFID and computer vison-based technique, etc.), historical data (maintenance records, inspection reports, etc.). Crucial information can be extracted from these data including the space occupancy rate, electricity and water usage, light, audio, and surrounding environment-related information, operation & maintenance, and emergency information (Lu et al. 2020).

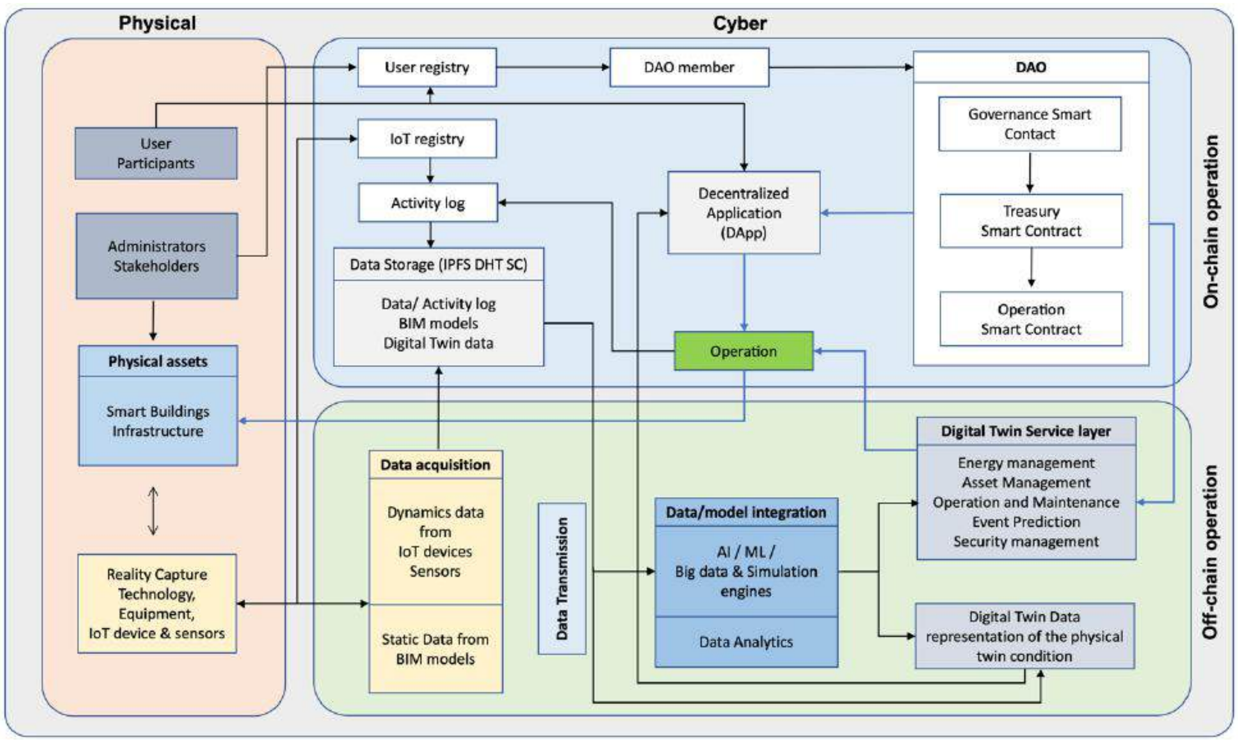


Figure 2. DT-DAO Framework Architecture.

Basic technology layer. This layer encapsulates various fundamental technologies associated with the DT-DAO framework e.g., Blockchain, Digital Twin, Artificial Intelligence, Data Analytics, Internet of Things (IoT), and other technologies. DAO's most significant characteristics are decentralization, autonomy, and automation. Blockchain technology serves as the backbone component of DAO in manifesting its functions. Blockchain's consensus mechanism ensures that all nodes in the decentralized system agree on the legitimacy and modification of the system. In addition, a smart contract is encoded with rules and operational tasks and will be self-executed when the predetermined criteria are satisfied.

DT-related operations such as data acquisition, data/model integration, data transmission, and manifested service are the key components in the DT-DAO framework. IoT-related sensors and devices play vital roles in gathering live data from the physical twin's operation. Upon the data acquisition stage, several data transmission techniques (REST API, decentralized oracle network) could be implemented to transfer the obtained data onto the decentralized storage on chain. The data can be called from the blockchain and fed into the DT in real-time. Also, the enormous amounts of historical data gathered from physical systems can be analyzed using machine learning algorithms which can make possible the AI decision and prediction support system such as predictive maintenance, real-time monitoring, energy usage, and performance optimization. Data analytics can extract patterns, derive deeper insight and detect anomalies and potential issues in the physical infrastructure's operations.

Governance layer. The governance layer comprises all relevant on and off-chain governance-associated rules, roadmap, and logic that control the operations within the DT-DAO framework. The main purpose of on-chain governance is to establish, modify and maintain the consensus within smart contracts. On-chain governance component includes the DAO's proposal submission and voting mechanism, decision-making, execution, determination of governance structure (organization structure), smart contract consensus mechanism, dispute resolution, etc. In addition, the user's registry and authentication and registration of physical assets' embedded IoT devices and sensors to the blockchain network are also under the on-chain management. Given the current DAO technological limitation, off-chain collaboration tools (e.g. messaging platform) are often used for communication, coordination, and consensus facilitation compared to the on-chain counterpart (Wang et al. 2019). In addition, in the physical world, there are also certain levels of governance on the assets with the interaction between human actors to the physical assets.

Treasury Management Layer. DAO's treasury can be referred to as the pool of funds used to support the DAO's operations, growth, and future development. There are three main different aspects of treasury management in the DT-DAO framework namely, incentive mechanism, tokens distribution, and revenue and expenditure management. DAO's tokens are the cryptocurrency tokens issued by the DAO at the launching stage which represent the ownership and decision-making power of the organization. Different token distribution models, circulation, and other settings can be adjusted and adapted corresponding to each type of DAO. The incentive mechanism motivates members to participate in governance activities and contribute to the growth and cause of DAO. Incentive mechanism comes in different form including tokens reward, staking, and reputation system. For instance, in the reputation-based DAO, reputation will be rewarded corresponding to the level of activeness and contribution of members to the DAO. In addition, in the case of the DT-DAO context where physical entities are an integral part of the system, DAO revenue-generated activities should heavily rely on the services offered by DAO-based building infrastructure.

Smart contract layer: Smart contract is the backbone of DAO. This layer is comprised of multiple smart contracts responsible for managing DAO's general operations within the systems, authentication, and transaction mechanism. This includes the operational, treasury, governance, IoT, and user authentication smart contracts. The number and types of smart contracts and their level of detail might vary depending on the complexity and type of smart buildings and the scope of each project. This section provides a set of fundamental contracts for the framework. The operation smart contract controls the activities of the DT tasks and the automation of the operations in the physical infrastructure. For instance, smart contracts can be used in automation, control access (Yang et al. 2022), and automation of smart cities' control systems (Pradhan and Singh 2021). The smart contract is also an integral component within the use of blockchain technology in DT-associated operations such as data acquisition, data sharing (Dietz et al. 2019), and information management (Putz et al. 2021). The treasury smart contract handles DAO's incentive mechanism, revenue, and expenditure. This contract determines how the DAO-based physical entities can get paid for its provided service to its users and manage the expenditure of its corresponding operation cost. The IoT registry smart contract aims to validate the legitimacy of IoT devices to be used in the on-chain operation. Similarly, the user registry smart contract is responsible for authenticating the participant identity (users, administrative staff, etc.). Operations in the framework are recorded in the activity log before being uploaded to the IPFS-powered decentralized storage system. Governance smart contract determines the configuration of logic and decision-making in the system which handles the on-chain proposal submission, voting, executions, and DAO's rules and regulation updates. It also regulates how various smart contracts in the framework are connected and react to the trigger events in one another. As a result, this will also trigger a corresponding reaction from the physical assets based on the written rules in the smart contract.

Application layer. This layer encapsulated the application and main features of the DT-DAO framework. These include a DAO-based building automation system, decentralized data storage for DT and smart infrastructure's related data, a secure data communication system between DT and physical sensors and integration, and DT and DAO integrated decentralized application for service. The potential use cases and implementation of DT-DAO in smart building FM will be discussed in detail in the next section.

POTENTIAL USE CASES

One of the possible applications of this framework is autonomous building infrastructure with self-governing FM capability, a concept that could potentially transform the way buildings and other civil infrastructure are managed and operated (see Figure 3-a). In this scenario, DAO can be programmed to access DT data to monitor building performance, energy and security system, and other infrastructure management-related platforms. By doing so, a DAO can be deployed to govern different aspects of the physical asset's operations, such as daily operation automation, maintenance, repairs, security, and energy optimization (Ye et al. 2018). The embedded IoT devices and sensors provided live data that will be used as the oracle and fed into the blockchain which will enable smart contracts to execute any specific task given the predetermined condition or threshold are met. Physical infrastructure equipment/facilities will then react to the smart contract feedback and perform corresponding changes. For instance, DAO's smart contracts could be used for automatic lighting and HVAC control where the equipment will adjust itself based on occupancy levels, and weather conditions, thereby optimizing energy usage, which would reduce energy consumption, and costs and foster sustainability. These functions/reactions can be more expansive and complex and not limited to the tasks mentioned in the DT service layer in Figure 2. Also, DAO can be used in conjunction with IoT systems for maintenance purposes. As an example, in case of the building's elevator breakdown, the sensor will report detecting the damage and report the information back to the blockchain and DAO. Based on the predetermined smart contract, DAO might have multiple responses such as contacting maintenance personnel, purchasing replacement units, etc.

Besides, DAO can be integrated with DT, and IoT for real-time asset monitoring applications (see Figure 3-b). For example, in the event of the detection of early sign failure in any building component by the DT component, DAO will be notified by the real-time sensor data and necessary predictive maintenance measures will be activated to prevent further damage. In addition, occupants can also report maintenance issues or request a work order/service through Decentralized Application (DApp). Moreover, decentralized oracles network and IPFS are employed to retrieve and store the collected sensor data by enabling automatic data uploads from the IoT device to the DT system and IPFS server (Garg 2022). Therefore, DT will be fed with the real-time sensor data directly from the blockchain which will guarantee the integrity and security of DT and its data.

Additionally, with the autonomous, self-supported FM capability provided by DT-DAO, different kinds of smart buildings can provide users/occupants with value and services through DApp (see Figure 3-c). DApp offers a user-friendly graphical interface which in this case could enable users to access the live representation of the physical twin, gather data and insight from DT and interact with the physical infrastructure service and blockchain. For instance, in a commercial building, a DAO-based retail space can generate its revenue by leasing itself to the users and making profits after paying back the operational cost. DT of the physical space and related real-time data can also be viewed from the DApp by the user before reserving. Similarly, in an educational building, the occupancy and indoor environment-related data of a conference and study room can be detected by the installed IoT sensors before updating the DT. By using DT-DAO integrated DApp, students and faculty can view the live condition of the room and reserve the space. Also, users can be incentivized for their contributions and rewarded by the DAO system. For example, tenants can be incentivized to engage in energy-saving efforts by reducing energy consumption during peak hours. Users can also contribute by providing feedback and personal data in an effort of improving the DAO system and more efficient digit twin.

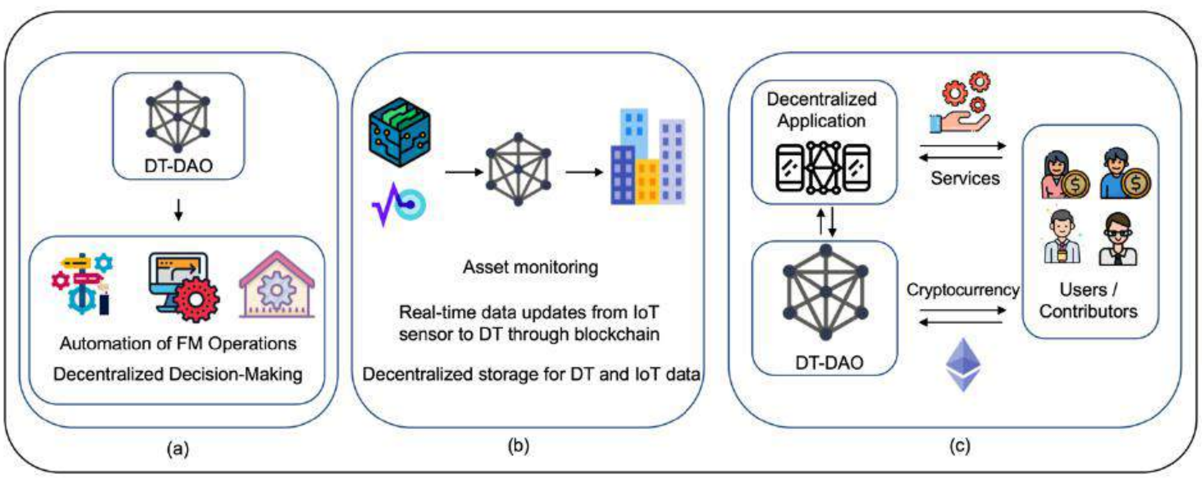


Figure 3. Potential use cases of DT-DAO framework.

CONCLUSION AND FUTURE WORK

This study proposed DT-DAO, a conceptual integration framework that incorporates the Internet of Things, Digital twin, and decentralized autonomous organization to enhance the cybersecurity and integrity of DT and IoT-related data as well as provide the decentralized governance and automation capabilities of FM-related operations within smart buildings. This integration framework can also serve as the reference point in the development of future autonomous physical entities. We described the proposed six layers framework and their related operations in detail and provide the prospective use cases of the DT-DAO framework in the context of implementing autonomous built infrastructure. The research on the technical aspect of DAO is still in its infancy stages. Future research needs to explore the essentials of the DAO and DT integrations, DAO-based physical entities, organizational models, governance structure, and further practical use cases. Another important area of future research is to focus on the implementation strategies and the related technical challenges for the DAO-based autonomous infrastructure and DT and DAO integration and to broaden the scope of the DT-DAO framework beyond the facility management application to the entire construction life cycle.

REFERENCES

Al-Breiki, H., Rehman, M. H. U., Salah, K., and Svetinovic, D. 2020. Trustworthy Blockchain Oracles: Review, Comparison, and Open Research Challenges. *IEEE Access* 8, 85675–85685.

Alcaraz, C., and Lopez, J. 2022. Digital Twin: A Comprehensive Survey of Security Threats. *IEEE Commun. Surv. Tutorials* 24, 1475–1503.

Borth, M., Verriet, J., and Muller, G. 2019. Digital Twin Strategies for SoS 4 Challenges and 4 Architecture Setups for Digital Twins of SoS, in: *2019 14th Annual Conference System of Systems Engineering (SoSE)*. IEEE, Anchorage, AK, USA, pp. 164–169.

de las Morenas, J., da Silva, C. M., Funchal, G. S., Melo, V., Vallim, M., and Leitao, P. 2020. Security Experiences in IoT based applications for Building and Factory Automation, in: *2020 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, Buenos Aires, Argentina, pp. 322–327.

Dietz, M., Putz, B., and Pernul, G. 2019. A distributed ledger approach to digital twin secure data sharing, in: *Data and Applications Security and Privacy XXXIII: 33rd Annual IFIP WG 11.3 Conference, DBSec 2019*, Charleston, SC, USA, July 15–17, 2019, Proceedings 33. Springer, pp. 281–300.

Dounas, T., Lombardi, D., Vele, J., and Prokop, S. 2022. A crypto-twin framework for the aec industry: enabling digital twins with blockchain technologies. *Architecture and planning journal* 28.

Fakhri, D., and Mutijarsa, K. 2018. Secure IoT Communication using Blockchain Technology, in: *2018 International Symposium on Electronics and Smart Devices (ISESD)*. Presented at the 2018 International Symposium on Electronics and Smart Devices (ISESD), IEEE, Bandung, pp. 1–6.

Garg, R. 2022. Decentralized transaction mechanism based on smart contracts. *Presented at the 3rd International Conference on Blockchain and IoT*, Sydney Australia.

Hasan, H. R., Salah, K., Yaqoob, I., Jayaraman, R., Pesic, S., and Omar, M. 2022. Trustworthy IoT Data Streaming Using Blockchain and IPFS. *IEEE Access* 10, 17707–17721.

Havard, N., McGrath, S., Flanagan, C., and MacNamee, C. 2018. Smart Building Based on Internet of Things Technology. *Presented at the 2018 12th International Conference on Sensing Technology (ICST)*, IEEE, Limerick, pp. 278–281.

Hunhevicz, J. J., Wang, H., Hess, L., and Hall, D. M. 2021. no1s1 - a blockchain-based DAO prototype for autonomous space. *Presented at the 2021 European Conference on Computing in Construction*, pp. 27–33.

Lee, D., Lee, S. H., Masoud, N., Krishnan, M. S., and Li, V. C. 2021. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in Construction* 127, 103688.
Lessig, L. 2000. Code is law. *Harvard magazine* 1, 2000.
Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J., and Schooling, J. 2020. Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. *J. Manage. Eng.* 36, 05020004.
Novo, O. 2018. Blockchain Meets IoT: An Architecture for Scalable Access Management in IoT. *IEEE Internet Things J.* 5, 1184–1195.
Opoku, D.-G. J., Perera, S., Osei-Kyei, R., and Rashidi, M. 2021. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering* 40, 102726.
Pradhan, N. R., and Singh, A. P. 2021. Smart contracts for automated control system in Blockchain based smart cities. *AIS* 13, 253–267.
Puķīte, I., and Geipele, I. 2017. Different Approaches to Building Management and Maintenance Meaning Explanation. *Procedia Engineering* 172, 905–912.
Putz, B., Dietz, M., Empl, P., and Pernul, G. 2021. EtherTwin: Blockchain-based Secure Digital Twin Information Management. *Information Processing & Management* 58, 102425.
Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. 2020. Construction with digital twin information systems. DCE 1, e14.
Sharma, P. K., and Park, J. H. 2018. Blockchain based hybrid network architecture for the smart city. *Future Generation Computer Systems* 86, 650–655.
Tasca, P., and Thanabalasingham, T. 2017. Ontology of Blockchain Technologies. Principles of Identification and Classification. SSRN Journal.
Wang, S., Ding, W., Li, J., Yuan, Y., Ouyang, L., and Wang, F.-Y. 2019. Decentralized Autonomous Organizations: Concept, Model, and Applications. *IEEE Trans. Comput. Soc. Syst.* 6, 870–878.
Yang, Y., Xu, C., and Shi, H. 2022. Smart Contract-Based Distributed Access Control for Smart Home, in: *2022 2nd International Conference on Consumer Electronics and Computer Engineering (ICCECE)*. IEEE, Guangzhou, China, pp. 454–460.
Ye, Z., Yin, M., Tang, L., and Jiang, H. 2018. Cup-of-Water Theory: A Review on the Interaction of BIM, IoT and Blockchain During the Whole Building Lifecycle, in: *34th International Symposium on Automation and Robotics in Construction*. Taipei, Taiwan.
Zyskind, G., Nathan, O., and Pentland, A. 2015. Enigma: Decentralized computation platform with guaranteed privacy. arXiv preprint arXiv:1506.03471.

