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The Metaverse in Construction: Foundations, Frameworks, and Potentials

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ABSTRACT: *In an era marked by rapid technological advancements, the term "metaverse" has emerged at the forefront of discussions, yet its conceptualization remains nebulous, especially in specialized domains such as construction. The metaverse represents an interconnected digital realm where physical and virtual realities converge, enabling transformative experiences and collaborations. This study seeks to disambiguate the notion of the metaverse, particularly contextualizing it within the construction industry's paradigm. By juxtaposing the metaverse with existing technologies like Building Information Modeling (BIM) and digital twins, this paper elucidates the unique technological components that would define a construction-centric metaverse. This paper highlights precepts and requirements for a construction domain metaverse. Potential applications of the metaverse within construction settings are explored, offering practitioners insights into avenues for research and development. This research aims to offer a guide for industry professionals, technologists, and researchers, providing clarity on harnessing the metaverse's capabilities effectively and setting the foundation for its meaningful integration in construction endeavors.*

KEYWORDS: *Metaverse, Web 3, Blockchain, Virtual Reality, Digital Twins, BIM*

1. INTRODUCTION

In today's rapidly advancing technological landscape, the term "metaverse" has emerged as a topic of significant interest and discussion. However, its precise definition and applicability, particularly within specific sectors such as construction, remains shrouded in ambiguity. Fundamentally, the metaverse represents a visionary concept where the traditional boundaries separating the physical and virtual realms are blurred, offering the potential for profoundly enriching interactions and collaborative endeavors. This paper aims to provide much-needed clarity to this metaverse concept, specifically within the construction industry. The construction sector has long grappled with fragmented practices, disconnections between design and construction phases [1], issues in quality assurance, and safety concerns [2]. In light of these challenges, technologies capable of fostering improved communication, enhanced collaboration, heightened motivation, and advanced visualization hold immense promise. Within this context, the metaverse emerges as a transformative force, poised to usher in new possibilities and potentials. Leveraging technologies rooted in web 3.0, game engines, advanced visualization tools, reality capture, social platforms, and virtual economics, the metaverse offers new opportunities across diverse industries, including construction [3]. Nevertheless, despite widespread interest and recognition of its potential benefits across various sectors, there exists a prevailing lack of clarity and skepticism regarding the practicality and relevance of the metaverse within the construction domain. Additionally, studies have proposed "metaverse applications" that, in essence, do not deviate significantly from commonplace virtual reality experiences. In light of this current landscape, this paper aims to engage in a discourse on the metaverse concept in the construction domain. It endeavors to discuss the foundational requirements for its realization within the construction industry and explores its potential applications. After the introduction, the paper explores existing metaverse definitions, to provide the necessary background for the discussions that follow. Section three delves into a set of foundational precepts specific to the metaverse's role in the built environment. Section four outlines the essential requirements that underpin the development and integration of a metaverse within the construction sector. The fifth section explores diverse areas where the metaverse could find practical application, while the final section, Section 6, offers discussions and conclusions based on the established discourse.

2. DEFINING THE METAVERSE

The concept of the Metaverse has recently captivated technologists, researchers, and the general public alike, with its potential to revolutionize the way we interact and engage in virtual environments [4]. A substantial body of literature has emerged in the last 2 years, discussing the potentials and implications of metaverse technologies in finance[5], banking [6], security [7], healthcare [8]. However, it seems various studies focus on different defining features of "metaverse". Certain studies conceptualize the metaverse as a virtual platform or realm enabling user congregation, communication, and socialization. Other viewpoints extend this notion, proposing virtual environments that facilitate user engagement in real-world analogous activities with tangible implications, such as financial gains. The literature offers varied definitions of the metaverse, reflecting its multifaceted nature. However, the definition put forth by Mathew Ball offers a comprehensive and nuanced understanding of the metaverse, emphasizing key characteristics that set it apart from the conventional notion of "virtual reality." It encompasses the idea of a *"massively scaled and interoperable network of real-time rendered 3D virtual worlds that can be experienced synchronously and persistently by an effectively unlimited number of users with an individual sense of presence, and with continuity of data, such as identity, history, entitlements, objects, communications and payments."* [9]. This definition highlights several critical aspects.

