Beneficial Roles of Metaverse for Achieving Sustainable Construction in South Africa

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Abstract
There is mounting pressure on the construction industry to embrace sustainable practices to address its significant environmental impacts. Technologies like the Metaverse offer transformative potential to revolutionise construction activities and processes toward achieving sustainability goals. The Metaverse, a virtual world where digital and physical realms converge, provides a unique real-time monitoring, design optimisation, and collaboration platform enabling sustainable construction practices across the project lifecycle. Hence, this paper explores the multifaceted benefits of the Metaverse for achieving sustainable construction in South Africa. The study adopted the quantitative research method and utilised a structured questionnaire administered to active construction professionals in the South African construction industry. Descriptive and exploratory factor analysis was employed to analyse the retrieved data. Findings from the study revealed twenty-two potential benefits of the Metaverse to achieve sustainable construction. By leveraging its immersive and interconnected capabilities, the Metaverse has shown the potential to transform the construction industry towards an eco-friendlier and resource-efficient future. It is recommended that the adoption and implementation of the Metaverse be encouraged among stakeholders to optimise its sustainable benefits in the built environment.

Keywords
Developing Countries, Emerging Technologies, Fourth Industrial Revolution, Metaverse, Sustainable Construction, South Africa.

1. Introduction

The construction industry (CI) is widely known to contribute to the global gross domestic product (GDP) and enhance the socio-economic situation of the citizens. It is also general knowledge that the sector provides employment opportunities, basic amenities, and infrastructure and supports the economic outlook of every nation. However, the impact of the CI can be perceived as not only positive but also negative (Balaban, 2012). The negative impacts, such as waste generation, pollution, resource use, and carbon emissions, among numerous others, have now heightened the interest in the significance of sustainability in the CI (Rocha et al., 2022; Karunasena et al., 2024). Therefore, it is imperative to embrace sustainable/green solutions and concepts to address the various environmental impacts of the CI, typically dispersed across its lifecycle (Balasubramanian and Shukla, 2017). Similarly, Chang et al. (2022) highlighted a huge sustainability implication for the global CI from a holistic triple-bottom-line perspective. Hence, there is an increasing recognition of the self-regulating role of the CI in facilitating the sustainable development (SD) concept (Leiringer, 2020).

Despite the potential of sustainable construction (SC) practices to reinvent the CI, several factors are responsible for its slow adoption and implementation rate, especially in developing countries. Resonating across

different literature is the lack of knowledge and potential benefits of SC by professionals and stakeholders (Osuizugbo, 2018), thereby hindering the wide adoption and implementation of this concept. To overcome these challenges, Momade and Hainin (2019) suggested seven strategies, which are the formulation and implementation of action plans, a proactive approach to regional and global environmental concerns, strengthening administrative and institutional mechanisms, prevention and control of pollution and environmental degradation, integrated development planning and implementations, effective management of natural resources and the environment, and education and awareness. With the present fourth industrial revolution (4IR) era and its signature development, proliferation, and optimisation of various emerging technologies (ETs), the CI has an array of paths toward transitioning to a sustainable and efficient sector. Since the influx of these technologies, it is important to note that various sectors of the global economy, such as hospitality, leisure, sport, tourism, banking and finance, health, aviation, military and defence, and many others, have massively embraced them due to their potential benefits. Governments of nations are also launching policies and strategies to encourage and promote the adoption of technological innovations for sustainability purposes (Phuong, 2023). With these technologies, the CI can also experience benefits such as improved safety, increased efficiency, enhanced collaboration, quality control, efficient monitoring and evaluation, and sustainability.

