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Integrating Multimodal Generative AI and Blockchain for Enhancing Generative Design in the Early Phase of Architectural Design Process

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Abstract: Multimodal generative AI and generative design empower architects to create better-performing, sustainable, and efficient design solutions and explore diverse design possibilities. Blockchain technology ensures secure data management and traceability. This study aims to design and evaluate a framework that integrates blockchain into generative AI-driven design drawing processes in architectural design to enhance authenticity and traceability. We employed a scenario as an example to integrate generative AI and blockchain into architectural designs by using a generative AI tool and leveraging multimodal generative AI to enhance design creativity by combining textual and visual inputs. These images were stored on blockchain systems, where metadata were attached to each image before being converted into NFT format, which ensured secure data ownership and management. This research exemplifies the pragmatic fusion of generative AI and blockchain technology applied in architectural design for more transparent, secure, and effective results in the early stages of the architectural design process.

Keywords: multimodal generative AI; generative design; blockchain; and architectural design process

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1. Introduction

The architectural design process has significantly transformed over the past few decades with generative design emerging as a powerful tool for exploring diverse possibilities quickly and precisely [1]. Although generative design originated in specialised software environments decades ago, it has become more accessible, even in widely used programs like Revit [2]. It enables a broader range of architects to incorporate advanced design techniques.

Nowadays, the application of AI in architectural design has introduced unprecedented opportunities for creativity and efficiency, allowing architects to explore new forms and functions with the aid of generative models [3,4]. Ben Dreith [5] highlighted AI's potential to transform architectural and product design's creation and conceptual stages. Generative AI applications like Midjourney, DALL-E, and Stable Diffusion, created by diverse technology firms, utilise text-to-image and image-to-image inputs to produce AI-generated images, prompting discussions about their forthcoming impact on design and architecture [6,7]. Architects can use these AI applications to explore various design possibilities, enhance their creative abilities, and receive immediate feedback for iterative improvements [8,9]. However, some argue that AI should complement and strengthen architects' skills and intuition, not replace them. Human interpretation and critical thinking remain essential in the creative process.

Traditional architectural design processes often involve iterative conceptualisation, refinement, and implementation cycles, requiring significant time and resources [10]. In comparison, Ploenings and Berger [11] noted that generative AI has shown promise in automating aspects of design generation. The image generation process starts with collecting a varied dataset from online repositories [12]. Consequently, challenges persist in ensuring the security, transparency, and traceability of design data and transactions throughout the architectural lifecycle. Moreover, the process of human–AI generative design introduces legal risks, particularly concerning intellectual property infringement and various security concerns, including issues related to data privacy and copyright [13–16]. Despite these hurdles, leveraging generative AI for architectural design presents innovative possibilities. It focuses on job augmentation and collaborative synergy between human designers and AI systems. However, achieving this synergy demands careful consideration of copyright interests and ethical implications, requiring ongoing research and dialogue [17].

Blockchain technology offers an alternative solution for dealing with challenges in creating images through generative AI. Blockchain provides a decentralised and immutable ledger system that securely stores metadata related to image datasets, training parameters, and model outputs [18–20]. Blockchain technology offers a robust framework for securing digital assets, ensuring transparency, and maintaining ownership rights through non-fungible tokens (NFTs) [21–24]. Additionally, Nawari and Shriram [20] pointed out that by immutably recording transactional data, blockchain ensures that the integrity and origin of training data are protected, preventing unauthorised modifications or data tampering. Integrating generative AI and blockchain technology promises to revolutionise how the architectural design process is conceived, shared, and protected.

Despite the recognised potential of generative AI and blockchain in architecture design, a significant gap exists in understanding how these technologies can be effectively integrated to enhance design processes. The study explores the integration of multimodal generative AI and blockchain technology to address challenges in the early stages of architectural design, such as enhancing creativity, ensuring data authenticity, and improving collaboration between architects and clients. The study's objective is to investigate how multimodal generative AI, which leverages both textual and visual inputs, can be used to enhance design creativity in architectural projects. Furthermore, it aims to explore the application of blockchain technology in converting design metadata into non-fungible tokens (NFTs), ensuring secure, authentic, and traceable data storage. By positioning the research question within the context of these emerging technologies, the study seeks to contribute to the broader discourse on how AI and blockchain can be pragmatically applied to create more transparent, secure, and effective design processes in architecture.

The significance of this research lies in its potential to redefine architectural practice by providing architects and all teams involved with tools that augment their creative capabilities and protect their intellectual property in an increasingly digital world. By integrating AI-driven generative design with blockchain-based verification, architects can achieve higher creativity and innovation while ensuring their work remains secure and traceable.

2. Materials and Methods

This study explores the integration of multimodal generative AI and blockchain technology in the architectural design process. The research followed these key stages:

1. Research design: The hypothesis posits that combining generative AI with blockchain technology enhances architectural design by ensuring secure data storage and traceability. The research followed a structured sequence, progressing from design conceptualisation to implementing blockchain technology.
2. Material selection: Generative AI tools, such as Midjourney, were selected for their ability to generate diverse designs using both text and image inputs. The Ethereum blockchain was chosen for its secure NFT-based storage capabilities. Architectural datasets were sourced from online repositories, focusing on incorporating diverse styles.
3. Procedure: In the design phase, initial sketches and text inputs were fed into AI for design generation, with iterative refinement using blending and upscaling features. For blockchain integration, design metadata were created and stored as NFTs on Ethereum, utilising a Java application for uploading and converting metadata on Firebase.

4. Result: Documented outcomes with metadata linking each AI-generated design to its NFT, verifying authenticity and traceability and evaluating supported by relevant papers, highlighting the innovative use of AI in design and the critical role of blockchain in protecting intellectual property and ensuring data integrity.

The methodology encompasses two key techniques: multimodal generative AI and data storage on the blockchain system, which are illustrated comprehensively in Figure 1. This scenario-based approach reflects the rationale behind this integration's workflow with real-life applications, demonstrating the proposed framework for integrating multimodal Generative AI with blockchain technology in architectural design. It outlines the workflow from the initial design phase, where sketches and text inputs are processed by AI, to the final blockchain integration, where design metadata are stored as NFTs on Ethereum. This figure visually represents the structured process of creating, refining, and securing architectural designs using advanced AI and blockchain technologies.