1) Massive Scale and Interoperability: The metaverse's vast scale, characterized by numerous interconnected 3D virtual worlds, fosters a diverse range of experiences and interactions, transcending the confines of a single virtual environment while ensuring seamless connectivity between them.
2) Real-Time Rendering: The metaverse operates in real-time, enabling instantaneous creation and modification of virtual environments, setting it apart from static or pre-rendered virtual experiences and facilitating dynamic interactions within the digital realm.
3) Synchronous and Persistent Experience: Users can engage with the metaverse in real-time, promoting collaborative and social interactions, while the persistence of their presence over time ensures a continuous and evolving digital journey, contrasting with one-time virtual reality experiences.
4) Continuity of Data: Data integrity is paramount in the metaverse, with user identity, history, entitlements, objects, communications, and payments persisting consistently across various virtual worlds, ensuring coherence and accessibility throughout the user's metaverse experience.

Much like the internet, which constitutes a vast network of interconnected networks governed by shared standards and protocols, the metaverse is conceived on a similar scale. It envisions a multitude of interconnected virtual worlds, all adhering to shared standards and protocols, thereby facilitating interactions and experiences throughout its expansive digital expanse. Although we remain some distance away from realizing this ambitious vision, it serves as a guiding beacon for the ongoing trajectory of technological development. Building upon this definition, one can envision a construction metaverse as a kind of "proto-metaverse" or world characterized by shared standards and protocols. In this proto-metaverse, users can securely establish virtual identities, possess digital assets, and conduct financial transactions that extend not only within this proto-metaverse but also across other such proto-metaverses and the overarching metaverse at large (Figure 1). The subsequent sections expand on the precepts and foundational requirements for realizing the vision of a metaverse specifically for the construction domain.

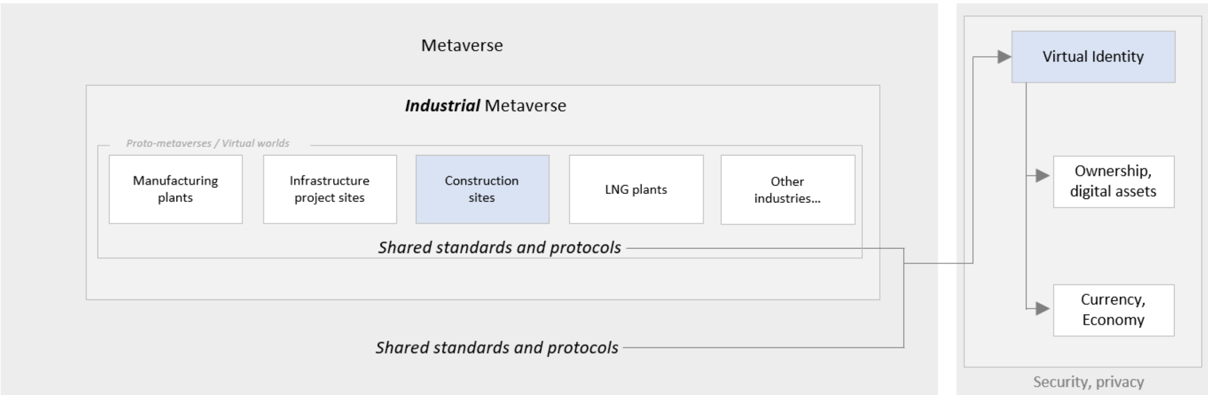

Figure 1: Metaverse concept and vision

3. PRECEPTS

3.1 Shared standards and protocols

Shared standards and protocols are imperative for the establishment of a construction metaverse. The construction industry operates within a multifaceted ecosystem involving various stakeholders, such as architects, engineers, contractors, and regulators, each utilizing distinct tools and platforms. By implementing shared standards and protocols, interoperability and data consistency can be ensured across these disparate systems, enabling seamless collaboration and data exchange. Moreover, in a construction metaverse, where real-time interactions and data continuity are essential, standardized protocols provide a common language that facilitates synchronous experiences and persistence of critical information, such as project history, asset entitlements, and quality control documentation, safety protocols and regulatory compliance records. Additionally, shared standards and protocols offer a foundation for security and data integrity, safeguarding users' identities, and financial transactions within the metaverse. In essence, these standards and protocols serve as the structural framework that underpins the functionality, coherence, and scalability of a construction metaverse, unlocking its full potential for transformative advancements in the industry.