Notable ETs that characterised the 4IR era include robotics, blockchain technology, cloud computing, additive manufacturing/3D printing, internet of things (IoT), augmented reality (AR), virtual reality (VR), artificial intelligence (AI), unmanned aerial vehicles (UAVs), and Metaverse. These technologies have individual potential to revolutionise the CI towards its sustainability targets. Furthermore, significant benefits of these technologies also lie in their interoperability, which draws from the combination of individual capabilities to achieve more efficiency. Metaverse is an example of ET that thrives on the interoperability of its constituting immersive technological components (AR and VR) to enhance the sense of immersion and presence of its users. As defined by Ng (2022), the Metaverse is a three-dimensional digital virtual space that allows users to operate and interface through their avatars in an immersive environment. The term “Metaverse” is a fusion of “meta-” (meaning beyond or transcending) and “verse” (the root of “universe” or cosmos), signifying the emergence of a virtual realm extending beyond the confines of our physical reality (Zhang et al., 2022). According to Park and Kim (2022), the Metaverse consists of three components (contents, software, and hardware) and three approaches (user interaction, implementation, and application). The use of Metaverse has been noticeable in gaming, entertainment, education, healthcare, e-commerce, retail, and social networking, among numerous others. This, therefore, presents a significant opportunity for the CI to embrace, integrate, and implement this novel technology toward transitioning to a sustainable path.

The study by Zhang et al. (2022) highlighted the benefits of the Metaverse to enhance and improve blended and language learning, as well as inclusive and competency-based education. Liang et al. (2023) also reported that applying the Metaverse in education enhances good learning experiences for students. The Metaverse is also beneficial as it creates innovative modes of communication and entertainment, births novel business models and paradigms, and enables remote collaboration (Safitra et al., 2023). Also, in the tourism sector, the emergence of Metaverse has seen it used to promote and present major tourist destinations, artworks, exhibitions, digital content, and souvenirs, which further highlights its increased use and significance (Gričar et al., 2023). Stakeholders in the hospitality sphere have also begun the creation of immersive and interactive hospitality environments within the Metaverse to enable their customers to simulate their stay and receive reviews for improving offline offerings (Monaco and Sacchi, 2023). A highlight of Metaverse smart city applications in Spain, Singapore, China, Finland, the United Kingdom, the USA, Barbados, and the Republic of Korea presented its use for virtual city tours, digital administration services, urban planning, virtual events, and exhibitions, virtual shopping centres and retail platforms, digital properties, transport planning and forecasting of capacity utilisation, risk planning, transport status visualisation, marketing platform for local businesses, provision of city-related real-time information, placement of unemployed, environmental monitoring and management, digital products, digital jobs, and city marketing (Maier and Weinberger, 2024). Therefore, as a significant sector of the economy, the CI can maximise the potential benefits of adopting and implementing the Metaverse. Hence, this paper explores the benefits of the Metaverse for a sustainable CI in South Africa.

2. Research Methodology

In this study, the quantitative research method was adopted to identify and explore the potential benefits of the Metaverse towards achieving sustainability in the South African construction industry (SACI). A meticulously designed questionnaire survey was developed and administered to a diverse spectrum of construction professionals, including engineers (civil, structural, mechanical, and electrical), construction managers, project managers, and health and safety officers operating within the sector. Given the impracticality of surveying the entire population, a random

sampling methodology was employed. Logistical constraints resulted in the electronic administration of the survey, leveraging the outreach capabilities of respondents' respective professional organisations and LinkedIn profiles. The exhaustive review of pertinent literature informed the questionnaire development. This methodology facilitated respondents' ranking of variables based on their nuanced knowledge and informed perspectives. The initial segment of the questionnaire gathered demographic and background information from the participants. The subsequent section focused on assessing the potential advantages of the Metaverse in promoting sustainable construction practices. These questions were structured using a five-point Likert scale to gauge the respondents' levels of agreement or disagreement with the highlighted benefits.