CPS: Small: Smart and Autonomous Building Cyber-Physical Systems

A. Research Description

Project Rationale: A significant portion of people's time is spent in indoor environments, with studies estimating that approximately 90% of human life is spent inside buildings [1]. Cyber-physical systems (CPS) such as smart buildings play a crucial role in enhancing occupants' satisfaction, productivity, and well-being with indoor environment optimization and efficient building operations [2]. However, the current communication protocols and data storage for Internet of Things (IoT) devices used in smart buildings and their corresponding digital twins (DT) systems are mainly based on the traditional centralized system and database [3], [4]. This centralized architecture creates a single point of failure [5], a vulnerability where the failure of a single component can lead to system-wide disruption, which can be exploited by cyber threats [6]. Previous studies reveal potential loopholes within traditional building automation systems (BAS) and their communication protocols such as BACnet, MQTT, and Zigbee, making the system susceptible to data breaches, tempering, forgery, and cyber-attacks such as spoofing, information eavesdropping, and denial of service attacks [7]. According to a comprehensive examination of smart building security conducted by Kaspersky in 2019, nearly four in ten (37.8%) smart building automation systems have been affected by malicious cyber-attacks [8]. As per IBM Security report, cyberattacks such as ransomware rose 41% in 2022 with the average cost per data breach being $4.45 million [9], [10]. Such attacks not only compromise building cyber-physical systems' data integrity but also disrupt its operational processes, leading to unexpected system downtime, compromised functionalities, potential safety risks, discomforts, and privacy concerns for the occupant [11]. *Therefore, it is evident that research in enhancing the security and privacy of IoT and digital twin data as well as the resilience of building automation operations is crucial in addressing the vulnerabilities and inefficiencies of the current smart building systems.*
Furthermore, the traditional facility management operations in smart buildings are operated on centralized organizational structures, where decision-making power typically resides among a few individuals such as building facility managers [12]. This centralized approach, while initially designed to streamline decision-making, could 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 [13]. Moreover, a growing body of research has also highlighted the limitations of the conventional centralized facility management operation and emphasized the importance of community-based facilities management [14], [15], [16], a participatory approach that fosters democratized and socially inclusive facility management practices that prioritize the diverse needs and perspectives of related stakeholders [17]. This approach not only enhances the transparency and accountability of the decision-making process but also encourages the engagement of all community members in shaping the management and operation of the shared facilities [18]. *Therefore, further research into decentralized and community-driven facility management models is crucial to address the shortcomings of traditional centralized approaches and better align with the interests of building occupants.*
In addition, research on autonomous buildings has emerged as a promising frontier in the realm of smart and sustainable infrastructure. Autonomous buildings are characterized by their ability to operate independently, exhibiting traits of self-management, self-sufficiency, and intelligent

Sample Proposal

operation [19], [20]. Researchers have investigated the use of different technologies such as building automation systems, artificial intelligence (AI), Internet of Things (IoT), and digital twins, aiming to enhance building autonomy and intelligence [21], [22], [23]. However, despite recent advancements in smart building research, different researchers suggest that to increase the level of autonomy within its system, the building infrastructure system needs to become both operationally and financially autonomous with the capability of decentralized self-governance and self-ownership [24], [25], [26]. *Therefore, there is a need for a holistic approach that integrates a decentralized governance mechanism with the above technologies to fulfill such needs.*
The emergence of distributed ledger technologies (DLT) [27] such as blockchain technology and decentralized autonomous organization (DAO) [28] presents a promising avenue for addressing the aforementioned issues. DAO is a digital and community-driven entity running on a blockchain network that functions transparently and autonomously with democratic and collective decision-making capabilities among its members while having its fundamental operations adhere to rules written in the smart contract code [29]. Blockchain's inherent security features such as cryptography-based verification, tamper-proof ledgers, and smart contracts are promising solutions to the security and privacy concerns of IoT and digital twin data storage and transmission while DAO-based decentralized governance mechanism will provide decentralized coordination of building facility management operation. Additionally, previous studies on DAO governance demonstrate that human and machine agents can co-create a decentralized organizational system or entity that is self-owned and autonomously operates without any centralized control [25]. Such DAO-powered entities range from a self-sustaining, generative AI-powered digital organization [30], [31], decentralized meditation space [26], and self-governing forest [32] to an on-chain and community-governed city [33]. However, the research on the integration of DAO with other advanced technologies such as AI and digital twins specifically in the context of physical infrastructure remains relatively unexplored. Therefore, it is also necessary to investigate the opportunities and feasibility of integrating DAO and AI into the building environment to create a self-managed, intelligent, and autonomous CPS infrastructure.

Aim and objectives:

The *overall objective* of this project is to transform and decentralize the dynamics and decision-making within building cyber-physical systems' facilities management operations and shape how physical space will be owned and operated in the future with the use of artificial intelligence and web3 technology [34]. Specifically, we seek to investigate the integration of distributed ledgers technologies (Blockchain technology and decentralized autonomous organization (DAO)) and artificial intelligence (AI) to (1) develop a decentralized governance platform for facility management operation and (2) distributed protocol for building data transfer and storage and (3) create a prototype of an intelligent, self-operated and autonomous building cyber-physical systems with AI and blockchain governance. We will attain this overall aim through the following three *objectives:*

Objective 1*: Assess the benefits of employing a decentralized mechanism in securing the digital twin and IoT data transfer and storage and enhancing the resilience and efficiency of building facility management operations.*

Objective 2*: Understand the benefits and implications of distributed coordination, democratic governance, and collective decision-making mechanisms in facility management through a decentralized governance platform.*

***Objective 3**: Investigate the scope and capacity to which blockchain technology, DAO-based governance mechanisms, digital twin, and AI-integrated systems can advance the development of intelligent and decentralized autonomous building cyber-physical systems.*

These research objectives will be realized through the following studies proposed in this project (Figure 1). (1) First, we will create a secure, blockchain-based building data transmission protocol and decentralized task automation algorithm for the facility management operation. This framework will strengthen the security of digital twin and IoT sensor data transfer and storage and enhance the resilience of building facility management operations against cyber threats. IoT data will be securely transferred to a digital twin platform for real-time visualization of building operational metrics, before triggering corresponding automation/actuation of the building facilities. (2) Next, we will develop a data-driven, DAO-based decentralized governance platform to foster inclusivity and democratic governance of building operations by providing stakeholders the ability to govern critical facility management decisions collectively and transparently. (3) Additionally, we will design and implement a blockchain-based incentivization scheme on the governance platform for community-based facility management purposes, which encourages occupants to report maintenance issues and provide improvement feedback for the building infrastructure. (4) Finally, we will leverage blockchain, DAO, AI, and the findings from previous studies to develop a prototype of a proposed concept, decentralized autonomous building cyber-physical systems (DABCPS), which we define as an AI and web3-based, community-governed building infrastructure that is operational and financially autonomous with self-management protocols.

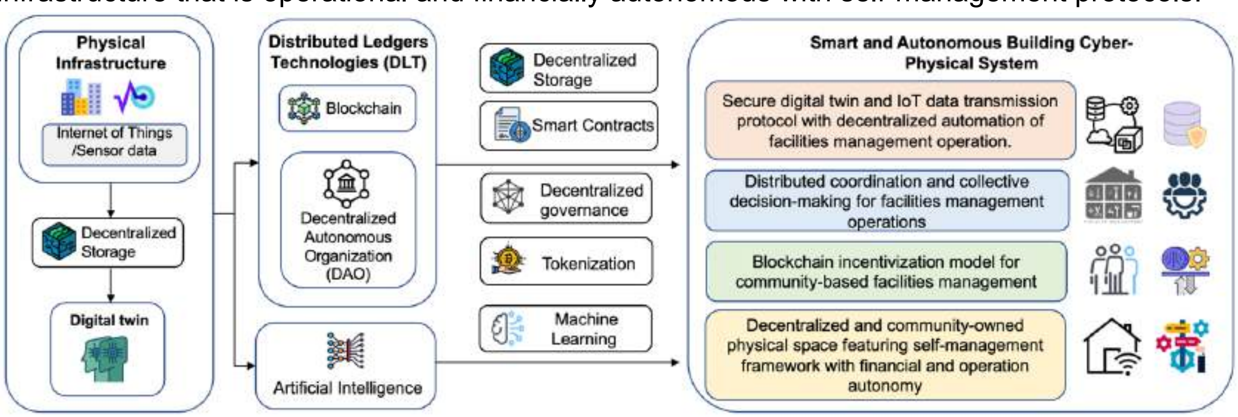


Figure 1: Overview of the proposed research

CPS Research Focus

The proposed research will yield foundational research contributions to the core cyber-physical systems research areas including autonomy, control, security and privacy, and mixed-initiative such as human-in-the-loop. The proposed project integrates the different cyber components including an AI assistant, decentralized governance platform, incentivization model, decentralized automation algorithm, and data transmission protocol, with the physical components such as human interaction, physical infrastructure, and facility management operation. Beyond the sensing application of CPS, the proposed studies in the project facilitate real-time interactions and feedback loops between cyber and physical components. The findings from this research will also be applicable across different CPS domains ranging from civil infrastructure, and transportation systems to smart cities.

Human-in-the-loop: First, the proposed decentralization governance platform contributes to the research in decentralized control and artificial intelligence for human-in-the-loop in cyber-physical systems [35], [36], [37], particularly in the human-building interaction domain [38], by integrating human expertise and collaboration as well as the large language model (LLM)-powered AI assistant [39] in the building facility management process. The platform provides a decentralized mechanism for community-driven decision-making capabilities, by incorporating human values and preferences into governance processes, which continuously enhance the inclusivity, transparency, and operational efficiency of the system. Similarly, the proposed incentivization model for community-based facility management encourages occupants to participate in building maintenance activities, leveraging human input and collective intelligence to drive positive behaviors and improvements to the building's cyber-physical systems. This platform incorporates human feedback loops into a decentralized decision-making system to influence the building environment behavior based on their preferences, thereby enhancing both human satisfaction and system performance. *Security, Privacy, and Control:* Additionally, through the development of the blockchain-based data transmission and storage protocol as well as the decentralized automation algorithm of facility management operations, this research will secure the IoT sensor and digital win data of the building CPS and enhance the cyber resilience of building facility management operations, thereby ensuring the data privacy and continuous functioning of the system. This system creates a feedback loop between indoor environmental sensing and decentralized actuation/automation of building operations. *Autonomy:* In addition, the proposed research on Decentralized Autonomous Building Cyber-Physical Systems will advance the research of CPS core research in autonomy. Through blockchain and DAO, this research introduces financial and operational autonomy into the physical infrastructure, allowing the system to self-operate, make financial transactions, and optimize its operations without any centralized intervention.

Intellectual merits

The intellectual merits of this project unfold across multiple dimensions, aiming to create a perspective shift in smart building facility management operation, and the governance and ownership structure of future physical spaces. This project aims to advance our understanding of how blockchain security features, tokenization, and decentralized control paradigms such as community-driven governance and democratic decision-making can foster decentralized collaboration and coordination, inclusiveness, and resilience of facility management operations and contribute to the research on autonomous building.

Decentralized governance platform: The proposed platform seeks to explore the capabilities of these digital entities in facilitating collective decision-making and coordination of building operations. By empowering stakeholders to participate in transparent and democratic decision-making processes, the research aims to foster inclusivity, transparency, and accountability in building operations. This governance model has the potential to revolutionize the way buildings are managed, shifting from centralized decision-making structures to community-driven governance systems. *Decentralized automation and data transmission protocol:* Additionally, the proposed research improves the security and efficiency of facility management operation and infrastructure cyber resilience by developing decentralized task automation algorithms and data storage and transmission protocol for digital twin and IoT data. *Blockchain-based incentivization model:* Also, the blockchain-based incentivization scheme leverages collective intelligence and active participation of occupants for the enhancement and maintenance of the shared physical space. This proposed DAO-based community-based facility management approach fosters a sense of empowerment, ownership, and accountability among stakeholders, potentially creating a community-driven and sustainable built environment. *Decentralized Autonomous Building Cyber-Physical Systems:* This project also contributes to the research on intelligent and autonomous building infrastructure. This research will advance the knowledge of how emerging technologies like blockchain, DAO, AI, and digital twins can transform the operation, governance, and ownership structure of physical spaces/infrastructure by proposing the development of web3-enabled, self-sufficient, and autonomous building systems with financial and operational autonomy. Furthermore, the proposed AI conversational agents for human-building interactions will also forge a path toward intuitive and inclusive engagement between human and physical environments and further advancing knowledge of machine learning for human-in-the-loop in cyber-physical systems.

Research Plan

Figure 2 shows the summary of research objectives and the related studies to be carried out over the three years. The studies are designed to address the identified research objectives and are detailed as follows:

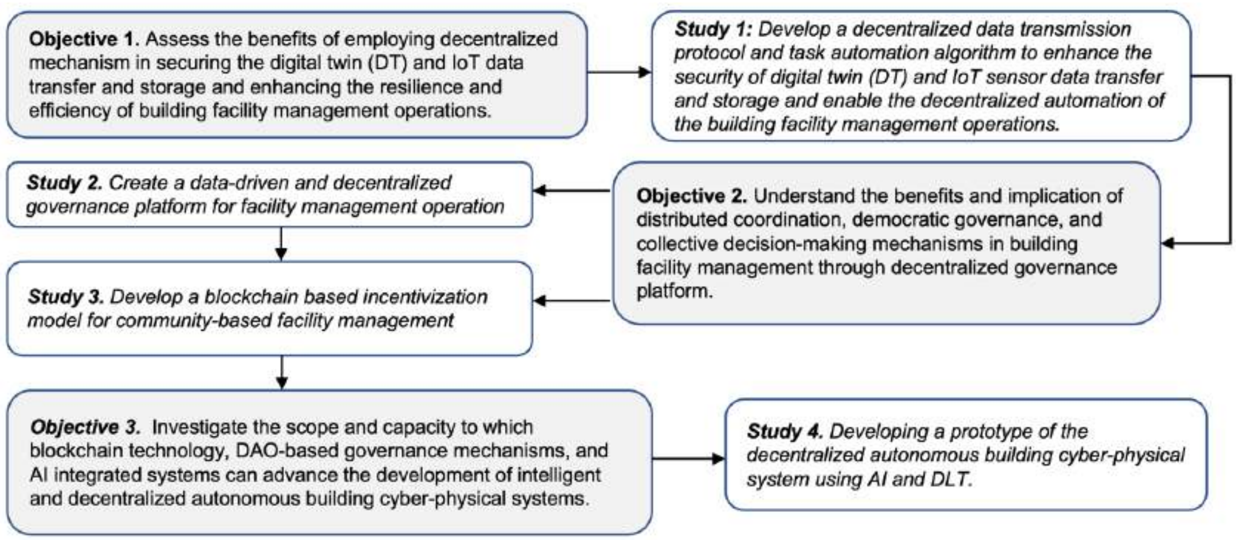


Figure 2. Summary of the Research Plan

Objective 1. Assess the benefits of employing a decentralized mechanism to secure the digital twin and IoT data transfer and storage and enhance the resilience and efficiency of building facility management operations.

Study 1: Develop a decentralized data transmission protocol and task automation algorithm to enhance the security of digital twin and IoT sensor data transfer and storage and enable the decentralized automation of the building facility management operations.

This study aims to develop a secure and resilient IoT and digital twin data transmission, and decentralized building operation automation protocol. In the proposed framework, the real-time environmental sensor data including light luminosity, humidity, occupancy, temperature, air quality, and carbon dioxide level will be first collected by the building's embedded IoT devices such as Raspberry Pi and related environmental sensors (light sensor, DHT11 sensor, MQ2 gas sensor, and motion sensor). These live sensory data and the digital twin-related information (e.g. building occupancy information, utility data, energy consumption pattern, building operational data, maintenance schedules, etc.) will be continuously transferred to a private/permissioned blockchain network before being logged and securely stored on the blockchain-based decentralized file storage [40] (e.g. Interplanetary File System (IPFS)) as the historical data. Additionally, the Autodesk platform service [41] and Autodesk Tandem [42] will be used to create a building digital twin platform as it provide useful tools and API for analyzing complex data streams. By leveraging blockchain's node js SDK and the provided Autodesk Tandem REST APIs, the live sensor data will be directly queried from the private blockchain network and securely fed into the building digital twin, providing a comprehensive real-time visualization of building performance metrics. In addition, the historical sensor and digital twin data stored on the decentralized file storage could also be retrieved for further analysis and optimization of building operations including predictive maintenance, energy usage, and occupant comfort improvement. In addition, Hyperledger Fabric [43], a private permissioned blockchain, is selected for this study as it provides a controlled environment where only authorized participants can join the network which ensures the privacy of access control and integrity of sensitive building operational data [44]. Previous studies have showcased Hyperledger fabric capability in different IoT domains including secured access control of smart home devices [45] secured data sharing [46] and IoT system cyber-resiliency [47]. Due to its permissioned nature, Hyperledger fabric has demonstrated great performance in terms of throughput, speed, latency, cost, and scalability [48], [49], [50] which is essential for handling large volumes of real-time IoT data streams and maintaining the efficiency of automation of FM operation the building cyber-physical systems. We will also conduct a comparative analysis between popular private permissioned blockchains (Hyperledger Fabric and Quorum [51]), public Ethereum networks, and traditional IoT protocols such as BACnet and MQTT. Key performance metrics such as cost, scalability, transaction throughput, and latency will be evaluated to determine their suitability for this framework.

Furthermore, we will develop a Hyperledger fabric chain code [52] (smart contract) to facilitate decentralized automation of FM tasks and building operations. The real-time data streams from IoT sensors will be first continuously ingested into this chaincode. Based on predefined logic and conditions programmed within the chaincode, specific events and FM-related actions will be triggered [53]. These can include predictive maintenance alerts, Heating, ventilation, and air conditioning (HVAC) system control adjustments (temperature setpoints, airflow, etc.), lighting automation, and other FM operations crucial for efficient building management. In this case, chain code will act as tamper-proof and immutable automation controllers that execute specific actions in a decentralized and deterministic manner in response to the incoming IoT data feeds. We will use Hyperledger Fabric's SDK Node JS library [54] to retrieve the emitted event/decision from the smart contracts and communicate with the smart home's facility including the smart home appliance, HVAC system, and building automation systems. This framework can facilitate informed decision-making and optimize operational efficiency within the smart building FM. In addition, the proposed decentralized protocol is based on open-source blockchain technology which offers cost advantages over proprietary centralized building automation system software with the elimination of licensing fees and reduction in infrastructure costs.