3.2 Interoperability

Furthermore, the establishment of shared standards and protocols within a construction metaverse is imperative to ensure interoperability with existing tools and workflows. Much like the internet serves as a vast umbrella under which users can access diverse web applications seamlessly, a construction metaverse could aim to achieve a similar scale, enabling users to navigate a multitude of management tasks and activities within its expansive digital realm. This necessitates the integration of various project management software, visualization tools, and other construction-related applications. Standardized protocols act as the common language that facilitates this integration, allowing stakeholders to access and utilize these tools cohesively within the metaverse. Ideally, construction professionals would be able to seamlessly transition between different functions, from project planning and design visualization to quality control and equipment management, all within a unified and interconnected metaverse environment.

4. FOUNDATIONAL REQUIREMENTS FOR A CONSTRUCTION METAVERSE

4.1 Capturing construction environments

Capturing construction environments is pivotal for the development of a construction domain metaverse. Digital twins, which are already gaining traction in the construction industry, represent an initial step toward meeting this requirement, primarily focusing on asset data. However, to fully realize a construction metaverse with applications for collaboration, training, progress tracking, scheduling, quality assurance, and safety management, advanced reality capture techniques are essential. Prominent reality capture technologies, including LiDAR scanning, photogrammetry, and laser scanning, offer the capability to capture detailed spatial information, such as as-built conditions and topographical data. LiDAR scanning, for instance, can generate highly accurate 3D point clouds of construction sites, enabling precise progress monitoring by comparing successive scans to identify deviations from planned schedules. Nevertheless, these reality capture technologies exhibit limitations, including cost considerations, data interoperability challenges, and integration complexities with other project management systems. While advances in technologies like 360-panoramic cameras, drones, and robot dogs hold promise for addressing some of these limitations, issues related to data processing, standardization, and scalability remain open challenges that must be addressed to fully harness the potential of reality capture towards a construction metaverse.

4.2 Integrating reality capture and jobsite data with BIM and Digital Twin data

Digital Twin data constitutes a pivotal step in the development of a construction metaverse. BIM already plays a significant role in construction information management by providing a centralized platform for various project-related data, encompassing geometric information, non-geometric data, material quantities, and work schedules, among others. To unlock the full potential of a construction metaverse, it is essential to establish methodologies for aligning geometric data with reality capture information effectively. This alignment enables a fusion of the virtual and physical aspects of a construction project, allowing stakeholders to gain insights into the as-built conditions and real-time progress. Adopting a digital twin perspective, data acquired through computer vision, sensors, and other Internet of Things (IoT) devices should also be seamlessly integrated into a shared visualization of the construction project. Such integration fosters a holistic understanding of the jobsite environment, enhancing decision-making processes, and enabling real-time monitoring of project parameters. In essence, the development of novel methods for interacting with jobsite environmental data, drawing upon advancements in BIM, IoT, reality capture, and virtual reality, represents a critical requirement for the construction metaverse, offering a comprehensive and interconnected view of construction projects for enhanced project management and collaboration. Furthermore, the concept of the "digital thread," which involves the seamless flow of digital information throughout the project lifecycle, becomes central in this integration, ensuring that data remains consistently connected from design through construction and into facility operations.

4.3 Leveraging game engine technologies

Leveraging game engine technologies represents a pivotal requirement for creating a robust and engaging construction metaverse. Game engines, exemplified by industry-leading platforms like Unity and Unreal Engine, are renowned for their capacity to craft immersive, visually captivating virtual environments that can redefine user experiences within the metaverse. These engines offer a dynamic means of engaging users, facilitating a wide array of activities and interactions that are essential for project participants within a construction metaverse. Such activities encompass user communication, interactive collaboration, the utilization of avatars for representation, diverse modes of navigation, content sharing functions, and even work simulations. These functionalities cater to the multifaceted needs of construction professionals, from architects and engineers to contractors and project managers, enabling them to actively participate and collaborate within the metaverse. Moreover, game engines are instrumental in bridging the divide between the virtual and physical worlds by integrating reality capture data, Building Information Modeling (BIM) data, and digital twin data. This integration empowers users to access real-time project information and visualize construction projects in unprecedented detail. However, as the construction metaverse evolves, the advancement of game engines must align with the growing complexity of construction data. This includes the incorporation of reality capture data for accurate project representations and the ability to process and display vast datasets efficiently. Standardizing protocols for the incorporation of these data sources into the metaverse ecosystem is paramount, ensuring that game engines can effectively harness these technologies to support a diverse range of construction-related functions and activities, ultimately enhancing collaboration, decision-making, and project management within the construction industry's digital frontier.