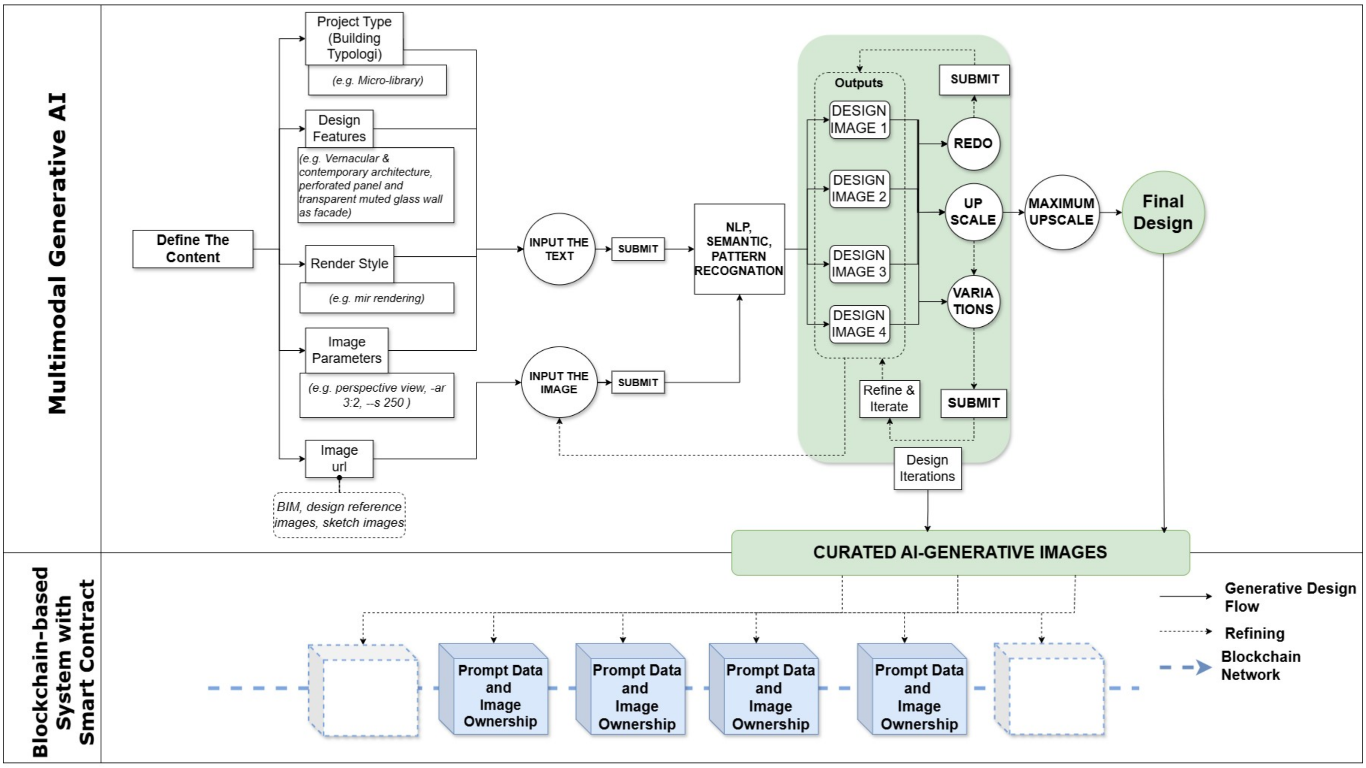
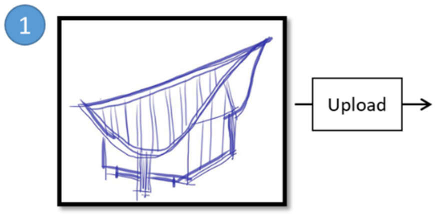
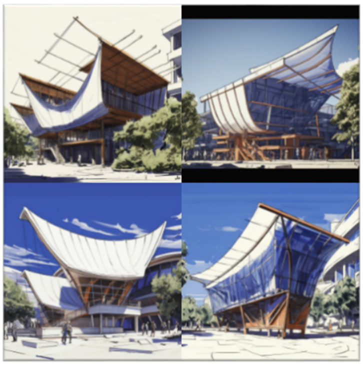
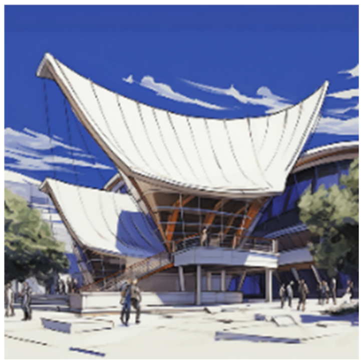
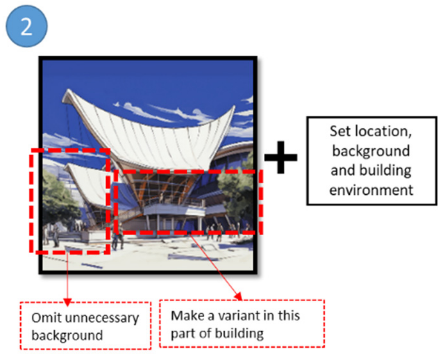
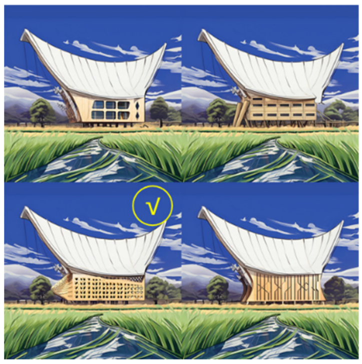
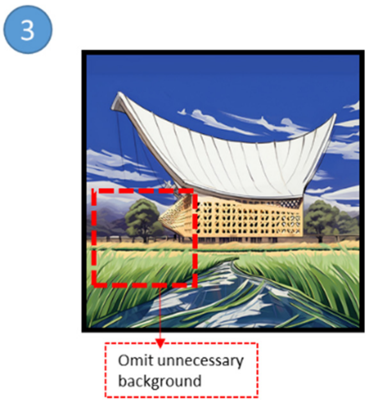
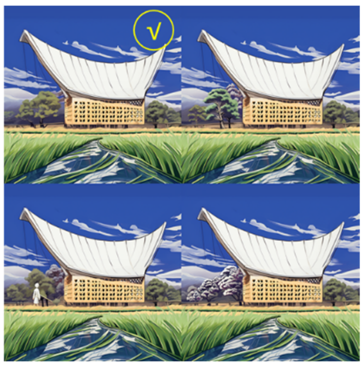


Figure 1. A framework for integrating multimodal generative AI and blockchain systems, created by the author.