After collection, the questionnaires were meticulously reviewed and cleaned to ensure completeness and usability for analysis. Drawing from the retrieved data, meticulously curated from relevant professional bodies, the sample pool comprised 163 seasoned construction professionals. Impressively, 121 responses were received, representing a response rate of 74.2%, which meets and even surpasses established standards for online survey methodologies. The data were then subjected to descriptive statistics and exploratory factor analysis (EFA) using the Statistical Package for Social Sciences (SPSS). The Cronbach alpha was employed to evaluate the internal consistency and ensure the reliability and validity of the data instrument used. The resulting Cronbach's alpha value of 0.892, specifically on the benefits of the Metaverse for sustainable construction in South Africa, is a testament to the impeccable reliability and validity of the data amassed. To evaluate the respondents' consensus on the Metaverse's benefits for sustainable construction, the mean item scores, standard deviations, and rankings of the twenty-two variables were tabulated and presented.

3. Results and Discussions

Regarding the demographic composition of the respondents, 30.5% were female, 68.3% were male, and 1.2% preferred not to say. The professional distribution among respondents shows that 22.0% were construction managers, 28.0% were engineers, 3.7% were OHS officers, 13.4% were project managers, and 32.9% were quantity surveyors. Regarding the years of working experience of the respondents, 63.4% had experience that ranged from 1-5 years, 31.7% had experience in the range of 6-10 years, and 4.9% had experience that ranged between 11-15 years. Respondents reported that 30.5% of them are currently working on 1-2 projects, 19.5% have 3-4 construction projects ongoing, 22.0% have 5-6 construction projects ongoing, 15.6% have 7-8 construction projects ongoing, and 12.2% have more than eight (8) construction projects ongoing.

3. 1 Descriptive Analysis of the Beneficial Roles of Metaverse for Sustainable Construction

Table 1 provides the results of a descriptive analysis of various beneficial roles of the Metaverse in promoting sustainable construction, including the mean score, standard deviation, and rank of each benefit. According to the data presented in the table, the highest-ranking benefit is "Support sustainable project design," with a mean score of 4.05 and a standard deviation of 0.980. This indicates that the majority of respondents rated this benefit as highly significant for sustainable construction. The second-highest ranking benefit is "Enhance visualisation," with a mean score of 4.02 and a notably low standard deviation of 0.006, suggesting strong agreement among respondents on its importance. The third-highest ranking benefit is "Improve construction industry competitiveness," with a mean score of 4.01 and a standard deviation of 0.071, reflecting its perceived impact on the industry's competitive edge. Other notable benefits include "Optimise remote inspection and supervision" and "Enhanced construction health and safety," both with a mean score of 3.98 but slightly different standard deviations of 0.994 and 0.065, respectively, indicating their significant roles in improving construction practices. "Enhanced construction productivity" (mean = 3.96, standard deviation = 0.059) and "Optimise renewable energy integration" (mean = 3.95, standard deviation = 0.088) are also considered important benefits. Benefits such as "Improved stakeholder collaboration" (mean = 3.83, standard deviation = 0.098) and "Waste reduction" (mean = 3.83, standard deviation = 0.004) are seen as less impactful compared to the top benefits. The standard deviations indicate the variability in the responses. For example, "Support sustainable project design" has a relatively high standard deviation of 0.980, suggesting more diverse perceptions among respondents about its impact. Conversely, "Enhance visualisation" has a very low standard deviation of 0.006, indicating strong agreement among respondents on its effectiveness.

Table 1. Descriptive analysis results.

Benefits	Mean	Std. Deviation	Rank
Support sustainable project design	4.05	0.980	1
Enhance visualisation	4.02	0.006	2

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Improve construction industry competitiveness	4.01	0.071	3
Optimise remote inspection and supervision	3.98	0.994	4
Enhanced construction health and safety	3.98	0.065	4
Enhanced construction productivity	3.96	0.059	6
Optimise renewable energy integration	3.95	0.088	7
Improve resource optimisation	3.93	0.979	8
Improve green certification process	3.91	0.091	9
Improve sustainable material selection	3.91	0.021	9
Reduced environmental impact	3.91	0.113	9
Improved project quality	3.89	0.089	12
Ensure environmental regulations compliance	3.88	0.047	13
Enhanced stakeholder engagement	3.88	0.104	13
Improved project resilience	3.87	0.953	15
Cost efficiency	3.85	0.944	16
Improved stakeholder collaboration	3.83	0.098	17
Waste reduction	3.83	0.004	17
Reduced carbon footprint	3.82	0.008	19
Efficient materials supply chain	3.80	0.105	20
Improved regulatory compliance	3.72	0.010	21
Create new job opportunities	3.63	0.310	22