4.5 Virtual identity and economics

Virtual identity and economics are foundational requirements for a construction metaverse, bringing forth a realm of possibilities that can reshape interactions and incentives for construction project participants. In a construction metaverse, incentive mechanisms play a pivotal role in motivating and rewarding various participants, including architects, engineers, contractors, and even regulatory bodies. These mechanisms can take the form of tokenized rewards, where participants receive tokens or digital assets for contributing to the project's success. For instance, architects who design energy-efficient structures or engineers who propose innovative construction methods could earn tokens, fostering a culture of innovation and excellence. Additionally, these tokens can represent ownership in virtual assets tied to construction projects, creating a sense of investment and ownership among participants. These mechanisms can be integrated into a larger virtual economic system within the metaverse, where users accumulate tokens or digital assets that represent their expertise, reputation, or contributions. Additionally, virtual identities within the construction metaverse could transform interactions. Users can have persistent digital personas that retain their credentials, certifications, and work history across different projects and collaborations. This identity continuity could streamline onboarding processes and engender trust among project participants, paving the way for efficient and secure collaborations. Foreseeable scenarios include architects showcasing their portfolios, engineers sharing their certifications, and contractors demonstrating their track record, all within their virtual identities. It is anticipated that web 3 technologies such as Blockchain, Non-Fungible Tokens, and Smart contracts, will be integral to realizing the vision of a construction domain metaverse, in which secure, efficient, and trust-based interactions among construction industry participants are possible.

4.6 Technical Requirements

The development of a construction domain metaverse entails addressing a set of technical requirements, each accompanied by its own unique challenges. First and foremost, the metaverse must possess real-time rendering capabilities capable of seamlessly generating and displaying highly detailed 3D virtual environments, which, in turn, demand substantial computational resources to achieve high fidelity. Additionally, establishing interoperable networks is essential for ensuring smooth data exchange and communication between diverse stakeholders, tools, and systems within the metaverse. However, achieving this level of interoperability requires standardized protocols and data formats, posing a challenge in itself. To accommodate the multifaceted nature of construction projects and a diverse range of users, the metaverse must scale to a massive level, akin to a network of interconnected virtual worlds. Scaling introduces complexities related to server infrastructure and network scalability that need to be addressed. Persistence is vital to guarantee that users' actions and assets remain consistent over time, fostering a continuous and reliable experience. Simultaneously maintaining persistence and enabling concurrency for multiple users poses additional challenges, as minimizing latency and server load while ensuring efficient data management and synchronization mechanisms is no small feat. These technical requirements illustrate the technological landscape that must be navigated to effectively realize a construction domain metaverse, emphasizing the need for innovative solutions to address these multifaceted challenges.

5. PROSPECTS

5.1 Virtual Design and Collaboration

Virtual Design and Collaboration in a construction metaverse can significantly address the historical disconnect between the design and construction phases of a project while also elevating communication and collaboration among various stakeholders throughout the construction lifecycle [1]. In the traditional construction process, design and construction teams often work in isolation, leading to misalignments, misinterpretations, and costly revisions [10]. The metaverse can bridge this gap by providing a shared virtual platform where architects, engineers, contractors, and other stakeholders can collaboratively design, review, and refine construction plans in real time. Web 3 and decentralized finance technologies would play a crucial role in enhancing information management during project delivery within the metaverse. Blockchain, for instance, could enhance data integrity, traceability, and transparency, enabling secure and tamper-proof documentation of project specifications, decisions, and changes. Smart contracts could facilitate automated execution of project milestones, payments, and other contractual obligations, reducing disputes and delays. Additionally, decentralized data storage and management systems ensure that all stakeholders have access to up-to-date project information, fostering a more agile and efficient construction process.

5.2 Virtual Training

One of the key areas of application is the development of real-world-based metaverse experiences for training purposes. By leveraging advanced reality capture and real-time rendering technologies, construction professionals can immerse themselves in lifelike virtual environments that replicate real-world construction sites. These immersive training scenarios enable workers to hone their skills, practice safety procedures, and familiarize themselves with complex equipment and machinery, all within a risk-free digital space [11]. In tandem with training, the metaverse can introduce cutting-edge NFT-based certifications, backed by blockchain technology, to validate safety training and regulatory compliance, providing employers and authorities with a tamper-proof means of verifying workers' qualifications. Moreover, the metaverse's potential extends to incentivizing further training through virtual economics, rewarding participants with digital assets and incentives, nurturing a culture of continuous learning. In line with this vision, Bao et al., [12] consider the feasibility of a token-incentive framework to motivate workers to participate in safety training. Beyond training, the metaverse can serve as a knowledge-sharing hub, enabling experts and practitioners to disseminate valuable insights and innovative solutions, thus fostering a collaborative construction community. These transformative possibilities hinge on advances in real-time rendering, reality capture, and the development of robust virtual identity and economic systems, all essential components in realizing the full potential of a construction metaverse.