As part of the multimodal shown in Table 1, we initiate the design process by outlining the building's intention through an initial sketch input into a generative AI application, like Midjourney. We use the application features and add/remove building elements within generated images iteratively. In the architectural design context, several terminologies are essential for stressing and clarifying how a beautiful building looks up to what finally ends after the practical stages provide shape. It may be through factors such as building typology, which describes the kind of project and its design, such as sustainability or cultural interpretation. For the next stage, we will design to provide context for buildings with a specific style in mind (modern architecture/postmodern/renaissance, or other desired style) and contextual designs like site or location data and details of the surrounding area. Then, the rendering style is also defined, and focus points, such as interior and lighting features, are given more depth. The generative AI system is provided with design parameters such as aspect ratio, negative prompts and level of detail in the case of 2D images to guide it toward the desired output. We put together a prompt accordingly to send over the AI model and receive an image representing our architectural concept. The following design iteration analyses the generated image to be traced back to what is intended for the final design concept.

Table 1. An example of the architectural design process using multimodal generative AI (Sketch, prompts and diagram created by the author; images generated by Midjourney).

Input	Output	
	Image Options	**Selected Images**
Design Intention: Micro-library is located in the rice field with a building concept modern house with a pyramid roof Produce a hand sketch depicting the intended shape of the building to ensure alignment with the desired design 	Prompt: https://s.mj.run/mzXZOLMb-Xw people walking, sunny day, architectural rendering --s 750 	Job [1] ID: 09effa33-8139-42cc-8704-feeddebf8186 
Modify the building and add the environment to adjust with design intention 	Prompt: Modern stilt house building with long cube shape with wooden material and perforated building façade 	Job ID: c4e63e2f-b027-4234-986b-ef2294080713 
Modify the building element 	Prompt: trees and sky—No building—Variations (region) 	Job ID: 8084c539-22e0-4cec-8163-84eba9190947 

[1] Job ID is a unique identifier (ID) assigned to each task or job that a user submits, allowing for tracking, managing, and retrieving the specific details and results of that task.

The elements integrated in generative AI applications, such as prompts, blending, upscales, variants, and remixes, are integral to the design process. These features enable a wide range of design options, offering designers a wide range of choices. Each resulting design drawing produces four variants, allowing further exploration and refinement. Alternative design options can be created by remixing the image and including additional parameters. The resulting images play a role in the architectural design process, whether they become the final result or not.

These models gain the ability to create art by discerning statistical patterns within pre-existing artistic media. The generative AI process involves training algorithms on extensive datasets comprising various art forms like paintings and photographs. These datasets are a foundation for algorithms to learn underlying patterns and stylistic elements within the artistic media. The training process includes the algorithm iteratively processing the data, refining its understanding of patterns, and gradually enhancing its ability to generate new art.

When generative AI models generate outputs based on training data, the ownership of that data can impact the generated content's legal, ethical, and regulatory implications. The training data may contain copyrighted material, and data ownership determines liability, attribution, and potential legal consequences. Moreover, data ownership plays a significant role in fostering innovation and promoting fair competition. For instance, when individuals or organisations invest time, effort, and resources into curating and creating high-quality training datasets, they should be able to derive value from their investments. It allows individuals and organisations to protect their data, influence usage, and assert their rights over the generated outputs. It also includes control and rights over the design images produced through generative AI applications, encompassing usage, modification, distribution, and monetisation. It is essential to clarify ownership boundaries and evaluate the implications of utilising specific design features to safeguard ownership claims in architectural design. By examining the role of these features in digital ownership, designers can navigate the complex landscape of control, rights, and responsibilities. This exploration can lead to frameworks and guidelines addressing the legal and ethical aspects of digital ownership and protection in architectural design.

This section will demonstrate the prompt data that could be stored within the blockchain system. Here, we utilise NFTs to store metadata, establishing data ownership for AI-generated images in the architecture design process. The application processing is available in our dataset [25].

The process begins with generating architectural images using generative AI and curating selected images. Subsequently, metadata for each image are created and stored as a .json file. The linkage between metadata and images is established, and the data are stored in cloud storage. To facilitate this, we develop a Java uploader application to store the images and their associated metadata in Firebase Storage by Google. Finally, the metadata are transformed into NFT metadata, and the entire process is deployed and executed in Remix using the ERC721 standard presented in Figures 2 and 3.

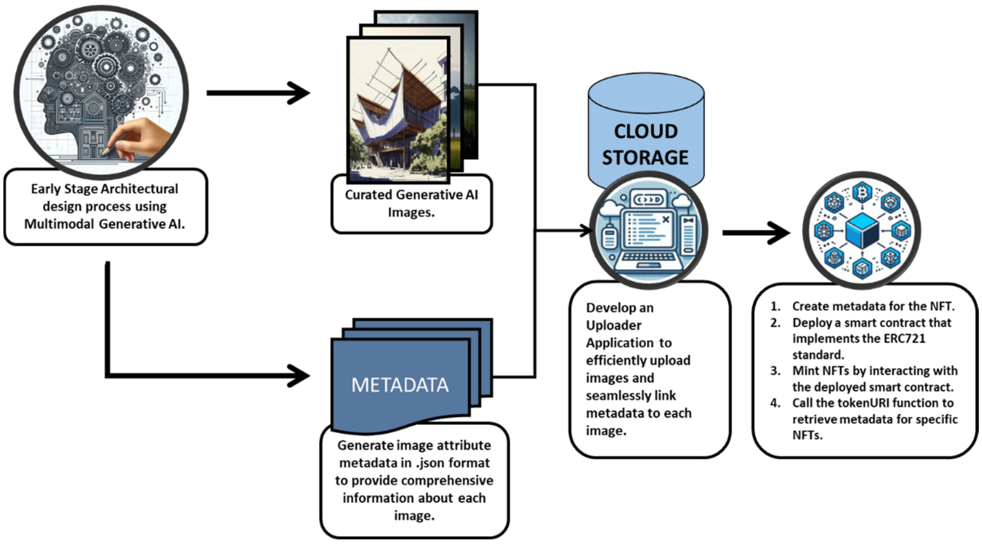


Figure 2. AI-generated images to NFT metadata: a streamlined process created by the author.