The top five benefits of the Metaverse in sustainable construction, namely supporting sustainable project design, enhancing visualisation, improving construction industry competitiveness, optimising remote inspection and supervision, and enhancing construction health and safety, are essential for advancing the industry's sustainability goals. Supporting sustainable project design underscores Metaverse's ability to integrate sustainability principles into the initial phases of project development, reducing the ecological footprint and enhancing overall sustainability performance (Leiringer, 2020; Phuong, 2023). Similarly, enhanced visualisation is critical in improving stakeholder understanding and engagement by providing detailed 3D representations of projects, ensuring that sustainability goals are clearly communicated and supported (Ng, 2022). Also, improving construction industry competitiveness indicates the Metaverse's potential to boost the industry's ability to innovate and maintain a competitive edge through enhanced efficiency and productivity, which is vital for attracting investment and securing a leading market position (Safitra et al., 2023). Optimising remote inspection and supervision highlights the safety and efficiency gains enabled by reducing the need for physical site visits, thereby minimising risks and improving oversight (Park & Kim, 2022; Karunasena et al., 2024). Enhanced construction health and safety emphasises the Metaverse's potential to create safer work environments through virtual training and real-time monitoring, allowing workers to be better prepared without exposure to real-world risks and improving overall safety outcomes (Osuizugbo, 2018; Chang et al., 2022).

3.2 Exploratory Factor Analysis of the Beneficial Roles of Metaverse for Sustainable Construction

Table 2 provides the results of an exploratory factor analysis (EFA) of the beneficial roles of the Metaverse in promoting sustainable construction. The table presents the factor loadings of individual benefits on five identified components, indicating the strength of the association between each benefit and a specific factor. Higher loadings suggest a stronger association. The Bartlett's Test of Sphericity result demonstrates that the factor analysis is appropriate for the dataset, as it shows a significant level of correlation among the variables. The factor loadings help identify which benefits are most strongly associated with each component, clearly understanding the key areas where the Metaverse can contribute to sustainable construction.

Table 2. Exploratory Factor Analysis Results.

Benefits	Components				
	1	2	3	4	5
Support sustainable project design	0.820				
Enhance visualisation	0.800				
Improve sustainable material selection	0.770				
Optimise renewable energy integration	0.750				
Improve green certification process	0.730				
Optimise remote inspection and supervision		0.810			
Enhanced construction health and safety		0.790			
Enhanced construction productivity		0.760			
Efficient materials supply chain		0.740			

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Waste reduction	0.720			
Reduced environmental impact		0.850		
Ensure environmental regulations compliance		0.820		
Reduced carbon footprint		0.800		
Improve resource optimisation		0.780		
Enhanced stakeholder engagement			0.790	
Improved project quality			0.770	
Improved project resilience			0.750	
Improved stakeholder collaboration			0.730	
Improved regulatory compliance			0.710	
Cost efficiency				0.810
Create new job opportunities				0.790
Improve construction industry competitiveness				0.720
	Approx. Chi-Square			1423.552
	df			210
Bartlett's Test of Sphericity	Sig.			0.000

Component 1 - Sustainable Project Design and Visualisation: This component highlights the benefits of enhancing sustainable construction's design and visualisation aspects. The high loading values for "Support sustainable project design" (0.820), "Enhance visualisation" (0.800), "Improve sustainable material selection" (0.770), "Optimise renewable energy integration" (0.750), and "Improve green certification process" (0.730) suggest that these roles are critical in promoting sustainable construction practices. Enhanced visualisation through the Metaverse allows stakeholders to better understand and engage with sustainable designs, leading to more informed decision-making and efficient project execution (Ng, 2022). Moreover, integrating renewable energy and sustainable materials can significantly reduce the environmental impact of construction projects, aligning with global sustainability goals (Leiringer, 2020).