5.3 Asset lifecycle management

A construction domain metaverse holds immense potential for revolutionizing asset lifecycle management within the construction industry. By integrating advanced reality capture technologies, such as LiDAR scanning and photogrammetry, with robust digital twin frameworks, construction professionals can gain unprecedented insights into asset performance, maintenance needs, and predictive analytics. This integration could enable real-time monitoring of asset conditions [13, 14], allowing for proactive maintenance and timely interventions to optimize operational efficiency and extend asset lifecycles. Furthermore, the metaverse could facilitate the creation of a digital thread that spans the entire asset lifecycle, from design and construction to operations and maintenance. This digital thread ensures the continuity of data and information, enhancing decision-making processes, reducing downtime, and minimizing costly errors. Additionally, the metaverse could leverage blockchain technology to provide secure and transparent records of asset history, maintenance activities, and ownership changes, bolstering trust and accountability in asset management. In essence, the construction metaverse promises to empower industry stakeholders with the tools and capabilities needed to enhance asset lifecycle management, maximize return on investment, and drive sustainable practices in construction asset management.

5.4 Project monitoring and tracking

The prospect of remote inspections, project monitoring, and progress tracking is another promising application of a construction domain metaverse. With advanced reality capture and real-time rendering capabilities, stakeholders could conduct remote inspections. Project participants would be able to analyze as-built conditions, detect deviations from design specifications, and check for building defects —all without needing to be physically present on-site. Additionally, metaverse-powered project monitoring could offer real-time oversight of construction progress, schedule adherence, and quality control. In this envisioned future, users would access a shared digital environment that provides dynamic visualizations of the construction site, enabling quick identification of bottlenecks, safety issues, and deviations from project plans. Importantly, the construction metaverse would enable concurrent and persistent experiences, promoting collaboration among dispersed project teams and improving decision-making. To realize this transformative vision, foundational technologies like the Internet of Things (IoT), advanced sensors, computer vision, edge computing, and reality capture methods are critical. It is worth noting that this vision overlaps with the objectives of digital twin technologies in the construction industry.

6. DISCUSSION AND CONCLUSION

A construction domain metaverse presents a compelling vision for the future of the construction industry, with transformative possibilities across various facets of project delivery, management, and operations. Through a discussion of the foundational precepts, requirements, and potential applications, this paper elucidates a path towards realizing this ambitious vision. The concept of the metaverse, as defined within the construction context, signifies more than just a convergence of virtual and physical realities; it embodies a paradigm shift in how construction projects are conceived, executed, and managed. By leveraging shared standards and protocols, in tandem with advances in reality capture, digital twinning, and game engines, a construction metaverse could foster unprecedented collaboration, efficiency, and innovation within the industry. Moreover, the integration of web 3 technologies, such as blockchain and smart contracts, offers secure and transparent mechanisms for data management, identity verification, and incentive systems within the construction metaverse. These technologies are envisioned to lay the groundwork for establishing trust, accountability, and seamless interactions among project participants, thereby facilitating the realization of shared objectives and goals.

The prospects outlined in this paper, including virtual design and collaboration, virtual training, asset lifecycle management, and project monitoring shed light on the potential applications and benefits of a construction domain metaverse. From improving communication and decision-making to optimizing asset performance and lifecycle management, the metaverse holds the potential to reform traditional practices and processes within the construction industry. However, realizing the full potential of the construction metaverse requires overcoming various technical, organizational, and cultural challenges. Issues such as data interoperability, scalability, privacy concerns, and workforce readiness must be addressed to ensure successful adoption and integration of metaverse technologies within construction workflows. In conclusion, while the construction metaverse represents a visionary concept with vast potential, its realization hinges on collaborative efforts from industry stakeholders, technologists, and researchers. By gradually addressing the aforementioned open issues and challenges, the construction industry can embark on a journey towards a more connected, efficient, and sustainable future enabled by a construction domain metaverse.

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