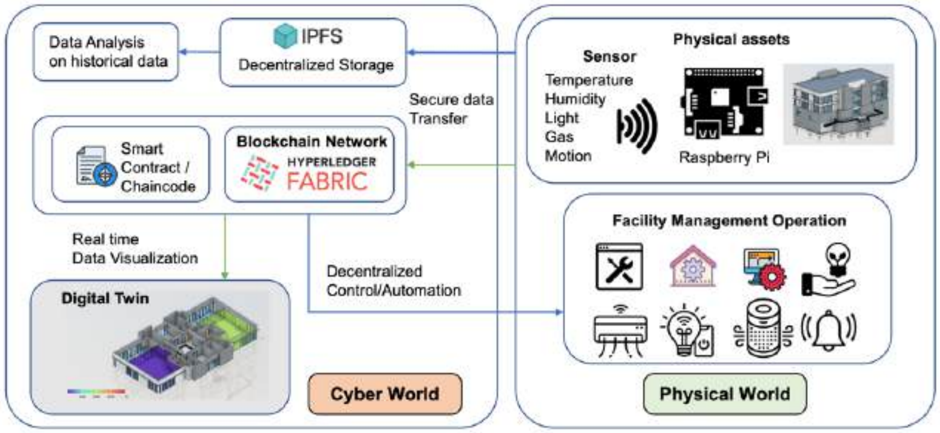


Figure 3: Decentralized data transmission and facilities automation protocol.

Objective 2: Understand the benefits and implications of distributed coordination, democratic governance, and collective decision-making mechanisms in building facility management through a decentralized governance platform.

Study 2. Create a data-driven and decentralized governance platform for facility management operations.

Community-based facility management aims to drive fundamental changes in how buildings and infrastructure are managed by emphasizing inclusivity, transparency, and collective decision-making among stakeholders [14], [15], [16] [17]. In this study, we will extend the concept of community-based facility management by creating a data-driven and decentralized governance platform that empowers stakeholders to collaboratively participate in the management and coordination of building operations in a transparent and democratic manner through blockchain-based DAO and digital building twin. Depending on the functions of the building CPS, the governance platform in this study will be specifically customized/designed for a group of key and high-level stakeholders in the building CPS including building owners, building facility managers, administrative personnel, faculty, etc. The governance process is informed by real-time data visualizations through the live digital twin of the building infrastructure and analysis of historical data stored on decentralized storage proposed in Study 1. This data-driven approach allows stakeholders to make informed decisions based on actual building performance metrics, energy consumption patterns, and occupancy data. This governing body can leverage the transparency and collective decision-making capabilities of a DAO to democratize the governance of core building CPS operations including automation of building operations, settings of HVAC or lighting systems, energy and space management, maintenance policy, asset monitoring, emergency and response, and other critical FM operations. This design can decentralize the control of these high-stakes decisions from a single centralized authority while also offering oversight from authorized entities with comprehensive knowledge and accountability.

Once the DAO system is deployed on the blockchain network, a specified amount of governance tokens will be minted and distributed to each member corresponding to their roles and responsibilities. These tokens determine the participants' voting rights and power over the decision-making process. This study will use the ERC-20 tokens standard [55] for the governance tokens as they provide token fungibility and transferability between DAO members. This enables fractionalized ownership or voting power within the DAO and provides an option for the member to delegate their voting power as needed. This platform will adopt, a token-based quorum voting mechanism [56] where the greater number of tokens held will equal the higher value of voting power.

Through tokenization, eligible DAO members can transparently submit proposals, review existing policies, and participate in on-chain voting to collectively decide whether to enact changes on the settings of building operation automation (e.g. HVAC system setpoint, threshold, etc.) and FM-related policy in the building CPS system that were previously programmed in the smart contract. Members can also propose a change in the policy of the DAO governance platform itself through the upgradable smart contract. In addition, the governance platform can propose the actuation of both on-chain and off-chain activities from the transfer of cryptocurrency assets to the deployment of machine learning model training on the building of operational and sensor data.

In this study, the proposed decentralized governance platform will be developed in the form of a full-stack decentralized application (DApp) [57], an open-source application that operates on a peer-to-peer blockchain network. Due to the collaborative nature of the governance platform, we will design and implement the DAO application on the public/permissionless blockchain network. We opted for Ethereum networks [58] since it is very well documented and provide a rich set of tools for DAO development. For research purposes, Ethereum's test network, Sepolia, will be used as it provides all the necessary functions of Ethereum without any fees. The Ethereum-based DAO smart contracts will be written in the Solidity programming languages [59] and leverage the OpenZepplin library [60] which offers secured and audited codes, with community-standardized contracts for tokenization, and useful features such as contract upgradability. In addition, NodeJS, Web3 JS, and Ethers JS will serve as the backend for handling server-side operations including listening for events from the blockchain network. ReactJS, CSS, and HTML will be used to create the DAO's web application frontend with interactive graphical user interfaces to ensure a friendly experience for DAO participants.

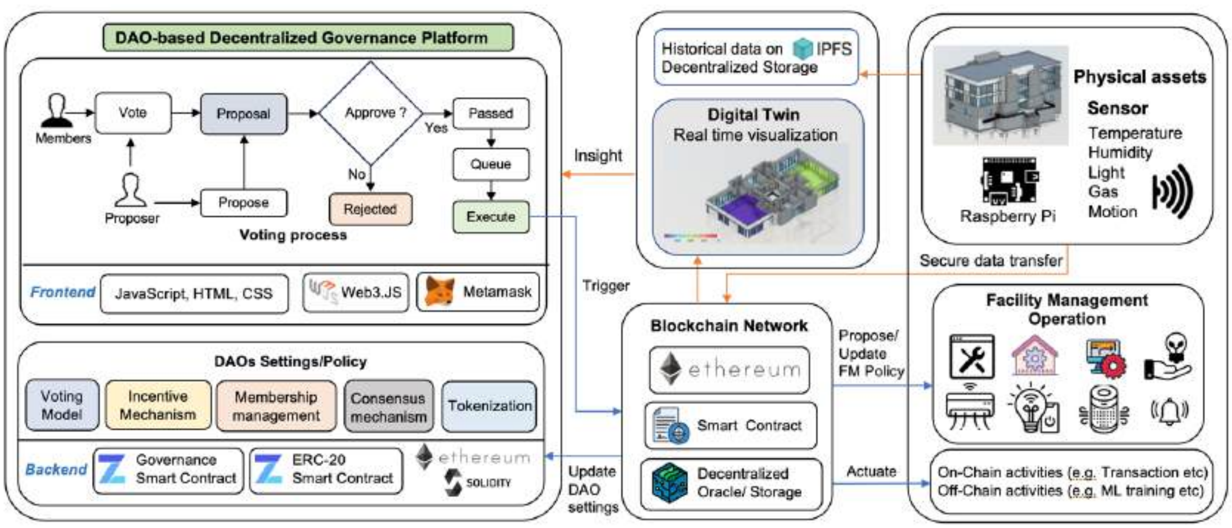


Figure 4. Data-driven and decentralized governance framework for facility management

To evaluate the usability and effectiveness of the decentralized governance platform, we will recruit a group of students to participate in the platform's experimental testing. The testing will involve having the students complete common governance tasks on the platform, such as submitting proposals and voting participation. We will conduct a post-experiment survey to gather qualitative feedback and insight on the platform usability and participant's perception of the level of inclusivity, and transparency of the proposed governance platform.

Study 3. Develop a DAO and blockchain-based incentivization model for community-based facility management.

In this study, we will create a governance platform emphasizing community-based facility management by broadening the participation on the governance platform to the broader building occupants' demographics including tenants, students, staff, etc. The differences between this governance platform to the one in study 2, lie in their focus and scope of facility management. Instead of providing decentralized coordination to ensure the efficiency and functioning of the facility management and operation of the building CPS, this governance model aims to foster a sense of collective ownership for the occupants and related stakeholders and encourages them to actively contribute to the upkeep, improvement, and sustainability of the shared built environment. This approach also promotes social inclusivity by giving occupants a voice in decision-making processes that impact their daily experiences within the built environment which enables more occupant-centric outcomes and improved overall occupants' satisfaction.

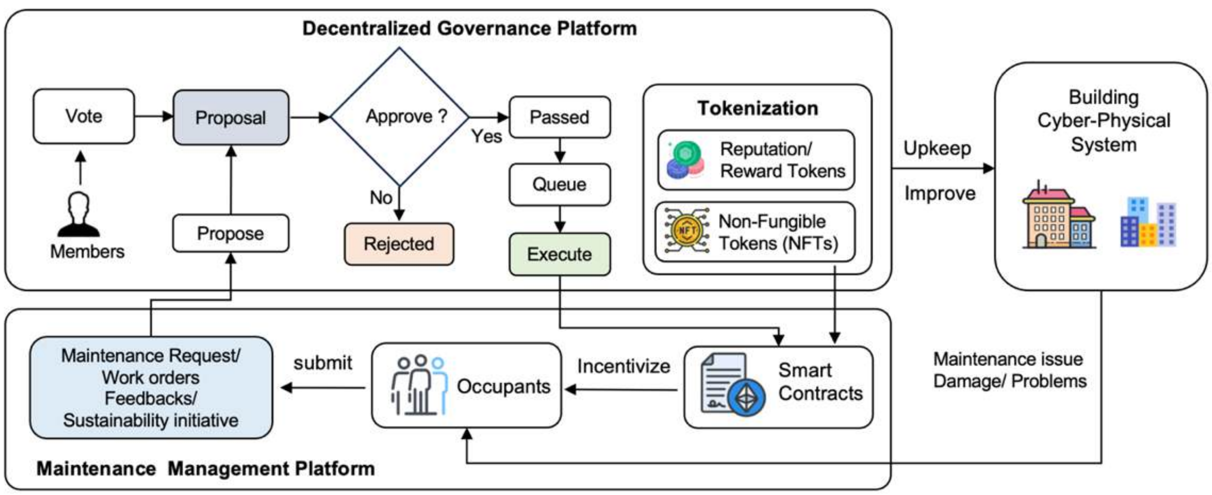


Figure 5. Blockchain and DAO-enable Incentivization Model for Community-based Facility Management

In this study, expanding upon the developed governance platform in study 2, we will implement a blockchain and DAO integrated incentivization framework that encourages occupants to report any building maintenance issues and/or provide relevant feedback in contributing to the maintenance and enhancement of shared building infrastructure. The scope of the issues to be reported may depend on the functionality and types of different buildings, ranging from, urgent maintenance needs, faulty or malfunctioning equipment, roofing, or exterior damage to defects in the building's structural integrity, etc. As a DAO member, occupants can create a proposal to report issues to the governance platform by including text descriptions, locations, and attachments of photos/videos of the problems through a custom-built decentralized application. The submission data will be uploaded on the decentralized storage (IPFS) as it is more cost-effective, scalable, and efficient than the blockchain network data storage while the corresponding content identifier (CID) of the submission will be recorded on the blockchain network. The data will be accessible to all DAO members where they can earn incentive tokens by reviewing the legitimacy and relevancy of the issues and participating in the voting process. Key stakeholders such as building owners, and facility managers who possess higher responsibility and expertise will be allocated more voting power compared to the occupant. The members with the approved proposal will be rewarded with the blockchain-based fungible tokens and the digital badge/reputation-based, non-fungible tokens (NFTs) based on the ERC-721 tokens standard [61]. Issues can be categorized based on severity/urgency, with higher rewards for critical reports. Similar to study 2, we will recruit students to participate in the usability testing of the platform to gather important insight into the platform's ease of use as well as the effectiveness of the incentive mechanism.

Objective 3: Explore how blockchain technology, DAO-based governance, and AI-integrated systems can advance the development of intelligent and decentralized autonomous building cyber-physical systems.

Study 4. Developing a prototype of the decentralized autonomous building cyber-physical system using AI and DLT.

In this study, we propose the concept of a decentralized autonomous building cyber-physical system (DABCPS) which is referred to as a web3 and AI-enabled, community-governed building infrastructure that functions autonomously with blockchain-based self-management protocols. At the core of the system is the integration of cyber components including blockchain, DAO, AI, and digital twins with physical components such as humans, IoT devices and sensors, physical space, and its related equipment. Using the findings from the previous 3 studies, we will implement a proof of concept of the framework by developing a prototype of the DABCPS as a decentralized rental space. In practice, the types of decentralized rental space can vary depending on the nature of the buildings, ranging from a retail space in a commercial building, a study, or conference room in an educational institution to a coworking space in an office building.

In addition to the decentralized automation, coordination, and governance capability of facility management proposed in the previous 3 studies, the proposed blockchain-powered physical space in this study will be both operationally and financially autonomous and assisted by an AI virtual assistant powered by large language model. This decentralized space will be programmed to earn blockchain's cryptocurrency or tokens (revenue) in exchange for renting/leasing itself to the users/occupants. A decentralized application (DApp) with a graphical user interface will be developed to provide users access to rental/booking services, facility control, and live digital twin visualization of the physical space. The space's functionality, including the provided digital twin platform, facility management, and building operations automation, will be governed by blockchain smart contracts as proposed in Study 1. Additionally, the DAO's governance framework, as outlined in Study 2, will be created to oversee the space's functional operation and financial aspect including managing its revenue and necessary operational expenses (e.g. maintenance fee, electricity usage, etc.) with DAO treasury and blockchain-based transactions, ultimately enabling a self-sustaining, nonprofit-seeking operation. Depending on the ownership structure of the physical space (public or private), DAO members can be comprised of various stakeholders including building owners, facility managers, maintenance team, or broader occupant demographics who will be responsible for data-driven and collective governance of the DAO physical space by collectively propose and vote on different matters such as funding allocation, space operational settings, maintenance schedules, etc. Similarly, the blockchain-based incentivization scheme as described in Study 3 will be implemented in the system to foster the collective upkeep and improvement of the physical space. These activities include maintenance reports and providing improvement feedback on the system.

The proposed system also incorporates an AI assistant powered by an open-sourced large language model, LLaMA3 [62]. The use of local and open-source LLM is driven by several factors, including data privacy and independence from third-party entities as all interactions and data processing are kept within the local infrastructure. The main objective of the AI assistant is to facilitate user interactions with the physical space using the function calling technique [63]. Users can communicate with the AI assistant through text and voice modality to perform tasks such as turning on/off or adjusting setpoints of various building facilities while using the physical space. Additionally, users can inquire about the current indoor environmental data and live sensor readings or check the availability of rooms within the space, integrating with the blockchain-based reservation system to facilitate the reservation process. The AI assistant also supports the DAO members or owners in their interactions with the blockchain. DAO members can instruct the AI assistant to vote on their behalf by calling the appropriate smart contract functions for executing transactions. The AI assistant can also assist DAO members in summarizing proposals and creating new DAO proposals to streamline the governance process.

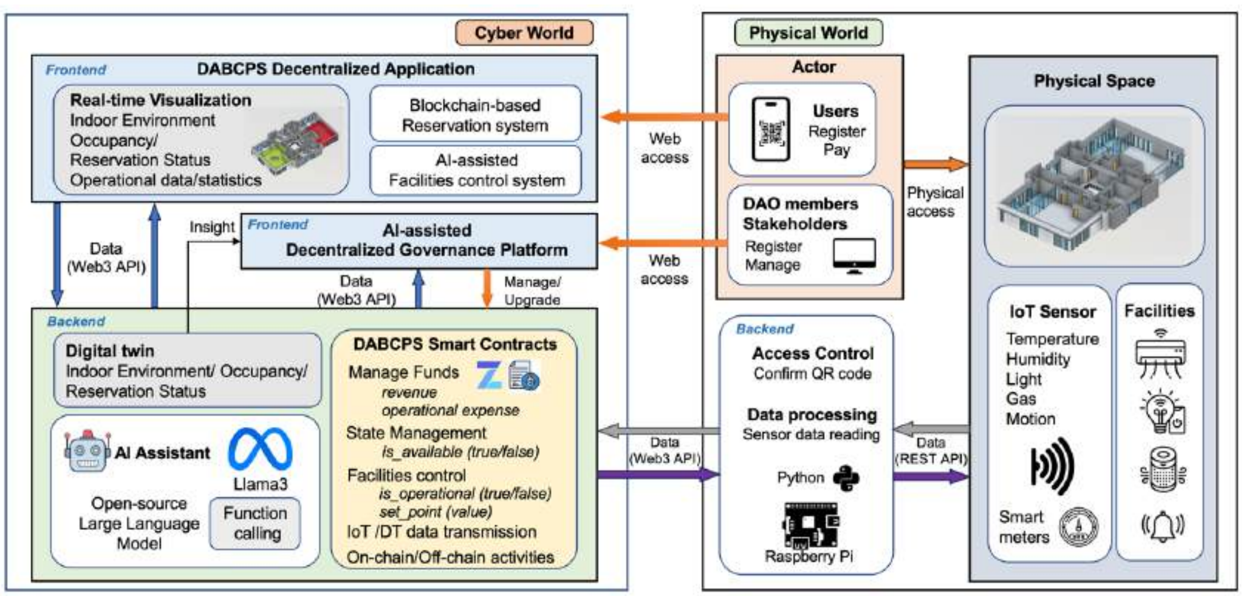


Figure 6. Proposed Decentralized Autonomous Building Cyber-Physical System (Orange arrow: Human interaction on the CPS, Grey arrow: Data from Physical to Cyber system, purple arrow: Response from Cyber to Physical system, blue arrow: Data flow between the cyber systems)

Theoretical Framework

The sociotechnical systems theory [64] is essential in examining the intricate interplay between the technological elements in this research which comprised artificial intelligence, distributed ledger technologies' components (Blockchain and DAO), and the social dynamics of occupants' collaborative decision-making and participation of stakeholders in the decentralized governance framework. Sociotechnical systems theory emphasizes the need to design systems that not only function efficiently from a technical perspective but also accommodate the diverse needs, values, and behaviors of human users [65]. The sociotechnical lens is crucial for the development of decentralized governance platforms in studies 2 and 3. Understanding the sociotechnical aspects of decentralized systems will guide the development of the proposed decentralized governance platforms that promote collaboration, transparency, and democratic decision-making among stakeholders (Study 2). By considering both the technical aspects of incentive structures (e.g., tokenomics) and the social dynamics of human actors including motivation, behavior, preferences, and values, sociotechnical systems theory can guide the design and development of an effective incentive system that will promote active participation of occupant in community-based facilities management and sustainability initiatives (Study 3). In addition, the proposed development of the distributed IoT and digital twin data transmission protocol and decentralized automation algorithm (Study 1) as well as the proposed decentralized autonomous building cyber-physical systems in this research (Study 4) is guided by the complex adaptive systems theory [66]. The theory conceptualizes systems as diverse entities that interact and adapt to emerge with novel properties and capabilities [67]. In this research, complex adaptive systems theory provides a model for conceptualizing how the physical components, machine, and human agents (e.g. physical infrastructure, IoT devices, digital twin, blockchain, DAO decentralized governance mechanisms, machine learning models, human stakeholders, etc.) will interact dynamically in enabling the self-adaptive and decentralized building cyber-physical systems. Additionally, complex adaptive systems theory emphasizes the concepts of self-adaptation, self-organizing, and decentralization within complex systems [68]. It guides the development of adaptive control mechanisms and feedback loops using machine learning that enable autonomous responses from building facilities to environmental changes and user needs. Furthermore, the Human Factor principles [69] will provide valuable insights into the aspect of the human-centered design of the proposed building cyber-physical systems and decentralized governance platforms. It emphasizes the importance of user interface design and user experience which can advance a comprehensive understanding of how human users interact with complex systems and how design choices impact user behavior and system performance [70]. This holistic approach ensures that the design and development of decentralized application (DApp) and decentralized governance platforms are informed by both technical considerations and human-centered design principles, ultimately leading to more effective and user-friendly solutions.