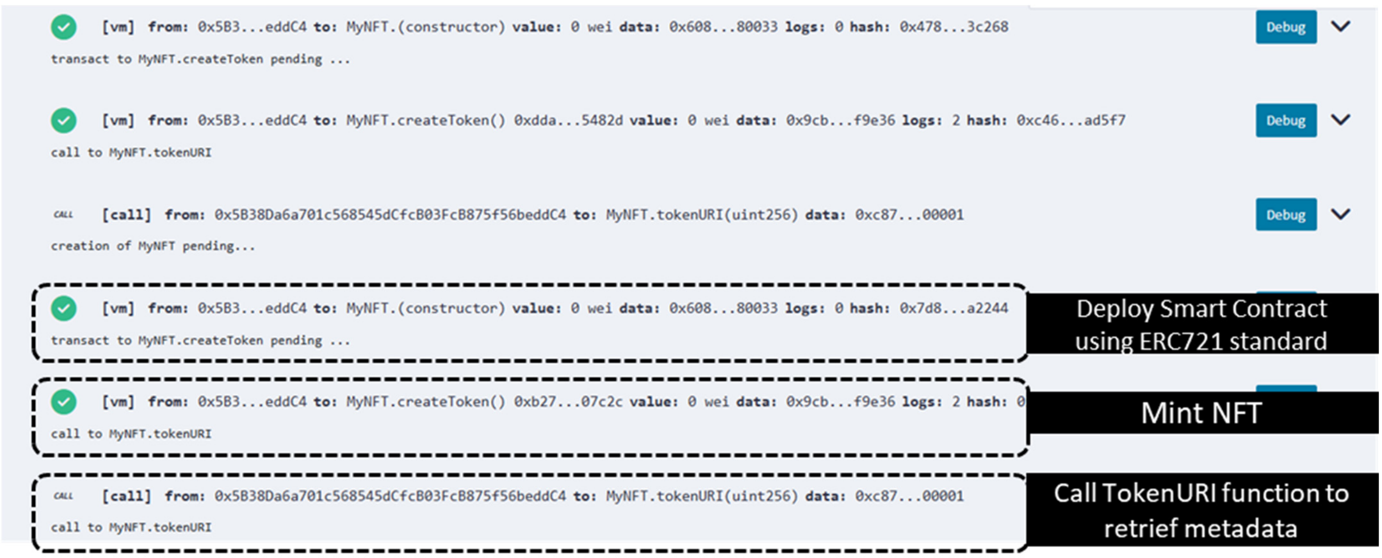


Figure 3. The screenshot depicts the deployment of NFT metadata using the ERC721 standard sourced from the dataset [25].

3. Results

This section presents the outcomes following the generative design procedure, which are stored as NFTs. These results encapsulate the prompt details as metadata linked to the resulting images. Table 2 displays pertinent information, including User ID, Job ID, Seed, and Timestamp. All data processing and implementation conducted as part of the pilot project are included in our research dataset [25].

The data in Table 2 indicate a successful transaction-deployed smart contract by representing unique identifiers of transactions or interactions within the Ethereum blockchain. Each Ethereum address represents an account or a contract on the Ethereum network. In this case, the contract address for this project is 0xb27A31f1b0AF2946B7F582768f03239b1eC07c2c, as shown in the references cited in Supplementary Materials. The transaction was successfully mined and executed (status 0×1) without generating additional output or logs. The contract deployment process is completed without errors, and the newly deployed contract is now available at the specified address on the Ethereum blockchain.

Table 2. NFT metadata, source [25].

Generative AI Image Linked to Metadata in Firebase Storage:	
	
Image Linked in Firebase [1] Storage:	
"https://firebasestorage.googleapis.com/v0/b/genainft-ac24b.appspot.com/o/image/1.png?alt=media&token=0aab1e85-3c98-4e04-ac79-db175ab7c82e (accessed on 15 April 2024)"	
Metadata (.json file):	

{
"attributes": [
{
"username": "digicliffnotes",
"user_id": "1084483399319822387",
"job_id": "c4e63e2f-b027-4234-986b-ef2294080713",
"creator_name": "Adam",
"creation_date": "April 13th, 2024 11:26 pm",
"creation_tool": "Midjourney",
"prompt": "modern_stilt_house_building_with_long_cube_shape_with_wooden_material_and_perforated_building_facade",
"image_link": "https://cdn.discordapp.com/attachments/1087237286707605535/1228727456182177862/digicliffnotes_modern_stilt_house_building_with_long_cube_shape_c4e63e2f-b027-4234-986b-ef2294080713.png?ex=662d189e&is=661aa39e&hm=e6931926dc71ae46f1f1966444fa2b5f344916e0a168a2b74e71688c1f69a478&"
}
],
"image":"https://firebasestorage.googleapis.com/v0/b/genainft-ac24b.appspot.com/o/image/1.png?alt=media&token=0aab1e85-3c98-4e04-ac79-db175ab7c82e",
"name": "Design_option #1"
}	

Link of Metadata in Firebase Storage:	
https://firebasestorage.googleapis.com/v0/b/genainft-ac24b.appspot.com/o/metadata/1.json?alt=media&token=c08b907d-b6f4-4653-9ceb-c8966e48e659 (accessed on 15 April 2024)	
Deploy and Transaction the Metadata using Smart Contract:	
The contract address:	0xb27A31f1b0AF2946B7F582768f03239b1eC07c2c
Token address [1]:	0x5B38Da6a701c568545dCfcB03FcB875f56beddC4
Token URI [2]:	"https://firebasestorage.googleapis.com/v0/b/genainft-ac24b.appspot.com/o/metadata/1.json?alt=media (accessed on 15th April 2024)"

[1] In transaction metadata using a smart contract, a token address is the unique identifier of a token contract on the blockchain, specifying which token is being interacted with; [2] Token URI is a unique identifier that points to the metadata of a specific token on the blockchain, often providing details like the token's name, image, description, and other attributes. URI (Uniform Resource Identifier) is a string of characters used to identify a resource on the internet, encompassing both URLs (Uniform Resource Locators) and URNs (Uniform Resource Names). Token refers to a unit of value or utility that is created and managed within a specific blockchain ecosystem.

Following contract deployment, a transaction executed the creation of a token within the deployed smart contract. This action resulted in minting an NFT token, incorporating metadata (data from the generated image), with ID 1 as the identifier for this metadata event. The transaction incurred a gas cost, representing the computational expense of executing the transaction on the Ethereum blockchain with an execution cost of 183,830 gas. The gas cost is the amount of Ether (ETH) required to perform transactions or execute smart contracts, reflecting the computational effort needed. In the next step, two logs were generated as a result of this transaction: the first indicating a transfer event, transferring ownership of the newly minted token to address 0x5B38Da6a701c568545dCfcB03FcB875f56beddC4, and the second representing an update of the metadata event, signifying the update of metadata associated with the token.

Subsequently, a call was made to the token URI function within the smart contract to retrieve the URI associated with token ID 1. The decoded output of this call provided the token URI, which was a URL pointing to the metadata stored on a Firebase storage bucket. In this instance, the token URI is (https://firebasestorage.googleapis.com/v0/b/genainft-ac24b.appspot.com/o/metadata/1.json?alt=media, accessed on 15 July 2024).

These metadata contain relevant information about the NFT, including its attributes, properties, and provenance. The token URI is a standardised method for accessing NFT metadata, enabling owners and users to retrieve detailed information about the digital asset. Functionally, token URIs enhance interoperability by providing consistent access to metadata across different NFT platforms and applications.