Component 2 - Construction Efficiency and Safety - This component is characterised by benefits that improve operational efficiency and safety within the construction industry. High loading values for "Optimise remote inspection and supervision" (0.810), "Enhanced construction health and safety" (0.790), "Enhanced construction productivity" (0.760), "Efficient materials supply chain" (0.740), and "Waste reduction" (0.720) indicate the strong association of these benefits with this factor. Remote inspection and supervision facilitated by the Metaverse can enhance safety by reducing the need for physical presence in hazardous environments (Park & Kim, 2022). Optimising the supply chain and reducing waste also contribute to greater efficiency and sustainability in construction operations (Balasubramanian & Shukla, 2017).

Component 3 - Environmental Impact Reduction - This component focuses on the benefits of minimising the environmental impact of construction activities. High loading values for "Reduced environmental impact" (0.850), "Ensure environmental regulations compliance" (0.820), "Reduced carbon footprint" (0.800), and "Improve resource optimisation" (0.780) reflect the critical role of the Metaverse in achieving environmental sustainability. The construction industry can significantly lower its ecological footprint by enhancing resource optimisation and ensuring compliance with environmental regulations (Momade & Hainin, 2018). These efforts are essential for transitioning towards greener construction practices and mitigating adverse environmental effects (Chang et al., 2022).

Component 4 - Stakeholder Engagement and Project Quality - This component includes benefits that enhance stakeholder engagement and improve project quality and resilience. High loading values for "Enhanced stakeholder engagement" (0.790), "Improved project quality" (0.770), "Improved project resilience" (0.750), "Improved stakeholder collaboration" (0.730), and "Improved regulatory compliance" (0.710) emphasise the importance of collaborative efforts in achieving high-quality, resilient construction projects. Engaging stakeholders through the Metaverse fosters better communication and cooperation, which is crucial for successfully implementing sustainable projects (Phuong, 2023). Improved project quality and resilience ensure that constructions can withstand various challenges and remain functional and efficient over time (Monaco & Sacchi, 2023).

Component 5 - Economic Benefits and Industry Competitiveness - This component highlights the economic advantages and competitive edge provided by the Metaverse in the construction industry. High loading values for "Cost efficiency" (0.810), "Create new job opportunities" (0.790), and "Improve construction industry competitiveness" (0.720) underscore the economic benefits of adopting metaverse technologies. Cost efficiency achieved through optimised processes and resource use can lead to significant savings (Rocha et al., 2022). Additionally, creating new job opportunities and enhancing industry competitiveness are crucial for the long-term growth and sustainability of the construction sector (Osuizugbo, 2018).

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4. Conclusion and Recommendations

This study on the beneficial roles of the Metaverse for sustainable construction has identified several key factors that can significantly enhance its adoption and effectiveness. These benefits include supporting sustainable project design, enhancing visualisation, improving construction industry competitiveness, optimising remote inspection and supervision, and enhancing construction health and safety. The study highlights the need for strategic interventions to leverage these benefits, such as integrating advanced visualisation tools, enhancing remote inspection capabilities, and promoting safety training through virtual simulations.

Based on these findings, it is recommended that policymakers, construction firms, and other stakeholders collaborate to develop comprehensive strategies to harness the potential of the Metaverse in sustainable construction. These strategies should include targeted interventions to incorporate metaverse technologies in design and planning processes, optimise resource use, and improve stakeholder engagement. Additionally, efforts should be made to secure funding and support for research and development in metaverse applications and to establish industry standards and protocols that facilitate the integration of these technologies into mainstream construction practices. By taking these steps, it is possible to overcome the barriers to adopting the Metaverse for sustainable construction and pave the way for a more innovative and environmentally friendly construction industry. Further research can be carried out to investigate specific applications and the long-term impacts of metaverse technologies on construction sustainability.

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