B. Evaluation/Experimentation Plan

The project design builds off multiple studies, each with a clearly defined outcome. We will provide a demonstration of the developed system, and conduct experiments in each of the proposed studies to obtain both qualitative insight and quantitative metrics before examining the extent to which each study's aim is accomplished.

In Study 1, the proposed data transmission protocol and decentralized automation algorithm will be validated through the implementation of a real-world case study. We will deploy the Hyperledger fabric blockchain network on the single board computer (e.g. Raspberry Pi 4 and Jetson Nano). The environment sensor will be retrieved through the device GPIO pin and uploaded to the blockchain network before feeding to the Autodesk tandem digital twin platform. Smart home devices such as smart bulbs [71] and humidifiers [72], as well as home appliances simulation API, [73], will be used to demonstrate our decentralized automation algorithm. We will evaluate the operational efficiency and robustness of our proposed blockchain-based data transmission protocol based on key performance metrics of the data transfers including transaction throughput and latency. Hyperledger Caliper [74], a benchmark tool for blockchain system performance, will used to test the throughput and latency of our smart contract/chain codes functions. Comparative analysis between popular private permissioned blockchains, Hyperledger Fabric and Quorum [75], public Ethereum network as well as the traditional IoT protocols (BACnet and MQTT) will be conducted. In addition, security analysis of the proposed system will be discussed through data immutability, non-repudiation, authentication, and authorization [76] to evaluate their level of resilience to cyber-attacks.

Additionally, the prototype system of the decentralized governance platform in studies 2 and 3 will be developed as a decentralized application and will also be validated through the implementation of a real-world case study. We will recruit participants to test different functionalities of the decentralized governance platform including proposing and voting on different proposals such as maintenance policy and changing the building automation setting (e.g. threshold for smart home facility automation as mentioned in study 1) etc. In addition, users will be recruited to interact with the proposed community-based facility management incentivization platform by submitting relevant maintenance issues and feedback to the DAO system. In addition to the security testing and operational metrics mentioned in Study 1, we will evaluate the usability of the governance platform/ decentralized application and the effectiveness of the incentive mechanism. In addition to the security and operational metrics mentioned in study 1, we will evaluate the usability of the governance platform, and student perceptions on the platform's level of inclusivity and transparency in decision-making by conducting a post-experiment survey with the platform participants using both the Likert scale rating and open-ended question format.

Furthermore, the proof of concept of decentralized autonomous building cyber-physical systems in study 4 will be implemented with a real-world use case by utilizing an actual physical space in an educational building. Similarly, besides performing a security audit on the system's smart contract code, participants will be recruited to test the blockchain-based space reservation system and digital twin on a decentralized application and to assess the usability of the system. In addition, the accuracy of the proposed machine learning model in the system will be evaluated to maximize the self-optimization capability of the cyber-physical systems.

C. Preliminary Works

In **study 1**, we have developed a proof-of-concept of the proposed decentralized protocol on the Hyperledger Fabric blockchain. The sensor data were securely transmitted to the digital twin on Autodesk Tandem for real-time visualization before being stored on the IPFS. Initial benchmarking on the sensor reading and writing functions shows that this architecture can handle about 590 transactions per second with an average latency of 0.03 seconds. To demonstrate the feasibility of decentralized automation, we have also created a Hyperledger chain code to autonomously adjust Xiaomi's smart lightbulb and humidifier setpoints based on the retrieved humidity and luminosity data. This preliminary experiment demonstrates the feasibility and initial performance of blockchain-based data transmission and task automation mechanisms for facility management. We aim to build upon this preliminary result by expanding integration to more IoT devices as well as optimizing the throughput and latency performance. In addition, in **study 2**, we have also built a full-stack web application (DApp) for a decentralized governance platform using React JS and Ethereum blockchain. This initial prototype allows stakeholders to make collective decisions by voting for the adjustment of the sensor data threshold variable of the facility automation in the smart contract. Next, we aim to further develop new voting functionality and the incentivization model proposed in **study 3** as well as refine the user interface of the DApp before conducting more formal usability evaluations. Furthermore, in **study 4**, we have developed an initial prototype of the reservation system DApp for our office space that can receive user bookings and payments. The decentralized data transmission and governance platform were also integrated into this system. We have also implemented an LLM-powered AI assistant for building facilities control.

D. Project Management and Collaboration Plan

We summarize the tasks, involved PIs, interdependencies, and research time frames in Table 1.

Table 1. Proposed project timeline and interdependencies

Task	PIs	Depends On	Year 1		Year 2		Year 3	
Objective 1: Assess the benefits of employing decentralized mechanism in securing the digital twin (DT) and IoT data transfer and storage and enhancing the resilience and efficiency of building facility management operations.								
Study 1: Develop secure IoT and DT data transmission protocol and decentralized task automation algorithm.	XX	-						
Objective 2: Understand the benefits and implication of distributed coordination, democratic governance, and collective decision-making mechanisms in facility management through decentralized governance platform.								
Study 2: Create a decentralized governance platform for facility management operation	XX	Study 1						
Study 3: Develop a blockchain based incentivization model for community-based facilities management	XX	Study 2						
Objective 3: Explore how blockchain technology, DAO-based governance and AI integrated systems can advance the development of intelligent and decentralized autonomous building cyber-physical systems.								
Study 4: Developing a prototype of the decentralized autonomous building cyber-physical systems	XX	Study 1,2,3						
Project Evaluation								
Education and Outreach								
Dissemination								

E. Broader impacts:

Research

<u>Decentralized governance platform:</u> At its core, the project endeavors to develop a decentralized governance platform for facility management operations, introducing a paradigm shift in management practices within the infrastructure cyber-physical systems. The platform will empower stakeholders to participate in transparent and collective decision-making processes that promote inclusivity, transparency, and accountability in CPS operations. The proposed governance platform with distributed coordination, and democratized decision-making in this project also serves as a blueprint for a different infrastructural domain that seeks to cultivate an inclusive, efficient, transparent, and distributed operational framework.

<u>Blockchain-based incentivization model:</u> Moreover, the proposed token-based incentivization model powered by blockchain and DAOs fosters people engagement, a sense of empowerment, ownership, and responsibilities towards upkeep, improvement, and management of shared spaces or public physical infrastructure. This model can also further be used to positively reshape civic attitudes and encourage their participation in sustainability initiatives that promote community resilience, and environmental and resource conservation in the built environment.

Decentralized Autonomous Building Cyber-Physical Systems: Furthermore, the proposed development of self-sufficient, nonprofit-seeking, and autonomous building cyber-physical systems with AI integration, and operational and financial autonomy aims to enhance the resilience, efficiency, and sustainability of building environments. Such decentralized, autonomous entities can revolutionize and complement the traditional centralized approaches of operation across different domains including civil infrastructure, transportation, and smart city.

Education and Outreach

In support of the broadening participation initiative, this project will also offer educational outreach activities including class modules on blockchain, machine learning, and cyber-physical systems and related research opportunities for undergraduate and graduate students as well as a workshop for K-12 students. In study 2,3 and 4 the PIs will recruit participants from diverse backgrounds to participate in the testing of our decentralized governance platform. We aim to ensure representation from various demographics, including individuals from underrepresented groups, to foster inclusivity and diversity within our research. Through these efforts, we seek to not only advance our research objectives but also contribute to the broader goal of fostering diversity and inclusivity in STEM fields.

Dissemination

The findings of the proposed research will be disseminated through various channels to a diverse set of audiences including professionals, scholars, and the public. The communication plan employs a multi-faceted approach that ensures widespread access to research outcomes.

- Peer-Reviewed Publications: The research findings will be mainly disseminated through high-impact peer-reviewed conference papers and journal publications in the domain of construction engineering, smart buildings, cyber-physical systems, and blockchain technology. This approach enables research contributions to reach a broad academic audience.
- Open-Source Code Sharing: All implemented codebases in this project including DAO governance platforms DApp, smart contracts, and decentralized automation algorithms and protocol will be publicly shared on the open-source platforms such as GitHub. Documentation will be provided to assist in the replication of the results. This approach aligns with the principles of open science, allowing other researchers and practitioners to build upon our work and fostering a collaborative research environment.
- Participation in Conferences: The research team will actively participate in conferences, including the Construction Blockchain Consortium (CBC) and the Construction Research Congress (CRC). Presentations and publications at conferences provide opportunities to engage and share research outcomes with academics and professionals in the construction and blockchain domain and receive valuable feedback from the community.
- Annual CPS PI Meeting: The project team will actively participate in the annual CPS PI meeting, presenting findings and engaging with the broader CPS community. This venue provides an invaluable opportunity to share experiences and gather insights from the researcher within the CPS community.

Multimodal AI-Augmented Construction Education: Enhancing Learning, Safety, and Equity through Real-Time Embodied Interaction

1. Vision

Traditional learning methods in construction often rely on static resources such as blueprints or digital models, which are limited in their ability to convey the dynamic and spatial complexity of real-world construction environments [1]. Similarly, current methodologies for assembly task training, relying primarily on written instructions or video demonstrations, fail to provide the immediate, tactile feedback essential for developing practical assembly skills [2]. Furthermore, existing approaches to safety training tend to focus on generalized rules and static simulations, which inadequately prepare students for the diverse, context-dependent hazards encountered in real-world construction environments [3].

The rapid development of immersive technologies, particularly in Augmented Reality (AR) and Mixed Reality (MR), has opened new opportunities for transforming education, especially in fields like construction that require hands-on learning and spatial reasoning. Immersive learning environments offer unparalleled advantages over traditional methods, such as textbook learning or 2D screens, by enhancing students' interaction with 3D models, simulations, and real-world scenarios [4]. In construction education, where understanding spatial relationships, material properties, and safety procedures is crucial, AR and MR provide an ideal platform for delivering interactive, engaging, and contextually rich learning experiences [5].

The integration of Artificial Intelligence (AI) into AR and MR platforms further enhances the educational potential of these technologies, especially in STEM areas [6]. AI has already demonstrated its value in various construction-related applications when combined with mixed reality. For instance, AI-powered object detection systems have been successfully implemented in AR environments for real-time identification of building defects [7], construction elements, and potential safety hazards and safety violations on construction sites [8]. However, these traditional AI models typically train on a specific training dataset for specific tasks, which restricts their ability to handle open-ended tasks or adapt to unique, real-world construction scenarios. Furthermore, they are limited in their ability to provide detailed explanations for their decisions or recommendations, which is crucial for deepening students' understanding of complex concepts, comprehension of construction processes, and problem-solving strategies. Moreover, these systems often have difficulty adapting to unexpected scenarios or novel questions from students, as they are confined to their initial training data sets.

The advent of generative AI, such as large language models (LLMs), offers a promising avenue to overcome these limitations. LLMs exhibit remarkable capabilities in natural language processing, which could enable seamless human-machine interactions and intelligent decision-making processes [9]. Unlike conventional AI models, LLMs possess a deep understanding of contextual information and can engage in human-like conversations, allowing for more intuitive, personalized, and adaptive learning experiences [10][11]. Moreover, multimodal generative AI, such as the Vision Language Models (VLMs) [12], has the potential to revolutionize construction education by creating dynamic, multimodal learning environments by integrating voice, textual, and visual data such as images and video for more comprehensive learning.

Despite the evident potential of integrating generative AI with an extended reality environment construction education, there is a significant gap in the current research landscape. While

generative AI has been applied in various educational contexts, such as chatbots and virtual assistants [13], its application in real-time, embodied interaction within immersive environments, specifically for construction education, remains largely unexplored. Given this context, the primary objectives of this research are to develop and implement a generative AI-powered extended reality system for construction education that integrates a multimodal AI to enhance student learning through immersive, embodied interactions. This system aims to provide students with real-time, context-aware feedback on complex construction processes, improve their spatial reasoning and problem-solving abilities, and offer personalized learning experiences by dynamically adjusting the instruction and feedback based on each student's performance patterns, learning pace and demonstrated competency level. By leveraging AI's natural language processing and visual recognition capabilities within AR/MR environments, the research seeks to bridge the gap between theoretical knowledge and practical application, ultimately enhancing students' understanding of construction workflows, safety procedures, and assembly tasks.
Figure 1 provides a comprehensive overview of the proposed research, illustrating how our AI-augmented mixed reality system addresses current challenges through innovative technological and pedagogical solutions. The project uniquely combines cutting-edge technological innovation—including multimodal AI processing, mixed reality visualization, and real-time embodied interaction—with learning science innovations in spatial reasoning, safety training, and embodied cognition. Through parallel implementation at [redacted] (undergraduate education) and [redacted] (workforce training), the research will generate fundamental insights into how technology-enhanced embodied learning can support diverse learner populations. The project promises significant broader impacts by developing accessible, equitable solutions for construction education while advancing theoretical understanding of technology-mediated learning in spatially complex domains. This transformation of construction education through AI-augmented mixed reality will help prepare a more skilled, safety-conscious workforce while establishing new paradigms for technology-enhanced learning in practical, hands-on fields.

Figure 1: Transforming Construction Education through AI-Augmented Mixed Reality [redacted]

2. Intellectual Merit

The proposed research advances scientific knowledge and understanding at the intersection of learning sciences, artificial intelligence, and construction education through several innovative contributions. First, the research extends embodied cognition theory by examining how multimodal AI-augmented mixed reality environments influence spatial reasoning and technical comprehension in complex construction systems. By focusing specifically on plumbing and structural systems, the study investigates how technology-mediated embodied experiences support the development of advanced spatial understanding in domains where three-dimensional comprehension is crucial. This theoretical advancement will shed new light on the mechanisms through which embodied interaction supports the development of expert-level spatial reasoning skills. Second, the research develops novel technological approaches for real-time processing and integration of multimodal learning data. The system's ability to process simultaneous text, voice, video, and physical interaction inputs while providing contextually relevant feedback represents a significant advancement in educational technology. This innovation extends current capabilities in multimodal AI by developing new algorithms for real-time learning analytics and adaptive feedback generation in spatially complex environments. Third, the parallel implementation at two distinct sites with different learner populations (undergraduate students and workforce trainees) provides unique insights into how embodied learning principles translate across educational contexts. This comparative approach enables the investigation of how prior knowledge, learning goals, and educational settings influence the effectiveness of AI-augmented mixed-reality learning environments. The findings will contribute fundamental knowledge about the relationship between learner characteristics and technology-enhanced embodied learning. Fourth, the research develops new methodological approaches for studying technology-enhanced learning in complex spatial domains. By combining quantitative measures of spatial reasoning and technical comprehension with qualitative analysis of learning processes, the study establishes novel frameworks for evaluating the effectiveness of AI-augmented learning environments. These methodological innovations will benefit future research in technology-enhanced learning and construction education. Fifth, the research advances the understanding of how to design equitable and accessible AI-augmented learning environments. The focus on both higher education and workforce training contexts, particularly through collaboration with [redacted] - enables investigation of how technological interventions can be designed to support diverse learner populations effectively. This contribution is particularly significant given the pressing need for inclusive approaches to construction education and workforce development.

The interdisciplinary research team brings together expertise in computer science, construction engineering and education, and workforce development. This convergence of perspectives enables the development of innovative solutions that address both theoretical and practical challenges in construction education. The team's track record of successful collaboration and relevant preliminary work demonstrates their capability to execute the proposed research effectively. The research outputs, including peer-reviewed publications, open-source software, and evidence-based design principles, will advance multiple fields simultaneously. The findings will contribute to learning sciences by expanding the understanding of embodied cognition in technology-enhanced environments, to computer science by developing new approaches to multimodal AI in educational contexts, and to construction education by establishing evidence-based methods for teaching complex spatial concepts. Through these contributions, the proposed research promises to transform the understanding of how technology-enhanced learning environments can support the development of crucial spatial reasoning and technical skills in construction education. The knowledge generated will inform both theoretical frameworks for technology-enhanced learning and practical approaches to construction education across diverse educational contexts.

3. Theoretical framework:

This research is theoretically grounded in embodied cognition theory, which posits that cognitive processes are deeply rooted in the body's interactions with the world (Wilson, 2002; Shapiro, 2019). The theory suggests that learning and understanding are not purely mental processes but are intrinsically linked to physical experiences, sensorimotor activities, and environmental interactions. This framework is particularly relevant for construction education, where spatial reasoning and practical skills are fundamental to professional competence. In construction education, this theoretical perspective suggests that learning complex spatial and technical concepts requires more than visual or verbal instruction—it demands active physical engagement with spatial relationships and construction processes. Figure 2 illustrates the three key mechanisms of embodied cognition theory—sensorimotor coupling, environmental scaffolding, and action-perception cycles—and their integration within our proposed learning environment.

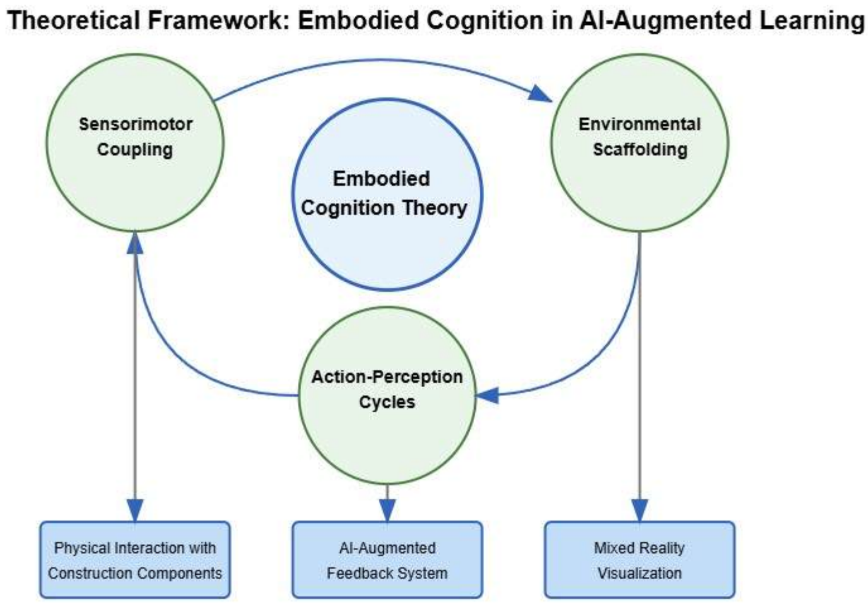


Figure 2: Theoretical Framework Visualization

The theory identifies three key mechanisms through which embodied experiences support learning: (1) Sensorimotor Coupling: Direct physical interaction with objects and spaces creates neural patterns that ground abstract concepts in concrete experiences. This coupling is essential for developing accurate mental models of construction systems and spatial relationships. (2) Environmental Scaffolding: The physical environment serves as an external support structure for cognitive processes, reducing mental load and enabling more complex problem-solving. In construction education, this suggests that manipulating physical and virtual objects can scaffold the understanding of complex systems. (3) Action-Perception Cycles: Learning occurs through continuous cycles of action and perception, where physical actions generate sensory feedback that informs subsequent actions. This cyclical process is crucial for developing both spatial reasoning and safety awareness in construction contexts.