The results of this study demonstrate the practical integration of generative AI and blockchain technology in the architectural design process. The methodology and implementation details have been systematically explored, highlighting the benefits and challenges of this innovative approach. Table 3 summarises the key points considered in this integration:

Table 3. Key points of scenario.

Key Points	Description
Framework for integration	Combines generative AI and blockchain for architectural design using a hypothesis scenario framework to outline the design process flow and real-life applications.
Generative AI design process	Involves initial sketches, prompt engineering, and iterative refinement to generate accurate AI outputs. Key elements include building typology, site details, materials, spatial layout, and rendering style.
Features of generative AI	Utilises variants, upscale, blends, remixes, and prompts to provide multiple design possibilities. AI models are trained on large datasets to identify artistic trends and stylistic components.
Data ownership and legal aspects	Emphasises the importance of data ownership in AI training datasets, impacting legal, moral, and regulatory implications. It includes rights to the usage, modification, distribution, and monetisation of AI-generated outputs.
Blockchain for data storage	Uses blockchain to store prompt data and AI-generated images as NFTs, ensuring secure data ownership. The process includes generating images, producing metadata, storing data in Google Firebase, and converting metadata into the NFT format.
Results and implementation	Showcases the outcomes of the generative design process with metadata linked to final images. Provides examples of metadata, storage links, and smart contract details for NFT deployment, demonstrating the practical application of the method.

This approach ensures transparency, security, and efficiency in the architectural design process, paving the way for future advancements in the field.

3.1. AI Serves as a Creative Catalyst for Multimodal Design Generation

Multimodal generative AI has emerged as a groundbreaking approach in architectural design, offering the potential to revolutionise the design process through the integration of diverse modalities such as text, images, and videos [26], delve into the system implications of multimodal generation, highlighting challenges and opportunities for text-to-image

(TTI) and text-to-video (TTV) models. There are two main categories of generative AI models: unimodal and multimodal [27]. Unimodal models take prompts from the same modality as the content they generate. In contrast, multimodal models can accept prompts from different modalities and produce results in multiple modalities, as shown in Figure 4. Unimodal models rely on a single type of input, such as text, to generate outputs, which may limit the richness and diversity of the designs produced. In contrast, multimodal models combine multiple types of inputs, like text and images, to produce more sophisticated and varied outputs, enabling more nuanced and comprehensive design possibilities in architectural contexts.

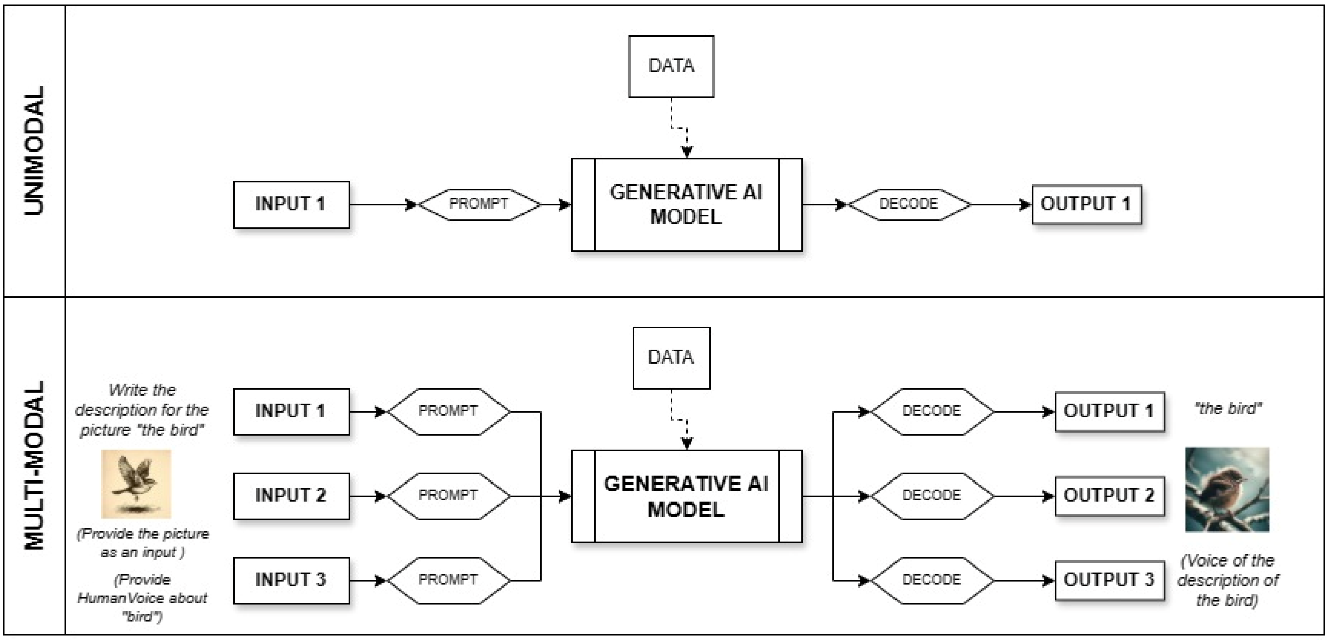


Figure 4. The difference between unimodal and multimodal generative AI, adapted from [27].

Reflecting on the case study presented in this paper, particularly as shown in Table 4, consider the difference between utilising a unimodal generative AI model solely from text input and integrating a multimodal approach using text and image prompts. When using a unimodal model, the architect's ability to convey nuanced design concepts may be limited by the constraints of text-only input.

Table 4. Comparing unimodal and multimodal generative AI in the architectural design phase.

Unimodal			
Input		Output (Generated Image by Generative AI)	
		Image Options	Selected Image
Design objective	Design iteration: Find the reference building with writing the prompt to develop the building shape suitable with the design intention	Job ID: 7c006bd2-07ad-4e8d-b9ef-47f00abc4732 	Job ID: f918bc31-bcff-4a1c-a49a-d98959652c05 
Image	-		
Prompts	Create a prompt as a trigger to draw the environment: [“micro-library, incorporating vernacular and contemporary architecture, combination of perforated metal panel and transparent muted glass wall as facade, mir rendering, perspective view, located in the rice field near the village in Taiwan, natural light”]		

Table 4. *Cont.*

		Multimodal	
Input		Output (Generated Image by Generative AI)	
		Image Options	Selected Image
Design objective	Design iteration: Combine the building to obtain wider range design options using blend	Job ID: f4e81d0e-b2e2-4057-8ee3-42a59f97551c seed 2798360210	Job ID: 8ede5825-a45c-452b-ba8e-bb22e6c2d14a seed 2798360210
Image	 		
Prompts	No prompt		

By incorporating image prompts alongside textual descriptions, architects, as users, can communicate their design intent more effectively and explore a broader spectrum of creative possibilities. This seamless transition between image and written prompts enables flexible and dynamic design exploration, ultimately generating novel and innovative design solutions. Integrating multimodal generative AI empowers architects to harness visual and textual inputs, enriching the design process and producing more robust and sophisticated design outcomes.