The proposed multimodal AI-augmented mixed reality system extends embodied cognition theory in several ways. First, it creates a novel form of embodied interaction that bridges physical and virtual environments, potentially expanding our understanding of how sensorimotor experiences contribute to learning. Second, the system's real-time AI feedback introduces a new form of environmental scaffolding that adapts to individual learning patterns. Third, the integration of multiple input modes (visual, verbal, tactile) aligns with the theory's emphasis on rich, multimodal learning experiences.

This research will advance embodied cognition theory by examining how technology-mediated embodied experiences influence learning outcomes. Specifically, it will investigate:

- How AI-augmented mixed reality environments extend the concept of sensorimotor coupling beyond purely physical interactions
- The role of adaptive feedback in supporting environmental scaffolding
- The impact of synchronized physical-virtual interactions on action-perception cycles

- The relationship between embodied learning experiences and the development of abstract spatial reasoning skills

The theoretical framework suggests several testable propositions:

1. Students engaging in AI-augmented embodied learning will develop more accurate mental models of construction systems compared to those using traditional learning methods.
2. The integration of physical and virtual interactions will lead to stronger connections between concrete experiences and abstract concepts.
3. Adaptive AI feedback based on multimodal input will enhance the effectiveness of environmental scaffolding for learning.
4. Real-time synchronization between physical and virtual elements will strengthen action-perception cycles and improve learning outcomes.

By testing these propositions, this research will contribute to both theoretical understanding and practical applications of embodied cognition in technology-enhanced learning environments. The findings will help refine our understanding of how technology-mediated embodied experiences support learning and inform the design of future educational technologies. This theoretical framework guides both the technical development and pedagogical design of the proposed system. The emphasis on embodied interaction informs the integration of physical and virtual elements, while the focus on environmental scaffolding shapes the implementation of AI-driven feedback. Through this theoretically grounded approach, the research will advance both our understanding of embodied cognition and its practical applications in construction education. Furthermore, this framework provides a foundation for measuring and evaluating the effectiveness of the proposed system. By examining how different forms of embodied interaction influence learning outcomes, the research will generate insights that contribute to both learning theory and educational technology design. The results will help bridge the gap between theoretical understanding of embodied cognition and practical implementation of technology-enhanced learning environments.

4. Research plan: study, task, research questions and objectives

This research advances both learning sciences and technology development through an innovative multimodal AI-augmented mixed reality system for construction education, with a specific focus on plumbing and structural systems education. The investigation examines the effectiveness of embodied learning approaches across formal higher education and workforce training contexts, recognizing the unique spatial and safety challenges inherent in these complex building systems.

Research Questions

The study addresses three primary research questions that span both plumbing and structural systems domains:

RQ1: How does multimodal AI-augmented mixed reality affect learners' spatial reasoning and comprehension of complex plumbing and structural systems, compared to traditional learning methods across different learner populations?

RQ2: What are the key mechanisms through which embodied interaction in augmented environments supports the development of spatial understanding and safety awareness in plumbing and structural systems installation?

RQ3: How can multimodal AI adapt its feedback strategies to accommodate different levels of prior knowledge and learning contexts while maintaining educational equity across diverse learner populations?

Research Objectives

The research pursues four interconnected objectives that bridge learning sciences and technological innovation in construction education: The **first objective** focuses on developing a multimodal AI system capable of processing and integrating multiple input streams (text, voice, video, and physical interaction) to provide contextually relevant feedback for both plumbing and structural systems education. This system will specifically address the spatial complexities of system integration and safety considerations unique to each domain. The **second objective** centers on implementing an augmented reality environment that enables embodied interaction with both digital Building Information Models (BIMs) and physical construction components. This environment will support the simultaneous manipulation of virtual and physical objects while maintaining precise spatial registration and tracking, which is essential for understanding complex three-dimensional relationships in plumbing and structural systems. The **third objective** involves evaluating the system's impact through parallel studies at [redacted] and [redacted]. At [redacted], the research will engage undergraduate construction and architecture students in formal educational settings. At [redacted], the study will work with construction workforce trainees through collaboration with [redacted], focusing on practical applications in [redacted] certification contexts. The **fourth objective** establishes design principles for equitable and accessible AI-augmented learning environments that can be effectively implemented across both higher education and workforce training contexts, ensuring broad applicability and impact.

Study Design and Methods

The research employs a comprehensive three-phase approach that examines both plumbing and structural systems education:

Phase 1 (Months 1-12) focuses on system development and initial testing, with particular attention to the unique challenges of representing complex plumbing and structural systems in mixed reality. The development process incorporates feedback from construction educators, industry professionals, and potential users at both research sites, ensuring the system addresses real-world learning needs.

Phase 2 (Months 13-24) implements parallel experimental studies at both sites. At [redacted], two cohorts of twenty undergraduate students will each engage with the system through structured learning modules. At [redacted], two cohorts of twenty construction trades workers recruited through [redacted] will utilize the system to complement their [redacted] certification training. Both groups will work with identical plumbing and structural scenarios, allowing for comparative analysis of learning patterns and outcomes across different educational contexts.

Phase 3 (Months 25-36) focuses on comparative analysis and implementation studies. This phase examines how different learner populations interact with complex spatial concepts and safety protocols in plumbing and structural systems, leading to context-specific implementation guidelines and best practices for technology integration.

Data Collection and Analysis

The research generates rich multimodal data streams analyzed through quantitative and qualitative methods. Quantitative analysis examines pre/post-test scores, spatial reasoning assessments, and system interaction logs across both sites and subject domains. Qualitative analysis explores interview transcripts, observational notes, and think-aloud protocols to understand how different learner populations develop spatial understanding and safety awareness. Learning analytics will be applied to multimodal interaction data to develop predictive models of student performance and identify effective learning strategies specific to plumbing and structural systems education.

Expected Outcomes and Deliverables

This research will produce a validated multimodal AI system specifically designed for plumbing and structural systems education, accompanied by evidence-based design principles for AI-augmented learning environments. The parallel implementation at two distinct sites with different learner populations will provide comprehensive insights into how technology-enhanced embodied learning can support spatial reasoning and safety awareness across educational contexts. The collaboration with [redacted] ensures direct industry relevance and immediate practical application in workforce development. The research systematically addresses both technical and pedagogical challenges while maintaining a focus on equity and accessibility. Through careful integration of learning sciences and technology development, this work advances our understanding of how AI-augmented mixed reality environments can enhance construction education while establishing scalable solutions for diverse educational contexts.

5. Technical Approach and Implementation

5.1 Multimodal AI Architecture for Construction Learning

Figure 3 presents the system architecture of our multimodal AI-augmented learning environment, demonstrating the integration of various input modalities and their processing through the AI core to generate adaptive feedback. The core technological innovation centers on the development of a multimodal AI system architected specifically for complex spatial reasoning in plumbing and structural systems education. The system integrates four distinct input modalities to create a comprehensive learning environment: textual interaction enables learners to engage in detailed technical queries about system components and safety protocols; voice interaction facilitates hands-free guidance during physical manipulation tasks; visual processing analyzes learners' interactions with both virtual and physical components through real-time computer vision; and spatial tracking monitors physical interactions with construction assemblies and tools.

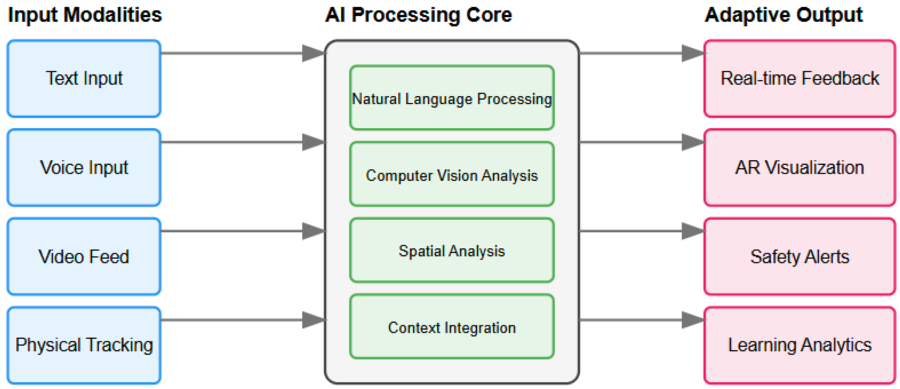


Figure 3: System Architecture

The multimodal AI system employs advanced natural language processing (Multimodal Large Language Models) reinforced with Retrieval Augmented Generation (RAG) to interpret domain-specific construction terminology, particularly in plumbing and structural systems contexts. Computer vision algorithms process real-time video feeds to identify spatial relationships, component orientations, and potential safety hazards. The system's spatial tracking capabilities enable precise monitoring of physical interactions with construction assemblies, allowing for immediate feedback on assembly procedures and safety protocols.

5.2 Mixed Reality Environment for Spatial Learning

The mixed reality environment synthesizes digital Building Information Models with physical construction components to create an interactive learning space focused on plumbing and structural systems. The environment enables simultaneous visualization of hidden components, structural elements, and system interactions that are typically challenging to observe in traditional educational settings. Through Microsoft HoloLens or equivalent affordable AR devices, learners can examine complex spatial relationships, such as pipe routing through structural members or load distribution patterns in structural systems. Figure 4 depicts the mixed reality learning environment, showing how physical components and digital overlays are synthesized to create comprehensive learning experiences for both plumbing and structural systems.

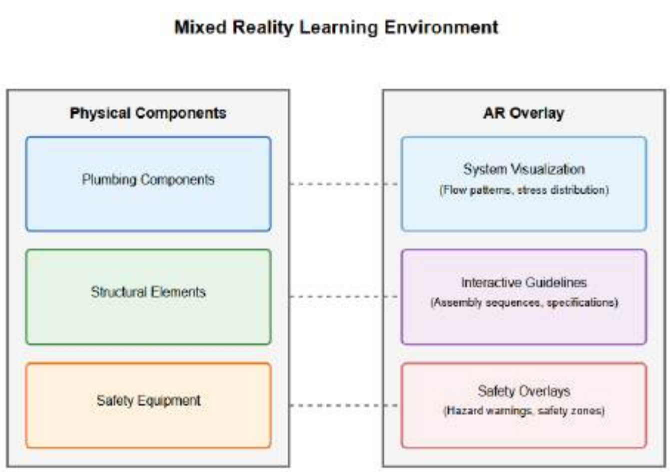


Figure 4: Mixed Reality Learning Environment

The system includes specialized modules for both plumbing and structural scenarios, each incorporating relevant safety considerations. For plumbing systems, learners can visualize water flow patterns, pressure distributions, and potential interference with structural elements. In structural scenarios, the system enables visualization of load paths, stress distributions, and critical connection points. This dual focus allows for a comprehensive understanding of both individual systems and their interactions.

5.3 Adaptive Learning Framework and Equity Considerations

The adaptive learning framework employs machine learning algorithms to analyze learner interactions across both higher education and workforce training contexts. The system adjusts its instructional approach based on learners' prior knowledge, learning patterns, and specific contextual needs. Figure 5 illustrates the specialized learning modules for plumbing and structural systems, highlighting the integration of safety considerations within each scenario. For undergraduate students at [redacted], the system aligns with formal educational objectives and theoretical foundations. For workforce trainees at [redacted], it emphasizes practical applications and [redacted] certification requirements. The framework incorporates bias detection and mitigation strategies to ensure equitable learning experiences across diverse populations. Continuous monitoring of system responses and learning outcomes enables the identification of potential biases in feedback generation or performance assessment. The development process includes regular evaluation of system behavior across different demographic groups and learning contexts to maintain fairness and accessibility. This technical approach creates a scalable and adaptable platform that supports both theoretical understanding and practical skill development in construction education. The integration of multiple input modalities, combined with context-aware adaptation, enables comprehensive support for spatial reasoning and safety awareness across diverse educational settings.

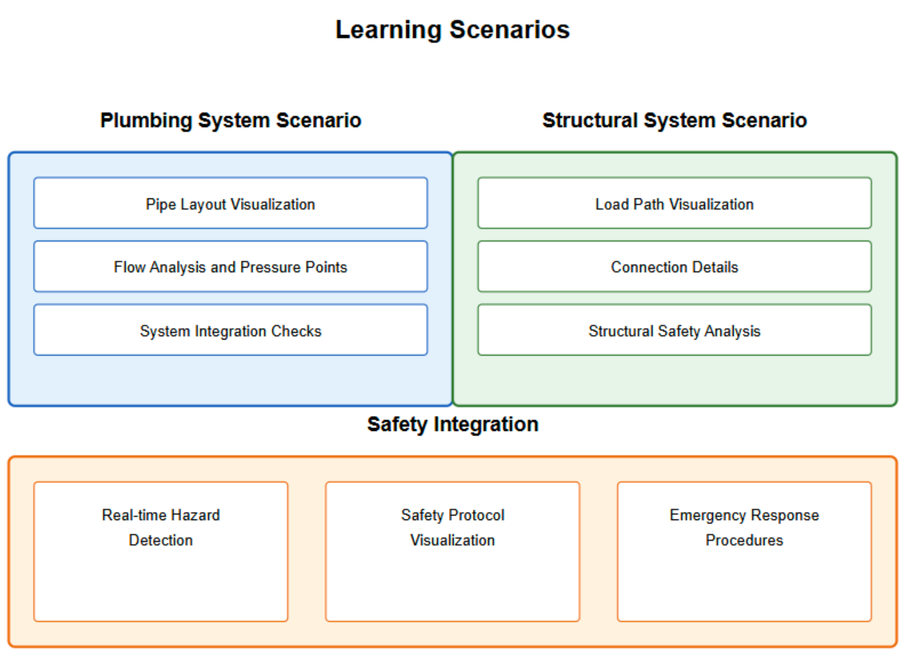


Figure 5: Learning Scenarios

6. Evaluation Plan

Figure 6 outlines our mixed-methods three-tier evaluation framework, encompassing learning outcomes assessment, system effectiveness evaluation, and implementation assessment across both research sites, focusing on plumbing and structural systems education.

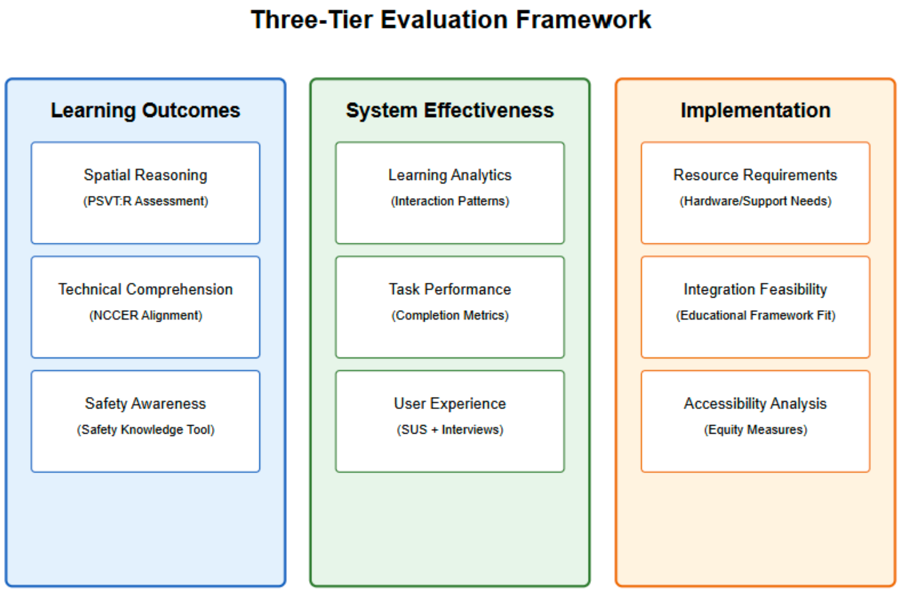


Figure 6: Evaluation Framework

Learning Outcomes Assessment

The evaluation of learning outcomes employs validated instruments administered at both [redacted] and [redacted]. Pre and post assessments will measure: (1) Spatial Reasoning: [redacted] will assess learners' ability to mentally manipulate three-dimensional objects, particularly relevant for understanding complex plumbing and structural systems. This standardized instrument enables comparative analysis across different learner populations. (2) Technical Comprehension: Domain-specific assessments aligned with NCCER certification requirements will evaluate the understanding of plumbing and structural systems. These assessments include both theoretical knowledge and practical application components. (3) Safety Awareness: A comprehensive safety assessment protocol aligned with OSHA guidelines and [redacted] safety certification requirements will evaluate understanding of safety protocols, hazard identification, and risk mitigation strategies specific to plumbing and structural work. This assessment includes both knowledge-based evaluations and practical scenario-based assessments.

System Effectiveness Evaluation

The evaluation of system effectiveness combines quantitative metrics with qualitative analysis using the following measures: (1) Learning Analytics: System interaction logs will be analyzed to identify patterns in learning progression, areas of difficulty, and effective learning strategies. This analysis will compare interaction patterns between undergraduate students and workforce trainees. (2) Task Performance: Structured tasks involving both virtual and physical components will assess learners' ability to apply spatial knowledge in practical scenarios. Performance metrics include completion time, accuracy, and safety protocol adherence. (3) User Experience: The System Usability Scale (SUS) and semi-structured interviews will evaluate the system's usability and effectiveness from learners' perspectives. This assessment will inform our understanding of how different populations interact with technology.

Implementation Assessment

The implementation evaluation examines the system's practicality and scalability using the following measures: (1) Resource Requirements: Documentation of hardware requirements, setup time, and technical support needs will inform scalability assessments. This includes analysis of costs associated with different deployment scenarios. (2) Integration Feasibility: Structured feedback from instructors and administrators at both sites will assess the system's compatibility with existing educational frameworks and potential implementation challenges. (3) Accessibility Analysis: Evaluation of system usage across different demographic groups will identify potential barriers to access and inform the development of mitigation strategies.

Data Collection and Analysis Timeline

The data collection and analysis will proceed in three main phases. The first year will focus on developing the system, establishing baseline measurements through pilots, initial usability assessments, and evaluation protocol development. The subsequent eighteen (6-month overlap with the third phase) months will involve continuous data collection through learning analytics, task performance assessments, user experience interviews, and implementation feasibility documentation. The final year will be dedicated to comprehensive analysis, including statistical evaluation of learning outcomes, comparative analysis across sites, synthesis of qualitative and quantitative data, and development of implementation recommendations.

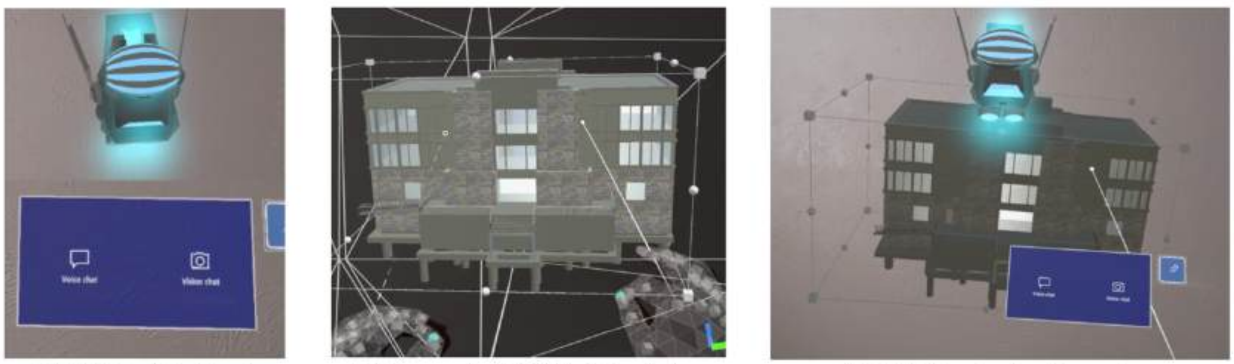
Success Metrics

The evaluation will consider the following key metrics:

1. Statistically significant improvement in spatial reasoning scores (target: 20% improvement over baseline)
2. Improvement in passing [redacted] certification requirements (target: 85% pass rate)
3. System usability scores above industry standard (target: SUS score > 70)
4. Positive implementation feasibility assessment from both research sites
5. Demonstration of equitable learning outcomes across demographic groups

Preliminary Work

We have developed preliminary prototypes that address Objective 1 and Objective 2 of this proposed project. Specifically, we have developed a prototype system that integrates multimodal AI systems and immersive interaction with BIM models within an augmented reality environment on the Microsoft HoloLens 2 device, as shown in Figure 7. The developed AI system is overlaid within the extended reality environment of the Microsoft HoloLens 2 (Figure 7(a)). The multimodal AI assistant is developed using the open-source Vision Language Model (VLM), LLaVa-34b [14], which processes comprehensive responses to both visual and voice-based queries. Additionally, the AI assistant leverages LLM, such as the LLaMA-3 13b model [15] , for text and voice chat functionality. Model inference for both the LLM and VLM is conducted via Llama.CPP [16], which serves as the backend server for the AI system within the augmented reality environment. Llama. cpp is a tool that allows the execution of quantized LLMs on local hardware with support for different types of GPU. Additionally, we have built a prototype system to enable embodied interaction with BIM models within an augmented reality environment, as shown in Figure 7(b). This setup allows users to manipulate and interact with an augmented BIM model, which provides hands-on experience with the building and structural components in real time. As can be seen in Figure 7(c), we have also integrated the proposed AI system within this environment to facilitate queries related to the BIM model, allowing users to receive contextual responses and additional information about the components.



(a) AI Virtual Assistant (b) Augmented digital building twin (c) AVATAR mixed reality system

Figure 7: Preliminary prototype of the proposed AI system on Microsoft HoloLens 2

8. Project Team and Timeline

The interdisciplinary research team brings together expertise in construction education, human-computer interaction, and augmented reality to address both the technological and pedagogical challenges of this research.

[redacted] - Assistant Professor of [redacted], brings expertise in construction education, artificial intelligence, and digital twin technologies. His recent work on multimodal AI applications in construction and extensive experience in technology-enhanced learning environments will guide the overall project direction and implementation.

[redacted] - Professor of [redacted], contributes extensive expertise in augmented reality, human-computer interaction, and usability engineering.

[redacted] - Associate Professor of [redacted], brings expertise in engineering education, simulation and visualization, and data analytics.

Timeline and Major Milestones

Figure 6 presents the project timeline and major milestones across the three-year duration, showing the parallel implementation at both research sites and key deliverables. The project will unfold over three years, beginning with system development and initial testing in Year 1, which includes requirements gathering, learning scenario development, and IRB approval, followed by the implementation of core AR capabilities and multimodal AI architecture. Year 2 will focus on parallel user testing at both sites, with two rounds of testing at [redacted]and [redacted] (n=20 each), accompanied by continuous system refinement and preliminary analysis. The final year will be dedicated to finishing the testing phase and conducting comprehensive data analysis, implementation guideline development, and dissemination of findings through publications and presentations.

Figure 7: Project Timeline and Deliverables [redacted]

Management Plan

The team will hold bi-weekly virtual meetings to ensure project coordination and progress. Monthly technical reviews will assess development progress and address any challenges. [redacted] will serve as the primary point of contact with NSF and manage overall project coordination. [redacted] will lead the AR technical development meetings. [redacted] will coordinate educational assessment activities and manage data collection efforts.

The team will leverage existing facilities, including:

- [redacted]
- Further details regarding the management of the project are presented in the Collaboration and Management Plan.

7. Broader Impacts

This research promises substantial societal impact through its innovative approach to construction education and workforce development, particularly in plumbing and structural systems training. Through strategic partnerships with [redacted], coupled with implementation at both major research universities and workforce development programs, the project creates multiple pathways for broader impact.

The project addresses critical workforce development needs by enhancing construction education accessibility and effectiveness. By developing technology solutions specifically for plumbing and structural systems—areas that face significant workforce shortages—the research directly contributes to economic development and infrastructure sustainability. The partnership with [redacted] and emphasis on [redacted] certification programs ensures immediate practical application in workforce development, potentially accelerating the training of qualified construction professionals in underserved regions.

Educational equity stands at the forefront of the project's broader impacts. The system's development using open-source platforms and compatibility with affordable hardware makes advanced learning technologies accessible to under-resourced educational institutions. This approach specifically addresses the technology gap often faced by community colleges and workforce training programs, ensuring that cutting-edge educational tools reach diverse learner populations. The project broadens participation in STEM fields by creating multiple entry points into construction careers. The dual-site implementation—at [redacted] and [redacted] —demonstrates how the same technology can support both traditional university education and workforce development programs. This approach particularly benefits underrepresented groups by providing flexible, technology-enhanced learning pathways that accommodate diverse educational backgrounds and career goals.

Knowledge dissemination extends beyond traditional academic channels through several mechanisms. The open-source nature of the developed software enables widespread adoption and adaptation by other institutions. Collaboration with [redacted] facilitates direct implementation in nearly 200 career and technical programs across [redacted], creating a model for statewide workforce development that other states can emulate. Regular workshops and training sessions will be conducted to help educators and trainers implement the technology effectively. The research advances public understanding of technology's role in education by demonstrating how AI and mixed reality can enhance spatial reasoning and safety awareness in practical, hands-on fields. Through engagement with industry partners and professional organizations, the project helps bridge the gap between academic research and practical application, showcasing how advanced technology can support both formal education and workforce development.

The project's impact on infrastructure safety and reliability emerges through its emphasis on improving spatial reasoning and safety awareness in plumbing and structural systems education. By enhancing the quality of construction education and workforce training, the project contributes to the development of a more skilled workforce capable of building and maintaining critical infrastructure systems safely and effectively.

The sustainability of project impacts is ensured through several mechanisms: the development of open-source software, the creation of implementation guidelines for different educational contexts, the establishment of partnerships with industry organizations, and integration with existing certification programs. These elements create a foundation for long-term adoption and continued development of technology-enhanced construction education beyond the project's duration. Through these broader impacts, the project advances NSF's mission of promoting scientific and technological innovation while addressing crucial societal needs in workforce development, educational equity, and infrastructure reliability.

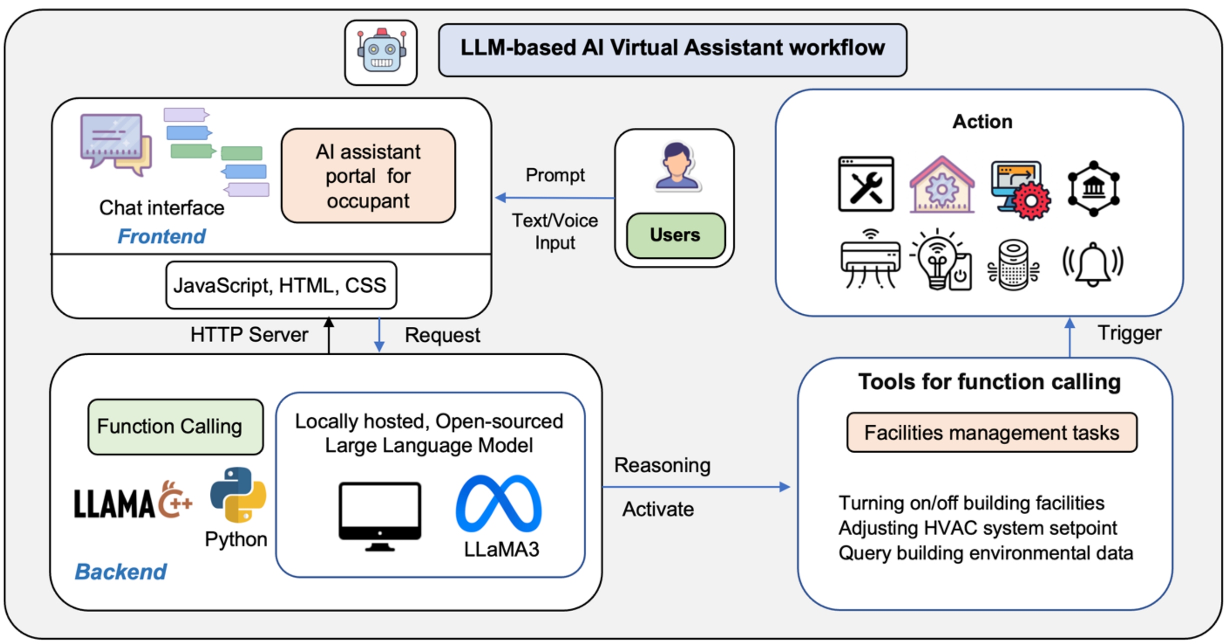
List of related Project

Project List

1. **AI assistant for smart building using Large Language Models**

Project description: The Project aims to facilitate the human-building interaction within smart buildings using open-sourced LLM such as LLaMA 3. This AI assistant provides smart and personalized assistance to occupants through web apps. Users can communicate with the AI virtual assistant through text and voice input to control various building facilities, adjust setpoints for the specific building smart facilities, or turn systems on or off as needed. The assistant also provides real-time information on indoor environmental conditions by accessing live sensor data from the IoT device. The Text-to-Speech (TTS) and Speech-to-Text (STT) models are powered by open-source tools and models such as Whisper and Piper.

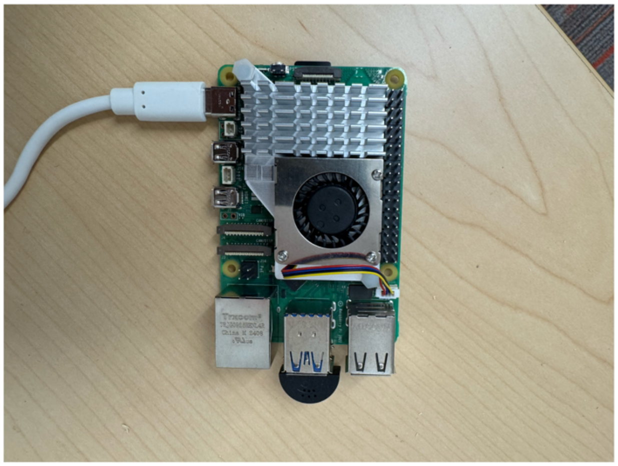
Link: GitHub Page (Description, Code, Video demo)



2. **Small Language Model-Based Smart Home Devices for Human-Building Interaction**

Project description: This project explores the integration of small language models (SLMs) with smart home environments by deploying the Phi-3 Mini model and Llama 3.2 onto a Raspberry Pi 5 to enable natural language interaction with building systems. The primary objective is to enhance human-building interaction through accessible, cost-effective, and localized AI-powered solutions. This project seeks to revolutionize human-building interaction by embedding generative AI within the built environment. By enabling localized AI-driven decision-making, the research contributes to the development of more responsive, secure, and sustainable smart home ecosystems, forming the backbone for future smart cities.

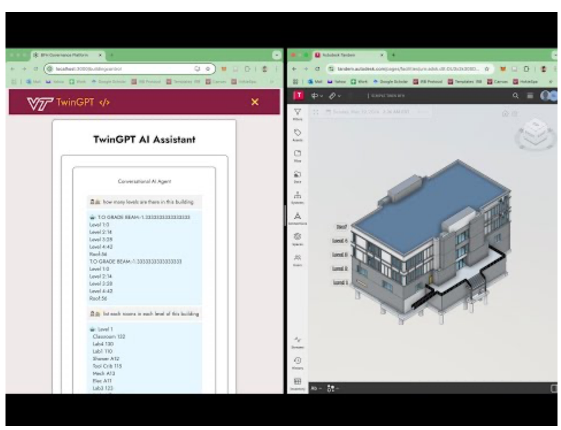
Link: GitHub Page (Description, Code, Video demo)



3. TwinGPT: Large Language Model-based AI assistant for Digital twin query

Project description: TwinGPT is an AI-powered digital twin query system designed for facility managers to interact with and extract insights from building data using a large language model (LLM). This system integrates static data, such as BIM (Building Information Modeling) details such as Rooms, Levels, and building assets, with dynamic data from sensors, environmental inputs, and occupancy information. It provides an intuitive interface for querying both historical and real-time building data. The platform offers an interactive AI chatbot, enabling facility managers to ask questions or communicate with the AI assistant to retrieve relevant building information quickly and efficiently. TwinGPT supports queries that span static BIM data and dynamic inputs, such as sensor readings, environmental conditions, and occupancy metrics. This platform is powered by the open-source AI system Llama 3.2, powered by the llama.cpp framework.

Link: GitHub Page (Description, Code, Video demo)



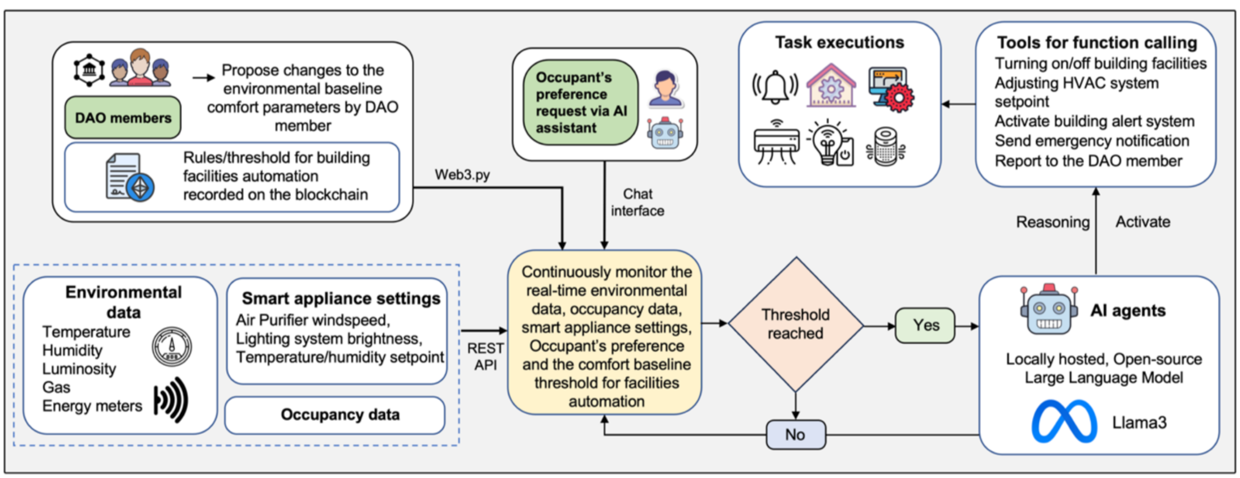
4. AI agent for Autonomous Building operation using Large Language Models

Project description: This project introduces an advanced AI agent designed to oversee autonomous building operation and facilities management. The proposed LLM-based autonomous building operation framework combines IoT devices, smart building facilities, LLMs, and blockchain technologies to create an automated system for managing building systems.

Threshold-Based Automation System: The threshold-based automation system utilizes the AI agent to continuously monitor real-time sensor data and compare it with these predefined thresholds. If the environmental conditions exceed these thresholds, the AI agent uses its function-calling capabilities to take action, such as adjusting HVAC setpoints, modifying lighting intensity, or triggering alerts to maintain optimal building conditions. These threshold values are the baseline comfort parameters for ensuring optimal comfort and indoor environmental quality.

Occupancy-Based Automation System The proposed AI agent will adjust the performance of building systems (e.g., HVAC performance or lighting intensity) based on occupancy level to dynamically optimize energy consumption. For example, during low occupancy periods, the AI agent may reduce HVAC intensity or dim the lighting to conserve energy. Conversely, during high occupancy, the agent ensures that environmental conditions are optimal for occupants. The system also accommodates user preferences and feedback through natural language processing, enabling users to provide specific requests or adjust system behaviors dynamically.

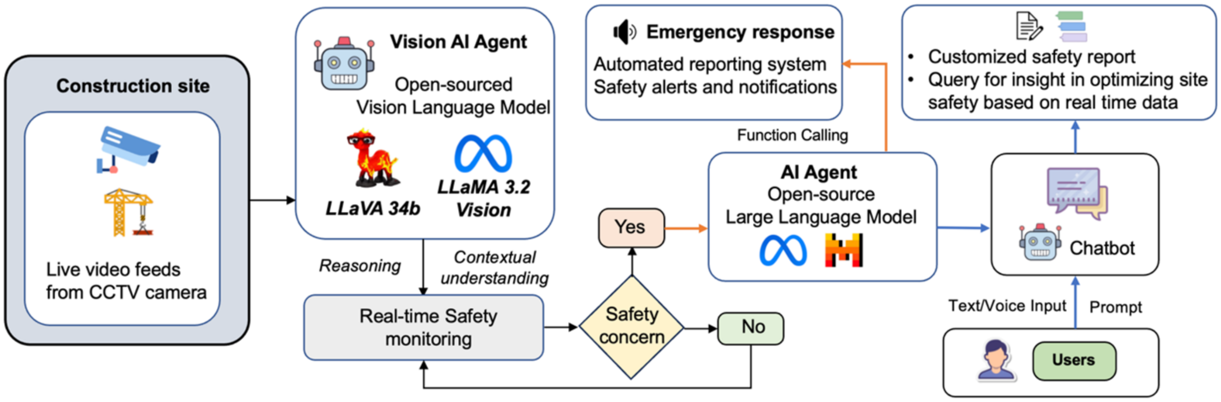
Link: GitHub Page (Description, Code)



5. Vision Language Model-based AI agent for Construction Site Progress and Safety Monitoring

Project description: This project involves developing a vision-language model (VLM)-based autonomous system to monitor construction site progress and safety conditions, thereby providing a comprehensive analysis of construction sites to ensure ongoing progress and adherence to safety protocols.