The multimodal AI design process involves multiple iterations and adjustments based on initial sketches and continuous modifications. This iterative nature requires significant time and effort, mainly when refining designs to meet specific architectural requirements. Consequently, project timelines may experience delays, and architects and designers may face an increased workload.

The effectiveness of multimodal generative AI highly depends on the data it is trained on. If the training data lack diversity or quality, the AI may produce repetitive or uninspired designs that do not meet the project's unique needs. Hence, there is a limitation in the AI's ability to generate creative and high-quality design options, potentially resulting in subpar architectural outcomes.

Based on the results and evaluation, particularly in the design process utilising multimodal generative AI, we conclude that three aspects significantly impact the architectural design process: efficiency, accuracy, and user interface.

Table 5 summarises the advantages and challenges of applying multimodal generative AI in design, as highlighted by various research studies. As the case study reflects, multimodal generative AI has significantly enhanced computational efficiency, accuracy, and user experience across multiple applications. On the other hand, all aspects also conclude some challenges in maintaining high accuracy, consistency, and reliability while optimising resource usage and ensuring adaptability across diverse contexts and environments, particularly in critical applications.

Table 5. Overview of the use of generative AI.

Aspect	Resume	Specific Generative AI Applications or Technology—Source
Computational efficiency	AI enables rapid design generation, exploration, and iteration.	[1] MidJourney—[28–30]; NS [2]—[31,32]; Dall-E [3]—[33].
	Designers can quickly produce, evaluate, and refine multiple options, leading to more innovative and optimised solutions.	NLP [4] and MMAIR [5]—[34] NS—[35–38]; Dall-E—[39,40]; Dde [6]—GAN [7]—[41]; CLIP [8]—[42].
	Generative AI tools for architecture need high computational power and complex algorithms.	NS—[4,36]; ChatGPT [9]—[43]; Bard AI [10]—[43]; Neural Canvas [11]—[44].
	Ensuring efficiency and accessibility for all firms is challenging due to large datasets, diverse inputs, and multiple design constraints.	NS—[4,36]; ChatGPT—[43]; Bard AI—[43]; NS—[34–38]; LLMs [12]—[45]
	These demands can slow down processing and increase resource consumption.	NS—[4,36]; Neural Canvas [44].
Accuracy	Significant improvement in imaging accuracy ensures high-fidelity imaging for precise applications.	CGANs [13]—[46]; U-Net Arch [14]—[46].
	Enhances reliability of multimodal communication and AI diagnostic processes.	GenAIVA [15] and FER [16]—[47]; ChatGPT—[48];
	Improves accuracy and transparency with visual explanations and textual analysis.	ChatGPT—[48]
	Maintaining high accuracy while optimising resource usage and ensuring adaptability across diverse contexts is challenging.	LangChain LLM—[49];
	Ensuring consistent and reliable accuracy, generalisability, and efficient knowledge transfer in resource-limited environments is crucial.	3DI [17]—[50]; MML [18]—[50]; GenAINet [19]—[51].
	Making visual explanations and textual analyses both accurate and comprehensible is challenging.	ChatGPT—[48].
User Experience (UX)	AI tools, like chatbots, improve adaptability, responsiveness, and user interaction by managing tasks and information efficiently.	ChatGPT—[52];
	Enhanced visualisation and engagement build trust in AI systems	MidJourney—[53,54];
	Integrating text, image, and voice modalities into one tool is technically complex.	NS—[55].
	Generative AI tools require new skills and workflows, causing potential frustration and reduced productivity.	Dall-E—[53]; OpenAI—[56]
	Interoperability issues and variable AI output quality may need refinement.	MidJourney—[53]; Dall-E—[53].
	Limited customisation can constrain designers' creativity.	NS—[55].
	Building user trust is challenging due to past unreliable performance and data privacy and security concerns.	[20] GAIS (IBM Watson)—[57]

[1] Generative AI program to generate images using natural language descriptions; [2] Non-specific; [3] Generative AI model developed by OpenAI; [4] Natural Language Processing; [5] Multimodal AI recognition; [6] Dde: Data-driven evaluator; [7] Generative Adversarial Network; [8] Contrastive Language-Image Pre-Training; [9] Generative Pre-trained Transformer; [10] Google' AI Chatbot; [11] AI Comic Generator; [12] Large Language Models; [13] Conditional Generative Adversarial Network; [14] Convolutional neural network; [15] Generative AI for Virtual Avatar; [16] FER: Facial Expression Recognition; [17] 3D Invariant; [18] Multimodal Machine Learning; [19] Generative AI networks; [20] Generative AI system.

The benefits of using generative AI to promote efficiency significantly contribute to increased architects' labour productivity and reduced design time. Firstly, generative AI saves time in the design practice. For example, while traditional methods may take several minutes to hours to render an image, generative AI can complete the rendering in seconds. Secondly, generative AI provides a non-linear interactive design process which catalyses design creativity. This flexibility allows designers to improvise on ideas in a random sequence not necessarily having to follow a stringent and sequential process. This flexibility will enable designers to explore and iterate on their ideas non-linearly, meaning they are not restricted to following a strict, sequential process. Instead, they can move back and forth between different design stages, making adjustments and refinements as needed. It becomes a dynamic and adaptive approach to optimising greater creativity, allowing designers to experiment with multiple ideas, receive instant feedback, and quickly incorporate changes. As a result, generative AI helps unlock new creative possibilities by driving innovative design solutions. Overall, generative AI is revolutionising the design process, making it an indispensable tool in architectural design and other fields.

3.2. Blockchain Provides Methods of Verifying and Tracing the Authenticity of AI–Human Generative Design

Blockchain technology ensures ownership by offering a transparent ledger that records and validates ownership transactions. This technology enables the creation and management of assets through non-fungible tokens (NFTs), which are unique tokens representing the ownership of a specific item or content piece.

Based on the case study in this research, illustrated in Figure 5, the "Transaction to execute **createToken()** function within NFT Smart Contract" and the subsequent processes related to minting the NFT token and updating metadata can be considered as part of the authentication process. This authentication involves verifying the transaction's validity and ensuring that the correct function is executed within the smart contract, ultimately leading to the creation and authentication of the NFT token. It will empower users to securely generate and possess digital assets on the blockchain. Furthermore, the "Token URI: Standardised Method for Retrieving Metadata Associated with NFT" process can be considered as part of the traceability process. This step involves accessing the metadata associated with the NFT through a standardised token URI. By retrieving these metadata, users can trace and verify information about the digital asset, including its attributes, properties, and provenance.