Link: GitHub Page (Description, Code, Video demo)

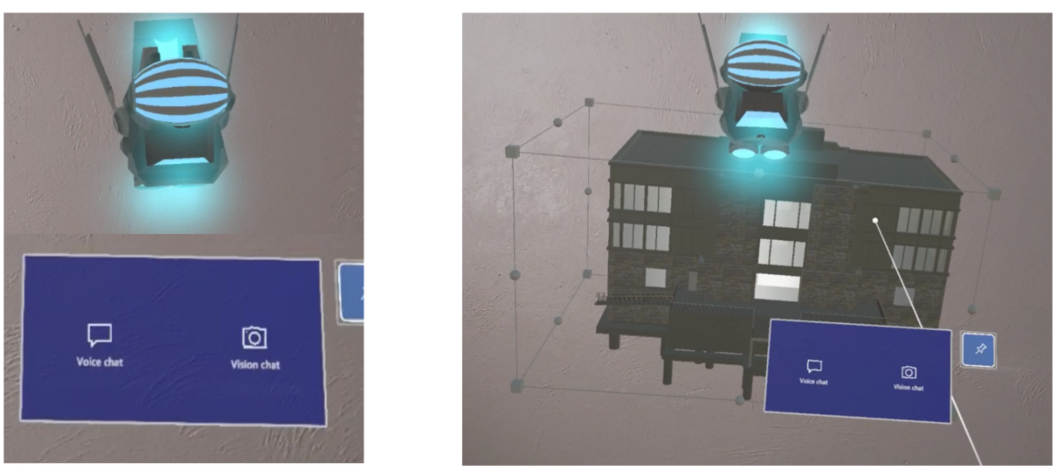


6. Vision Language Model-based AI assistant and AI agents and (XR) Extended Reality application

<u>Project description:</u> This project explores the integration of Vision Language Model (VLM), Large Language Model (LLM), and extended reality (XR) to create a Multimodal AI assistant with voice chat, Image understanding, and smart building control in immersive environments. This project aims to create an innovative solution for remote facility management and urban infrastructure monitoring.

The developed system deploys an LLM-based AI assistant and a digital building twin into an XR environment using Microsoft HoloLens 2. Users can interact with the BIM models and communicate with the Multimodal AI chatbot. Users can also interact with the AI assistant through voice commands to control building facilities. This setup enhances the ability of facility managers and occupants to interact with and control smart buildings remotely. The approach also holds the potential for scaling to multiple buildings or urban infrastructure, enabling immersive, real-time monitoring and management for smart city applications.

Link: GitHub Page (Description, Code, Video demo)

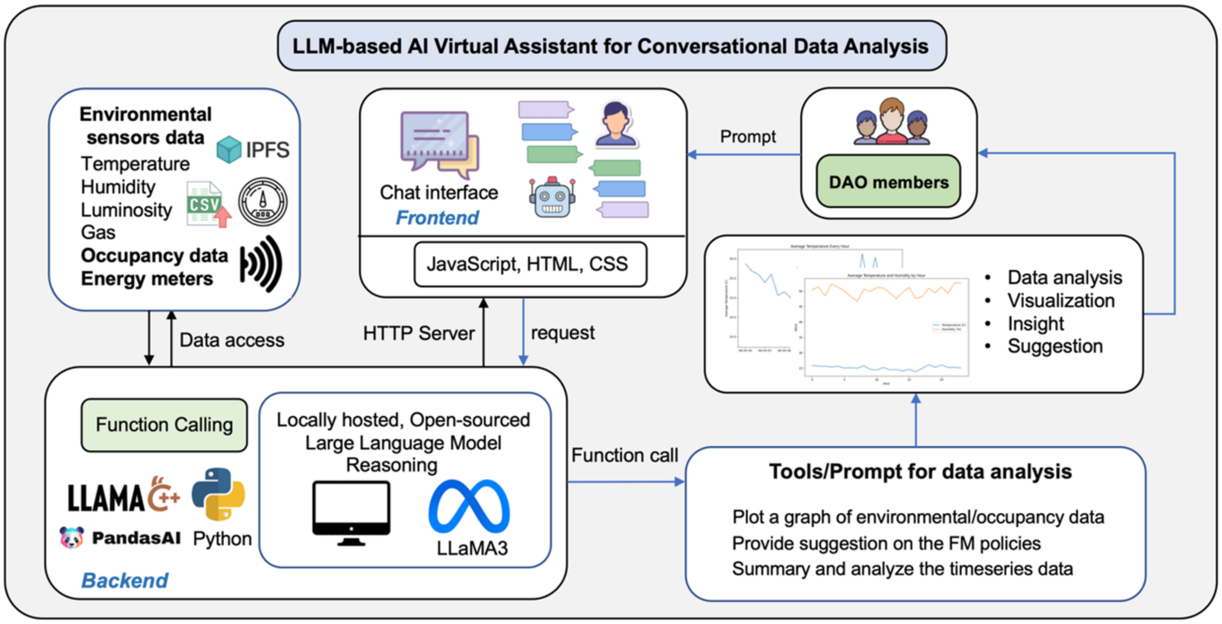


(a) AI Virtual Assistant (b) Augmented digital building twin with AI assistant

7. **Data-driven Smart Building Facilities Management using AI Assistant and Digital Twin**

Project description: This project focuses on implementing an AI and Digital twin-driven decision support system for smart building facilities management using digital twins, and large language models (LLMs). The aim is to enhance facility management through AI-driven insights and digital twin visualizations.

Link: GitHub Page (Description, Code, Video demo)



8. **Retrieval-Augmented Generation (RAG) Chatbot for Construction Safety using LLM**

Project Description: This project developed a RAG chatbot using LLaMA 3, Llamaindex, and a vector database to provide construction personnel with instant access to safety protocols and building codes. The AI-powered chatbot offers accurate and contextually relevant information from a construction safety standards database. This system enhances safety awareness and promotes a safer construction environment through efficient knowledge retrieval.

Link: GitHub Page (Description, Code, Video demo)

9. **A GenAI-Powered Prototype for Detecting Defects and Vulnerabilities in Smart Home Automation Systems**

Project description: To address this challenge, this project will develop SmartHomeSecure, an intelligent software prototype leveraging advanced Generative AI, LLaMA, to enhance smart home security and reliability. Specifically, the prototype will (i) identify and correct errors in YAML-based automation configurations through syntax and semantic analysis, (ii) detect vulnerabilities in smart home automations using control flow analysis, symbolic execution, and GenAI-powered insights, and (iii) simulate real-world scenarios to test automation performance under diverse conditions.

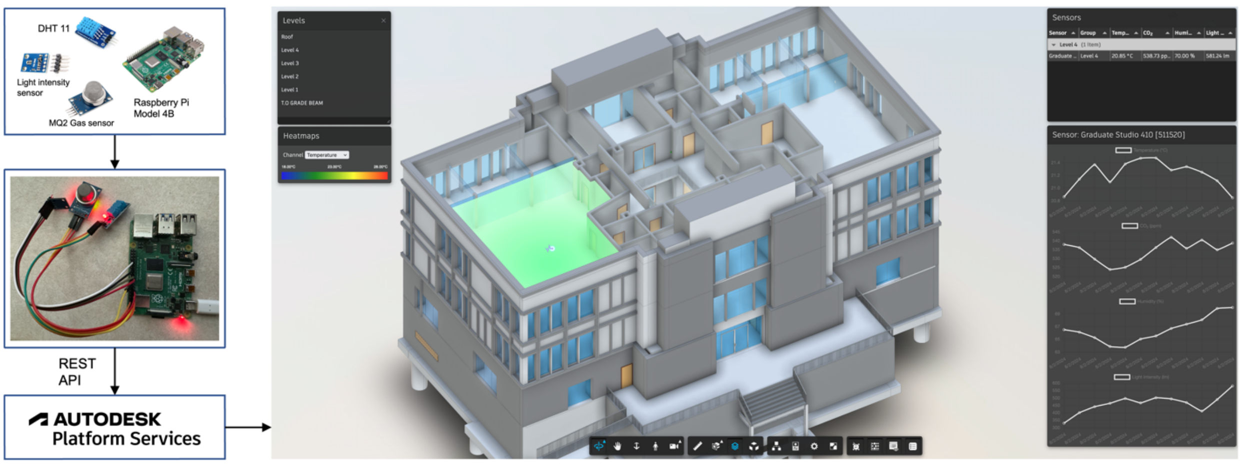
Link: GitHub Page (Description, Code, Video demo)

10. Digital building twin

Project description:

This project focuses on developing digital twins for visualization of environmental conditions within a physical building. The framework is demonstrated using a case study of Bishop-Favrao Hall, the home of the Department of Building Construction at Virginia Tech. This digital twin provides real-time visualization of environmental conditions, including temperature, humidity, lighting levels, and air quality, within the building.

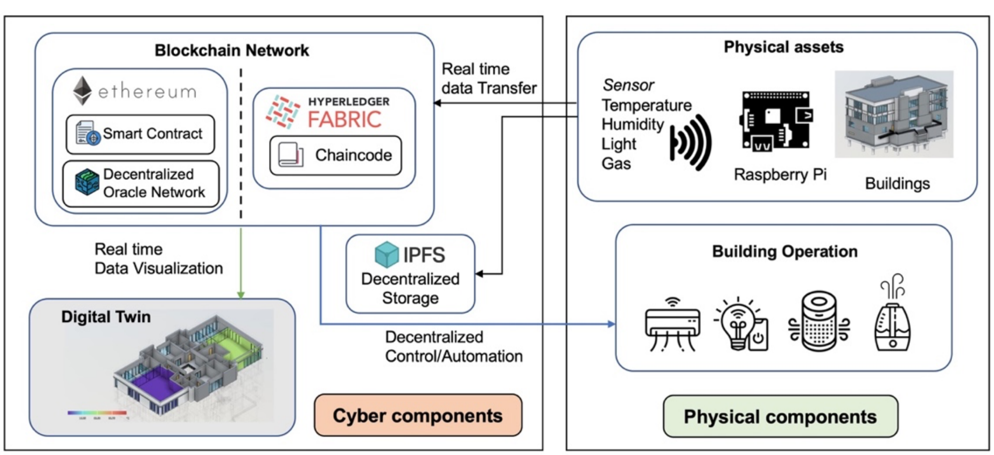
Link: [GitHub Page (Description, Code, Video demo)]



11. Decentralized Digital building twin using Public and Private Blockchain network

Project description: This project focuses on developing a blockchain-based IoT framework and digital twin model to automate and optimize building facilities operations. The project leverages Hyperledger Fabric, Ethereum blockchain, digital twin technologies, and various IoT sensors and devices.

Link: [GitHub Page (Description, Code, Video demo)]



Sample Course syllabus

Course syllabus

CMG 1000 - Introduction to Construction Management

Term: Fall 2025
Course Time: Monday, Wednesday and Friday: 9:00 AM to 9:50 AM
Classroom: Klehm Hall 2040
Course Dates: Aug. 25, 2025 – Dec. 12, 2025
Faculty: Dr. Reachsak Ly
Email: rly@eiu.edu (Preferred communication method)
Office: Klehm Hall 4014

Teaching Method: Lecture
Office Hours: Tuesday and Thursday, 11:00 AM to 1:00 PM or by appointment
Communication Response Time: Within 2 days

Required Textbooks and Readings

- **Required Textbook:** Jackson, B.J. (2020). Construction management jumpstart: The best first step toward a career in construction management. 3rd edition. Wiley & Sons, Hoboken, New Jersey
- **Suggested Textbooks**: Construction Project Management 2nd Edition by Dykstra published by Kirshner ISBN 9780-9827034-3-4
- **Readings**: Several readings will be posted on D2L.

Course description:

Major topics that will be discussed in class will include: The Construction Industry and Trends, Design and Construction Project Phases, Construction Contracts, Project Management, Pre-Construction, Estimating, Scheduling, Project Controls, Project Administration, Quality Control, Health and Safety, BIM, Sustainability and Technologies application in construction.

Course objectives:

This course will introduce the students to construction management processes and procedures, relationships, practices, terminology, project types, procurement methods, industry standards, contract documents, and career opportunities. Topics include the roles of the owner, architect, engineer, and contractor; project teams and organizations; their responsibilities and interrelationships; types of contracts; different project delivery methods; bidding and award documents and procedures; construction budgets; cost estimating; construction planning and scheduling; cost control; sustainability; technology; and managing quality, health and safety. In addition, the course will introduced different technologies used in construction industry.
A tentative schedule for this course is attached in the Course outline section below.

Student Learning outcome:

After completion of the course the student will:

- Understand the characteristics and challenges of the construction industry within the U.S. and role of construction manager/responsibilities.

- Understand the concepts relating to construction administration and project delivery systems, contracting requirements, project control and tracking, dispute resolution, safety, quality assurance and control, and bid process to contract award.
- Understand the principles of project scheduling/stages and explain network diagramming process leading to critical path method and calculations.
- Understand the basic building construction estimates for time, labor, and materials.
- Understand the latest technologies used in the construction industry.

Course Structure

- This course is mainly lectures and projects. You are required to attend each lecture, participate in the class discussion, and actively contribute to your group project.
- This course includes several homework assignments and pop-up quizzes.
- Two exams are scheduled for this course and NO final exam for this course.
- One team project is included for this course.

Graded Course Requirements Information

Homework Assignments and Quizzes

- The homework assignments cover all contents from lectures, textbooks, readings and class discussion.
- The quizzes are unannounced. Please note, there will be no chances for a pop-up quiz make up.
- Attending all lectures is the only way to not miss a pop-up quiz.

Team Projects

The team project includes two deliverables: (1) in-class presentation, (2) a report summarizing your findings written in an academic manner. Detailed information will be discussed in the lectures.

Exams

Two exams cover lectures, textbook, readings and class discussion.
No final exam is scheduled for this class.

Grading Structure

Content	Percentage
Attendance and Participation	10%
Homework assignment and quizzes	25%
Team Project	15%
Exam 1	25%
Exam 2	25%
Total	100%

Grading Scale:

Individual grade items and your final grade will be assessed as follows:
A = 100- 90%
B = 89- 80%
C = 79-70%
D = 69-60%
F = less than 60%

Grading Policies

Deductions to your assignments grade for late submission will be given as follows:
0-24 hours late a deduction of 15% of the earned grade
24-48 hours late a deduction of 40% of the earned grade
48-72 hours late a deduction of 60% of the earned grade
More than 72 hours late No credit.
Assignments must still be submitted to get a grade for this course.

Course Requirements:

1. Complete readings, assignments, attend class, and submit assignments and exams on time.
2. Demonstrating that you are interested and enthusiastic about learning is a good way to improve Participation scores. Be present in both body *and* mind.
3. Independent study of the textbook and other relevant material is required.
4. Attendance: If you do not attend and participate you will not succeed in this class. Only ***documented*** emergencies and legitimate University activity-related events (e.g., athletes for games, sponsored field trips for other classes) will be excused. Tardiness reduces points awarded by ½. No points are awarded for absences.
5. Homework Assignments, Tests, and Communication will be conducted through the campus learning management system. The student is required to access the system *daily* for updates and to submit assignments.

Course outline

* The course schedule is subject to change throughout the semester. Revisions will be noted in class.

Week	Date	Topics	Readings / Assignments / Quizzes
1	25-Aug	**Session 1A:** Course introduction	Read Syllabus & Chapter 1 and 2
	27-Aug	**Session 1B:** Construction Industry, Project Players, Construction Management	
	29-Aug	**Session 1C:** Presentation from the Lumpkin College Hub for Engagement, Leadership and Professionalism	
2	*1-Sep*	***No Class***	
	3-Sep	**Session 2A:** Project Delivery Methods **-** DBB, DB & CM Agency	Read Chapter 2
	5-Sep	**Session 2B:** Project Delivery Methods - DB Bridging, CM@Risk, & IPD	
3	8-Sep	**Session 3A:** Getting the Work	Read Chapter 3
	10-Sep	**Session 3B:** Project Stage - Predesign & Design Stage	Read Chapter 5
	12-Sep	**Session 3C:** Project Stage - Construction & Post-Construction	
4	15-Sep	**Session 4A:** Managing Teams	Read Chapter 6
	17-Sep	**Session 4B:** Contracts – Drawings and Spec	Read Chapter 4

	19-Sep	**Session 4C:** Contracts - Contract Types	
5	22-Sep	**Exam review**	
	24-Sep	**Exam 1**	
	26-Sep	**Session 5A:** Preconstruction	Read Chapter 7
6	29-Sep	**Session 6A:** Estimating	Read Chapter 8
	1-Oct	**Session 6B:** Contract Administration	Read Chapter 9
	3-Oct	**Session 6C:** Change Orders	
7	6-Oct	**Session 7A:** Construction Operation	Read Chapter 10
	8-Oct	**Session 7B:** Site Management	
	10-Oct	**Session 7C:** Planning and Scheduling 1	Read Chapter 11,
8	13-Oct	**Session 7C:** Planning and Scheduling 2	Read Chapter 11,
	15-Oct	**Session 8A:** Managing Quality & Safety	Read Chapter 13
	17-Oct	***No Class***	
9	20-Oct	**Workshop #1**	
	22-Oct	**Session 8B:** Monitoring Project Performance	Read Chapter 12
	24-Oct	**Session 8B:** Value Engineering and EVM	
10	27-Oct	**Session 9A:** Risk Management	Read Chapter 14
	29-Oct	**Session 9B:** BIM	Read Chapter 15
	31-Oct	**Session 10A:** IoT and Sensing	
11	3-Nov	**Workshop #2**	
	5-Nov	**Session 11A:** UAS	
	7-Nov	**Session 11B:** AR/VR	
12	10-Nov	**Session 12A:** Digital Twin	
	12-Nov	**Session 12B:** Machine Learning	
	14-Nov	**Workshop #3**	
13	17-Nov	**Session 13A:** Sustainability and Built Environment	
	19-Nov	**Session 13A:** Lean Construction	Read Chapter 16
	21-Nov	**Session 13B:** Introduction to LEED	
14		**Thanksgiving Break**	
15	1-Dec	**Exam Review**	
	3-Dec	**Exam 2**	
	5-Dec	**Presentation Preparation**	
16	8-Dec	**Team Presentation**	
	10-Dec		
	12-Dec		

Note: This is a tentative schedule, and subject to change as necessary. The instructor reserves the right to make changes to the topics or sequence of topics, schedule, assignments, grading plan, and content of the course.