NFTs play a pivotal role in establishing ownership rights in architectural AI images by providing a unique digital representation of the asset on the blockchain. These tokens serve as a digital certificate of authenticity, verifying the ownership and provenance of the associated digital asset. In architectural AI images, NFTs can be used to tokenise specific designs, renderings, or other creative outputs generated through generative AI algorithms. By minting these assets as NFTs, architects and creators can assert ownership over their digital creations and establish a transparent chain of ownership on the blockchain. It ensures that the creator's rights are recognised and protected in the digital realm, enabling them to monetise their work, license it to others, or transfer ownership as desired. Additionally, NFTs can embed metadata that provide detailed information about the architectural AI image, further enhancing its value and utility for potential buyers or users. NFTs offer a secure and transparent mechanism for asserting ownership and managing intellectual property rights in architectural AI images, fostering trust and accountability in the digital ecosystem.

The case study approach provides detailed insights into real-world implementations, capturing multiple perspectives by examining these technologies and enhancing the reliability of the findings. After demonstrating the integration of generative AI and the implementation of the NFT blockchain, we concluded that three main aspects must be evaluated. In Table 6, we highlight the usage of NFTs from several papers, focusing on several key aspects: authenticity and ownership, integration in the creative process, and application in digital environments.

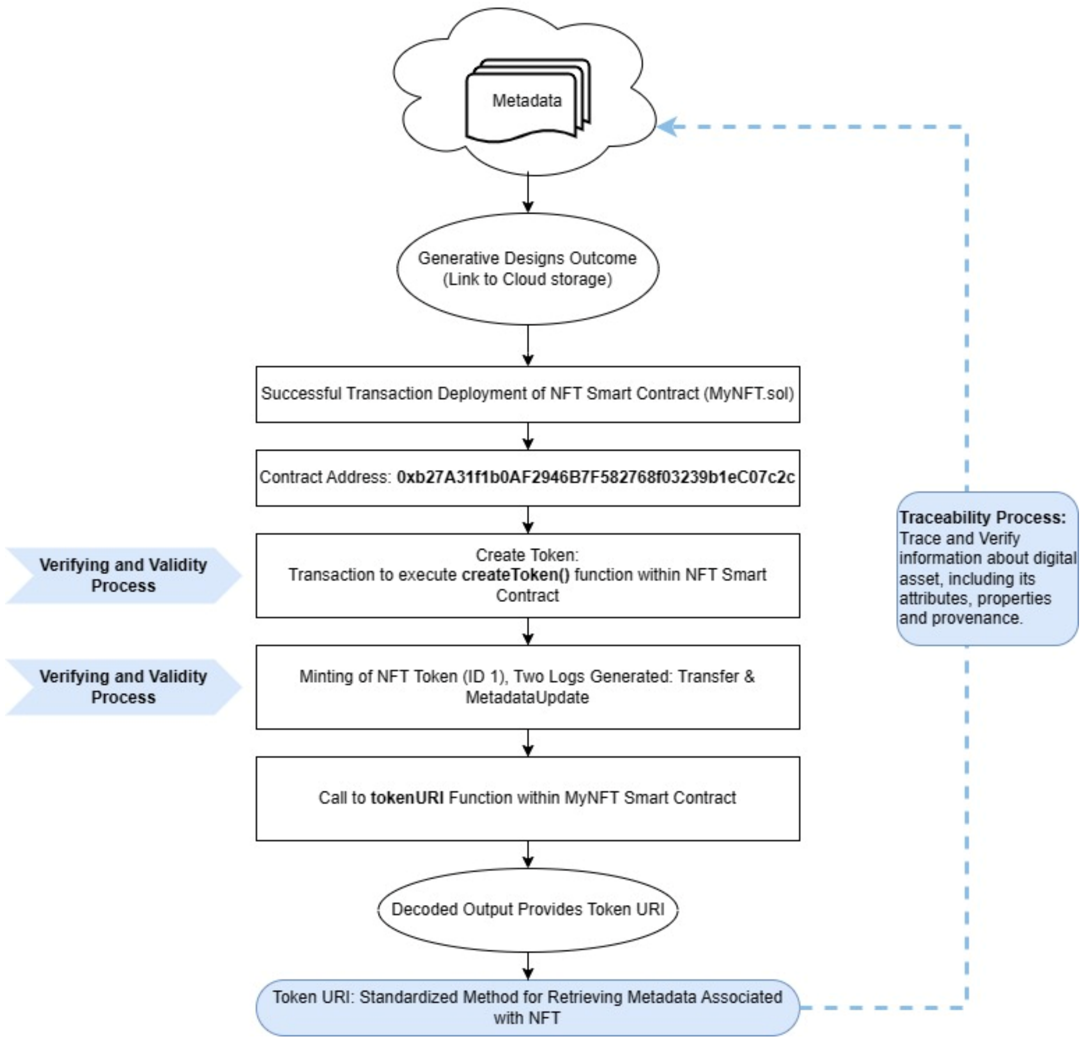


Figure 5. The process of NFT smart contract: verifying, validity and traceability.

Table 6. Overview of the aspect of using NFT and its integration.

Aspect	Resume	Source
Authenticity, certification and ownership	NFTs provide a robust method for certifying the authenticity of digital assets through blockchain technology.	[28,58–64]
	Blockchain's immutable nature ensures that the ownership records of NFTs remain tamper-proof and verifiable, thus guaranteeing the authenticity of AI-generated content.	[64–66]
	Proving ownership and authenticity in a decentralised NFT market can be complex.	[67,68]
	Ensuring the security of blockchain and NFTs against hacking, fraud, and other malicious activities is a significant concern that can impact the reliability of authenticity and ownership records.	[59,63,64]
Integration in the creative process	NFTs facilitate creating, owning, and distributing collaborative AI–human creations. This integration supports a new dimension of creativity where digital assets are co-created by humans and AI.	[59,61,65]
	Interoperability issues between different blockchain platforms can hinder seamless integration and data exchange.	[69–71]
	Complexity integrating NFT-based.	[21,72,73]

Table 6. *Cont.*

Aspect	Resume	Source
Scalability and traceability process	Blockchain-based NFTs simplify the registration, verification, and tracing of financial transactions related to digital assets, thus enhancing these transactions' overall security and transparency.	[60,63,66,74,75]
	NFTs offer a transparent and secure means to track and verify ownership of digital assets.	[76,77]
	Implementing blockchain solutions on a large scale can be complex and costly, limiting their practicality for verifying and tracking digital assets.	[21,72,78]

Integrating blockchain technology and NFTs forms a robust framework for ensuring the authenticity and ownership of digital assets within the generative AI design process. Features of generative AI, such as creating unique digital content, are enhanced by blockchain's ability to track and verify ownership securely. Legal aspects of data ownership are addressed through the immutable records provided by blockchain, ensuring clear attribution and reducing disputes. Blockchain is also a reliable digital asset storage solution maintaining authenticity and ownership. Results from various studies demonstrate the successful implementation of these technologies, highlighting their potential to revolutionise digital asset management by providing secure, transparent, and verifiable ownership of AI-generated content.