Academic Integrity:

Students are expected to maintain the principles of academic integrity and conduct as defined in EIU's Code of Conduct (http://www.eiu.edu/judicial/studentconductcode.php). Violations will be reported to the Office of Student Standards. In this class, students may assist each other in accomplishing a homework assignment, but the submitted work must be the student's own original work. **Copying work or plagiarism will not be tolerated. Students may *not* collaborate on tests or quizzes. Cheating or plagiarism will, at least, result in a zero on the assignment or exam.**

- *AI and Academic Integrity:* Students are not allowed to use advanced automated tools (artificial intelligence or machine learning tools such as ChatGPT, Grammarly, or Dall-E 2) on assignments in this course. Each student is expected to complete each assignment without substantive assistance from others, including automated tools.

Students with Disabilities:

If you are a student with a documented disability in need of accommodations to fully participate in this class, please contact the Office of Student Disability Services (OSDS). All accommodations must be approved through OSDS. Please stop by Ninth Street Hall, Room 2006, or call 217-581-6583 to make an appointment

Emergency Preparedness Plan:

Instructions regarding procedures to follow in the event of an emergency are posted in all classrooms. Students are responsible for acquainting themselves with these instructions so that they are prepared in the event of an emergency.

The Academic Success Center:

Students who are having difficulty achieving their academic goals are encouraged to contact the Academic Success Center (www.eiu.edu/~success) for assistance with time management, test taking, note taking, avoiding procrastination, setting goals, and other skills to support academic achievement. The Center provides individualized consultations. To make an appointment, call 217-581-6696 or go to 9th Street Hall, Room 1302.

Course syllabus

CMG 2223 - Print Reading and Introduction to Building Information Management (BIM)

Term: Fall 2025
Course Time: Tuesday and Thursday: 1:00 PM to 2:40 PM
Classroom: Klehm Hall 3135
Course Dates: Aug. 25, 2025 – Dec. 12, 2025

Faculty: Dr. Reachsak Ly
Email: rly@eiu.edu (Preferred communication method)
Office: Klehm Hall 4014

Office Hours: Tuesday and Thursday, 11:00 AM to 1:00 PM or by appointment
Communication Response Time: Within 2 days

Required Textbooks and Readings

Required Textbook:

- Print Reading for Construction (6th Edition), Walter C. Brown & Daniel P. Dorfmueller, ISBN: 9781605258027
- Daniel John Stine, “Design Integration Using Autodesk Revit 2022,” SDC Publications
- Readings: Several readings will be posted on D2L.

Course Prerequisite:

EGT 2043 - Computer-Aided Engineering Drawing

Course description:

This course provides an introduction to reading and interpreting construction drawings and specifications, along with an entry-level exploration of Building Information Modeling (BIM).
In the first portion of the course, students will learn how construction plans are organized and drawn, how to read and interpret architectural and engineering drawings, and how to apply this knowledge from conceptual design through final construction documentation.
In the second part of the course, students are introduced to the fundamentals of BIM, with a focus on creating and modifying 3D building models using Autodesk Revit. Students will learn how BIM supports the design, visualization, and documentation process in the construction industry, and how it differs from traditional computer-aided design (CAD) methods.

Course objectives:

Upon successful completion of this course, students will be able to:

- Read and interpret dimensions, line types, legends, and schedules.
- Explain the role of specifications and their relationship to drawings.
- Recognize and interpret site plans, floor plans, elevations, sections, and detail drawings.

- Identify symbols and notations for structural, mechanical, electrical, and plumbing systems.
- Interpret construction details for materials and systems such as concrete, masonry, wood, and steel.
- Describe the fundamental concepts and benefits of BIM in the architecture, engineering, construction, and operations (AECO) industry.
- Distinguish BIM from traditional CAD-based design methods.
- Create basic architectural and structural components in Revit.
- Modify and organize model elements to support design intent and documentation.
- Apply basic annotation, detailing, and sheet layout functions in Revit.
- Integrate model views and schedules for project communication.

Course Structure and evaluation

This course is a sixteen-week course. Sections are provided in the learning management systems with assignments for each module. Each section's assignment must be completed by due date and time. After the due date, the instructor will evaluate all student submissions.
The evaluation is based on engagement in-class activities, homework assignments, quizzes and final project. This course uses an active learning approach, in which students should be active outside of the classroom for learning. During the class time of the BIM section of the course we will have hands-on experiences to focus information modeling using Autodesk Revit.

Grading Structure

Content	Percentage
Print Reading assignments and quizzes	25%
Print Reading groupworks	15%
Revit assignment	35%
Team Project	15%
Attendance and Participation	10%
Total	100%

Grading Scale:

Individual grade items and your final grade will be assessed as follows:
A = 100- 90%
B = 89- 80%
C = 79-70%
D = 69-60%
F = less than 60%

Grading Policies

Deductions to your assignments grade for late submission will be given as follows:
0-24 hours late a deduction of 15% of the earned grade
24-48 hours late a deduction of 40% of the earned grade
48-72 hours late a deduction of 60% of the earned grade
More than 72 hours late No credit.
Assignments must still be submitted to get a grade for this course.

Course outline:

* The course schedule is subject to change throughout the semester. Revisions will be noted in class.

Week	Date	Class topics	Readings / Assignments & Due Date
Week 1	Aug 26 Aug 28	Overview of Class Syllabus Introduction to Book and Plans **Construction Drawing** Organization Plan-set Information Types of Prints Uniform Drawing System	Units 1 & 4
Week 2	Sept 2 Sept 4	**Plan Lines and Symbols** Alphabet of Lines Construction Drawings Construction Math Measuring Drawing Scales	Units 2 - 5
Week 3	Sept 9 Sept 11	**Reading Prints** Site Plans Plan Views Architectural Drawings	Units 5 & 8
Week 4	Sept 16 Sept 18	**Foundations & Structural Prints** Footings, grade beams, slabs Structural components	Units 10 & 11
Week 5	Sept 23 Sept 25	**Framing: Residential & Light Commercial** Components of Framing Roof Framing Load-bearing Partitions	Unit 12
Week 6	Sept 30 Oct 2	**MEP** Mechanical Plans Electrical Drawings Plumbing Prints	Units 13, 14 & 15
Week 7	Oct 7 Oct 9	**Specifications & Materials** Specifications CSI Format Welding Symbols Estimating	Units 6, 7, 16 & 17
Week 8	Oct 14 Oct 16	Introduction and overview of BIM Differences between BIM and CAD How is BIM changing the AEC industry? Uses of BIM Introduction to Revit Navigation	
Week 9	Oct 21 Oct 23	BIM Authoring – Architectural modeling (Modeling basics, setting up projects, modeling basic building exterior objects)	
Week 10	Oct 28 Oct 30	BIM Authoring – Architectural modeling Object hierarchy Modeling Process for an Example Building	
Week 11	Nov 4 Nov 6	BIM Authoring – Architectural modeling Modeling Process for an Example Building	
Week 12	Nov 11 Nov 13	BIM Authoring – Family Creation Custom Modeling	
Week 13	Nov 18 Nov 20	BIM Authoring – Structural Modeling Workshop	
Week 14		**Thanksgiving Break**	
Week 15	Dec 2 Dec 4	Schedules and Quantities Workshop	

Week 16	Dec 8 Dec 10	Work on Final Project	
Final exam week		**No Final Exam**	

Note: This is a tentative schedule, and subject to change as necessary. The instructor reserves the right to make changes to the topics or sequence of topics, schedule, assignments, grading plan, and content of the course.

Academic Integrity:
Students are expected to maintain the principles of academic integrity and conduct as defined in EIU's Code of Conduct (http://www.eiu.edu/judicial/studentconductcode.php). Violations will be reported to the Office of Student Standards. In this class, students may assist each other in accomplishing a homework assignment, but the submitted work must be the student's own original work. **Copying work or plagiarism will not be tolerated. Students may *not* collaborate on tests or quizzes. Cheating or plagiarism will, at least, result in a zero on the assignment or exam.**

- AI expectations: Check the FDIC recommendation https://www.eiu.edu/fdic/ai_guidance.php

Students with Disabilities:
If you are a student with a documented disability in need of accommodations to fully participate in this class, please contact the Office of Student Disability Services (OSDS). All accommodations must be approved through OSDS. Please stop by Ninth Street Hall, Room 2006, or call 217-581-6583 to make an appointment

Emergency Preparedness Plan:
Instructions regarding procedures to follow in the event of an emergency are posted in all classrooms. Students are responsible for acquainting themselves with these instructions so that they are prepared in the event of an emergency.

The Academic Success Center:
Students who are having difficulty achieving their academic goals are encouraged to contact the Academic Success Center (www.eiu.edu/~success) for assistance with time management, test taking, note taking, avoiding procrastination, setting goals, and other skills to support academic achievement. The Center provides individualized consultations. To make an appointment, call 217-581-6696 or go to 9th Street Hall, Room 1302.

Skill Requirements
An Internet connection is necessary to participate in the assignments, access readings, transfer course work, and receive feedback from your instructional associate and/or professor. For this course, students should have a basic working knowledge of computers and Internet use as well as access to a computer with a broadband (DSL, cable, satellite) Internet connection. At a minimum, you must have a computer with Windows 7.0 or MAC 10.6. Microsoft Office 2010 including Microsoft Word, PowerPoint, and Excel are necessary. Adobe Acrobat may be used only if necessary, and with the permission of the instructor. Microsoft Office is the standard office productivity software utilized by EIU faculty, students, and staff. Microsoft Word is the standard word processing software, Microsoft Excel is the standard spreadsheet software, and Microsoft PowerPoint is the standard presentation software. Copying and pasting, along with attaching/uploading documents for assignment submission, will also be required.

Course syllabus

TEC 5143- Research in Technology

Term: Fall 2025
Course Time: Tuesday: 6:00 PM to 8:30 PM
Classroom: Klehm Hall 4431
Course Dates: Aug. 25, 2025 – Dec. 12, 2025

Faculty: Dr. Reachsak Ly
Email: rly@eiu.edu (Preferred communication method)
Office: Klehm Hall 4014

Office Hours: Tuesday and Thursday, 11:00 AM to 1:00 PM or by appointment

Communication Response Time: Within 2 days

Required Textbooks

Practical Research: Planning and Design, (11th Edition), Paul D. Leedy; Jeanne Ellis Ormrod Publisher ISBN: 9780133741322 (Textbook)

Course description

This course introduces the means and methods of research used to define and investigate problems in technology-related fields. Topics include problem and scope definition, literature review, research methodologies, data collection, and data analysis. Students will learn the processes and tools for conducting both experimental and non-experimental research, with an emphasis on research design, analysis, interpretation, and reporting. The course also guides students in the development and writing of a research proposal.

Course objectives

Objectives of this course is to prepare students to conduct research in different technological fields. Students will be able to learn to define a research problem, to conduct effective research using library and online resources, write literature reviews and research reports, and to present their research findings in a professional manner in a group environment.

Student Learning outcome

At the end of the course the student should be able to understand the knowledge and skills required to:

1. Generate a research topic and a research problem statement and develop an empirical research question
2. Use the reference area of the library, interlibrary loan services, and computerized databases to locate relevant articles on a selected topic.
3. Execute literature reviews, Search and analyze literature to identify a gap in empirical knowledge.
4. Formulate a hypothesis statement.
5. Critical read reviews of research and critique as to:
    a. Definition of a topic or problem
    b. Adequacy of prior reviews in the area

c. Selection of studies to be reviewed.
d. Analysis of study findings and pertinent characteristics
6. Develop a system for collecting data about the characteristics and results of previously conducted research.
7. Analyze this collected data and interpret and report the results.
8. Use APA standards when writing a research proposal.
9. Develop a deliverable Research Portfolio that can be used in further research.
10. Describe ethical issues related to empirical research and expectations for ethical behavior
11. Describe the steps required to create an effective empirical research proposal
12. Evaluate appropriateness of data collection and analytical methods to answer empirical research questions

Grading Structure

Content	Percentage
Attendance and participation	10%
Literature review	15%
PowerPoint presentation	15%
Quizzes	10%
Journal entries	10%
Proposal related assignment	15%
Final Proposal	10%
In-class activities	15%
Total	100%

Grading Scale:
Individual grade items and your final grade will be assessed as follows:
A = 100- 90%
B = 89- 80%
C = 79-70%
D = 69-60%
F = less than 60%

Grading Policies
Deductions to your assignments grade for late submission will be given as follows:
0-24 hours late a deduction of 15% of the earned grade
24-48 hours late a deduction of 40% of the earned grade
48-72 hours late a deduction of 60% of the earned grade
More than 72 hours late No credit.
Assignments must still be submitted to get a grade for this course.

Reading Assignments
Students are expected to read the textbook chapters and course slides in the relevant Module before starting each course session on the D2L.

Participation
Face to Face (F2F) courses students will need to attend class and participate in classroom discussions or activities in order to receive participation points. We will have either have activities or online based activities to show participation for the week. Partial participation points will be given in certain approved circumstances with official proof provided, (i.e., doctors note, accident report, etc.)

Journal Entries
Journal entries are not for reciting facts. It is a self-reflection on what you have learned and how you plan to use or have used the information. You are required to complete a journal entry every week for 12 weeks during the semester. See the “Journal Entry Requirements” PDF document in the Assignment Explanation Module.

Literature Reviews
Each student is asked to provide a list of three scholarly articles that are relevant to his/her own research topic interest. Students will use these articles to create their qualitative, or quantitative research proposals. This exercise is also designed to provide the opportunity for students to demonstrate their skill at completing some basic steps necessary to conduct literature reviews. See the “Literature Review Requirements - Sample” PDF document in the Assignment Explanation Module.

PowerPoint Presentations
Each student will present their Research Project in a series of two PowerPoint presentations. The first will be a 5-minute presentation based on their Research Topic, the Research Problem, Sub-problems and your Hypothesis. This will be completed on Week 7. The second will be a 10-minute presentation based on their Proposal Introduction, Problem Statement, Objectives, Preliminary Literature Review, and Methodology. This will be completed in the final class meetings. Attendance is mandatory, even if you have already presented your Research.

Quizzes
The quiz date will be announced in advance and will cover material from specified chapters in the textbook and from PowerPoint slides in the course Modules. Each quiz will be worth 25 points based of 25 questions from True and False or Multiple Choice. Each quiz will be available on D2L.

Research Project Proposal
There will be an individual project proposal that each student will write based on the instructions provided in the D2L. There will be a series of assignments based on the components required to create a proposal. Students will prepare and submit their components in an approved format and APA style in a Word document. The details of the project will be announced on D2L throughout the semester. See the “A sample proposal with comment” and “Sample Proposal Format” PDF documents in the Assignment Explanation Module.

In-class Activities
Some in-class activities and additional assignments (Library, APA and Proposal Correction) are required during the semester. You are responsible to read the description of these assignments on D2L and complete them with instructions when the appropriate Module is discussed. Some of these exercises will require submission via d2l.

Course outline
* The course schedule is subject to change throughout the semester. Revisions will be noted in class.

Week	Date	Class topics	Reading	Assignments and Quizzes
Week 1	Aug 26	Course introduction Introduction to empirical research		

Week 2	Sept 2	The Nature and Tools of Research	Chapter 1	
Week 3	Sept 9	The Problem: The Heart of the Research Process Problem Statements	Chapter 2	
Week 4	Sept 16	Review of the Related Literature Literature Analysis Gap statement	Chapter 3	
Week 5	Sept 23	Planning your Research Project Research Questions	Chapter 4	
Week 6	Sept 30	Writing the Research Proposal	Chapter 5	
Week 7	Oct 7	Presentations Quiz #1		
Week 8	Oct 14	Quantitative Descriptive Research	Chapter 6	
Week 9	Oct 21	Experimental, Quasi-Experimental, and Ex Post Facto Designs	Chapter 7	
Week 10	Oct 28	Analyzing Quantitative Data	Chapter 8	
Week 11	Nov 4	Qualitative Research Methods Quiz #2	Chapter 9	
Week 12	Nov 11	Historical Research	Chapter 10	
Week 13	Nov 18	Analyzing Qualitative Data	Chapter 11	
Week 14		**Thanksgiving Break**		
Week 15	Dec 2	Mixed-Methods Designs Limitations	Chapter 12	
Week 16	Dec 8	Final Presentations		
Final exam week		**No Final Exam**		

Note: This is a tentative schedule, and subject to change as necessary. The instructor reserves the right to make changes to the topics or sequence of topics, schedule, assignments, grading plan, and content of the course.

Academic Integrity

Students are expected to maintain the principles of academic integrity and conduct as defined in EIU's Code of Conduct (http://www.eiu.edu/judicial/studentconductcode.php). Violations will be reported to the Office of Student Standards. In this class, students may assist each other in accomplishing a homework assignment, but the submitted work must be the student's own original work. **Copying work or plagiarism will not be tolerated. Students may *not* collaborate on tests or quizzes. Cheating or plagiarism will, at least, result in a zero on the assignment or exam.**

- *AI and Academic Integrity:* Students are not allowed to use advanced automated tools (artificial intelligence or machine learning tools such as ChatGPT, Grammarly, or Dall-E 2) on assignments in this course. Each student is expected to complete each assignment without substantive assistance from others, including automated tools.

Written work may be submitted through Turnitin in D2L. Turnitin includes an AI detection tool which indicates the amount of qualifying text within the submission that Turnitin's AI writing detection model determines was generated by AI. This information may be used, in addition to other evidence, if there are concerns with academic misconduct.

It is also the responsibility of the student to ensure that his or her work does not qualify as plagiarism. If a student does not understand plagiarism, then he or she must seek out information on the matter. The excuse of ignorance on the matter is not an acceptable excuse.

Students with Disabilities

If you are a student with a documented disability in need of accommodations to fully participate in this class, please contact the Office of Student Disability Services (OSDS). All accommodations must be approved through OSDS. Please stop by Ninth Street Hall, Room 2006, or call 217-581-6583 to make an appointment

Emergency Preparedness Plan

Instructions regarding procedures to follow in the event of an emergency are posted in all classrooms. Students are responsible for acquainting themselves with these instructions so that they are prepared in the event of an emergency.

The Academic Success Center

Students who are having difficulty achieving their academic goals are encouraged to contact the Academic Success Center (www.eiu.edu/~success) for assistance with time management, test taking, note taking, avoiding procrastination, setting goals, and other skills to support academic achievement. The Center provides individualized consultations. To make an appointment, call 217-581-6696 or go to 9th Street Hall, Room 1302.