4. Discussion

This paper has uncovered important new information about integrating multimodal generative AI with blockchain technology in architectural design. We have shown that this integration improves the AI's ability to create design options and tackles key concerns about ownership verification and data protection using blockchain technology. These results are a new addition to the field, especially in digital design and asset management.

In preceding studies, the literature focused extensively on generative AI's role in design or blockchain's utility in securing digital assets. For example, Castro et al. [79] highlighted the transformative potential of AI in the conceptual stages of design, while Chalmers et al. [80] emphasised blockchain's capability to provide secure ownership records through NFTs. Our study bridges these two domains by demonstrating how their integration can create a more robust and secure design process. This approach addresses the concerns raised by Chen et al. [81] regarding the legal and ethical challenges of AI-generated content.

The similarities between our findings and those of previous research, such as the role of AI in augmenting creativity [82,83], confirm the broader applicability of generative AI in creative industries. However, our research differs by incorporating blockchain technology to enhance security and traceability, which is a step that was not comprehensively addressed in earlier studies. This combination offers a dual advantage: fostering creativity while ensuring the creative outputs are securely managed and legally compliant.

The results of our study confirm our initial hypothesis that integrating multimodal generative AI with blockchain technology can significantly enhance both the creative and security aspects of architectural design. This integration provides a framework for addressing the challenges of data ownership and opens up new avenues for securely managing digital assets.

This study identified several challenges related to integrating multimodal generative AI and blockchain technology. Table 7 summarises our approaches to addressing these challenges and the remaining research gaps.

Table 7. Overview of the research challenges.

Aspect	Challenges	Addressing Challenges	Proposed Solution	Limitations
Authenticity and traceability	Ensuring the authenticity and traceability of AI-generated images	Developing a blockchain-integrated framework that ensures the authenticity and traceability of the generative AI process.	A blockchain system can be used to store AI-generated images and their metadata as NFTs, ensuring secure and traceable data.	Scalability and performance of integrated systems in large-scale applications
Integration of technologies	Integrating multimodal generative AI and blockchain technologies seamlessly	Develop a structured framework for integration.	Combine multimodal generative AI and blockchain technology in a streamlined workflow for architectural design. Potential integration with architecture design software.	Interoperability between different generative AI tools and blockchain platforms.
Data ownership and legal issues	Managing data ownership for AI-generated content	Addressing data ownership and regulatory issues by ensuring proper attribution and legal compliance through blockchain records.	Store AI-generated images and metadata in a blockchain system, ensuring data ownership and legal compliance through NFTs.	Comprehensive studies on legal and regulatory frameworks required to govern the use of AI and blockchain in architectural design.
User experience and interaction	Improving design efficiency, accuracy, and user interaction	Utilising detailed prompt engineering to ensure accurate and relevant AI-generated images that align with the intended architectural designs.	Use generative AI applications to create and refine architectural designs, ensuring user-friendly interaction and high-quality outputs.	User acceptance and trust in AI-generated designs and blockchain-based data management.

Future work should focus on expanding training datasets to include diverse architectural styles and exploring methods to disentangle style and organisation within generative design algorithms that should accommodate various aspects supporting the architectural design process, such as building function, architectural programming, building circulation, and environmental adaptability. Additionally, we must develop user-friendly tools and interfaces that enable architects and designers to integrate generative AI and blockchain into their design workflows easily. It could involve developing plug-ins for popular design software, such as Building Information Modelling (BIM) applications, that streamline generating AI-driven designs and recording them on the blockchain. Integrating BIM and generative AI makes generative design encompass a broader design exploration. It is not only for the architectural design process but also very possible in construction design. Moreover, numerous researchers and software developers are advancing the integration of BIM and blockchain in the AECO industry. Integrating those technologies will likely support the creation of smarter, more sustainable, more accurate, collaborative, and cost-effective buildings, ultimately benefiting all stakeholders and fields involved in the project.

5. Conclusions

This study highlights the advantages of combining generative AI and blockchain in architecture, such as improving the design process, safeguarding data ownership, and enhancing authenticity and traceability. By utilising multimodal generative AI, we explored new and innovative design forms and functions, significantly broadening the creative possibilities in architectural practices. At the same time, blockchain technology facilitated the secure storage and verification of these designs. By transforming AI-generated designs into non-fungible tokens (NFTs) and storing them on a blockchain, we ensured that the digital assets remained authentic and traceable. This method not only protected the intellectual property of the designs but also created a clear and unchangeable record of ownership, which is essential in today's digital economy.

The results of this study support the idea that merging generative AI with blockchain can greatly improve the creative and security aspects of architectural design. This combination of technologies effectively tackles the critical issues of data ownership, authenticity, and innovation, offering a well-rounded solution that meets the changing demands of the architecture industry.

Supplementary Materials: The following supporting information can be downloaded at https://data.mendeley.com/datasets/d9zh352rf2/1.

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Abbreviations

The following abbreviations are used in this manuscript:

3DI	3-Dimension Invariant
AECO	Architecture, Engineering, Construction, and Operation.
CGAN	Conditional Generative Adversarial Network
CLIP	Contrastive Language-Image Pre-Training
dApp	Decentralied Application
Dde	Data-driven evaluator
ERC721	Ethereum Request for Comment 721
FER	Facial Expression Recognition
GAI	Generative Artificial Intelligence
GAIS	Generative Artificial Intelligence System
GAN	Generative Adversarial Network
GenAIVA	Generative Artificial Intelligence for Virtual Avatar
GPT	Generative Pre-trained Transformer
ID	Identifier
JSON	JavaScript Object Notation
JobID	Job Identifier
LLM	Large Language Model
MMAIR	Multimodal Artificial Intelligence Recognition
MML	Multimodal Machine Learning
NFT	non-fungible token
NLP	Natural Language Processing
U-Net	U-shaped Convolutional Neural Network
URI	Uniform Resource Identifier
URL	Uniform Resource Locators
URN	Uniform Resource Names
UUID	Universally Unique Identifier

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