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METAVERSE IN DIGITAL ARCHITECTURE AND CONSTRUCTION ECOLOGY: A SHIFT IN SUSTAINABLE ENGINEERING PARADIGM

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Abstract

Currently, knowledge of possibilities and techniques for incorporating Immersive Technologies (ImTs) into building process workflows is fragmented and limited, given the novelty of ImTs connected to Digital Twin (DT), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in the setting of the metaverse and its swift and ongoing advancement in Building Information Modelling (BIM). As an outcome, the objective of this research is to investigate the patterns and advancements in immersive technology-driven BIM applications research, offering a useful resource for comprehending the state of the art and inspiring more investigation. The architecture, engineering, and construction (AEC) industry is difficult to digitise because of major obstacles to technology adoption. The study intends to advance the AEC sector's awareness of digital technologies in order to encourage technology adoption.

Keywords: *Metaverse, Construction, Digital architecture, Sustainable Engineering, Ecology*

1. Introduction

The Metaverse has become a tremendous force in the modern digital age that has the capacity to completely alter how people communicate, work together, and go about different parts of their life [13]. The Metaverse, a virtual environment where people can create parallel digital lives and participate in immersive experiences, is a growing reality that has its roots in science fiction [14]. The field of AEC is renowned for its antiquated practices and sluggish adoption of new and improved technologies. It is regarded as one of the least digitalised industries, with a notably lower R&D expenditure than other sectors [7, 8], and is also experiencing a severe workforce shortage.

Its productivity growth is therefore trailing that of other, more digitally-oriented industry sectors, such as the manufacturing sector [9]. Neal Stephenson's book Snow Crash was the first to present the idea of the metaverse [15]. It is described as a virtual digital environment that is inextricably linked to the real world, propelling the digital revolution in many facets of peoples' tangible existence. The metaverse, after thirty years of development, is now a prominent issue in study fields involving AI, blockchain, IoT, and other related technology-driven sectors.

Some of the factors which lead to the prolonged uptake of technology include the fragmented nature of the business, the project-based nature of construction (where buildings cannot be thought of as serial goods), and the transitory nature of supply chains. These elements make it difficult to organise information and communicate smoothly [10], which adds to the time lag in building projects [11]. Furthermore, building construction is typically done in accordance with stakeholder decisions and project-specific boundary constraints, but it also occurs in uncontrolled environments that are subject to changing external influences. This means that contrasted to other businesses, like manufacturing, implementing automation, for example, is more difficult.

Even if using digital technologies to transform the AEC sector is difficult, research and practice can benefit from improved understanding of technology deployments. In academia and business, there is a growing need for innovative forms of information packaging about digital technologies. The increasing interest in studying digital technologies and the emergence of new terms like virtual design construction, digital transformation, digitalisation, and Industry 4.0 serve as evidence of this [12]. These conceptualisations limit the range of technical phenomena and technology. Even though these conceptualisations have been employed in earlier research, there hasn't been much use of them in AEC sector studies. As a result, the terms need to be defined and used with more precision.

Digital technologies (DTs) are a potentially transformational instrument in addressing to sustainability concerns. Information and communication technologies (ICTs) that use digital binary computer language to handle information are included in DTs. During numerous stages of the procurement process, they support data capture, storage, processing, display, and communication. They vary from standalone systems to consolidated and web-based innovations in the construction industry. With its ability to streamline procedures, cut down on waste, and improve decision-making, DTs have the potential to dramatically advance the construction industry's sustainability goal.

The academic environment indicates a fragmented knowledge of DTs' influence on sustainability in building, despite increased recognition of their potential. It is difficult for industry stakeholders to develop a unified understanding of the function of DTs in advancing sustainability due to the diversity of research focusses, methodologies, and conclusions. One major obstacle to using DTs for sustainable construction practices is this fragmentation. This work undertakes a thorough evaluation of the literature on construction sustainability in order to close this knowledge gap. In order to give a clear, cohesive picture of how DTs are being used to promote sustainability in construction, the research findings will be compiled, analysed, and synthesised. Through a critical analysis of the relationship between DT implementation and sustainable practices, we hope to pinpoint effective approaches and draw attention to areas that warrant additional research.

2. Literature Review

Following the COVID-19 epidemic, there was an increase in need for virtual worlds and the digital economy. The phrase "Metaverse" is currently quite widespread in various spheres of society and the community. With the recent maturity of digital technology advancement in AR, VR, and networks, there has been an increased competition for the application of Metaverse in various domains. One of the key players in digital architecture, engineering, and building going forward is the metaverse, which should not be disregarded [1]. A deeper comprehension of the Metaverse, which encompasses the AEC sector, is necessary. It is imperative that AEC industry stakeholders initiate prior growth to align with the rapid growth, expansion, and worldwide trend of the Metaverse.

The Anthropocene's engineering design gave rise to the Grey Infrastructure. Our bond with nature is being removed by mechanisms advanced by globalised society. Humanity is being forced to use digital words that deliver hyper nature—fake nature conversions—by the autism metaverse. IT environments have an impact on human behaviour, which varies depending on the population. For the younger generations, who are digital natives suffering from nature deficit disorder, Industry 4.0 is becoming the Next Nature and is appealing. Reintegration and the shift from pathogenic to salutogenic systems are necessary for the design of Sustainable Infrastructure in order to develop [2]. By expanding bio-productive areas and preserving biodiversity, Intelligent Green-Blue Infrastructure will strengthen the capacity of coexisting ecosystems to regenerate themselves. The shift from I4.0 to Nature 4.0 is a gradual process that centres on the regeneration capacity and vitality of Society 5.0 members.

As it encompasses the idea of sustainable development, the smart city now provides the ideal condition of urban growth. Building information modelling (BIM), which is becoming a vital tool for the construction industry, and Construction 4.0, which has its roots in I4.0, are just two of the cutting-edge ideas and technologies that are being integrated into the construction industry to create a smart city. This is the first attempt in the literature to look at this multidisciplinary study topic using both macro-quantitative and micro-qualitative analysis techniques [3].

It is becoming more and more obvious that the Metaverse has the ability to generate value in the real world and unleash the next wave of digital disruption as it is defined iteratively. With its unique qualities of simultaneous interaction, user agency, and immersive experience, the Metaverse has the power to revolutionise every aspect of human existence. Concerns have been raised over the sustainability of the Metaverse's large-scale deployment and development due to the energy-hungry nature of its enabling technologies, which include AI, blockchain, digital twins, and extended reality [4]. For the first time, green metaverse networking is suggested in this article as a way to maximise the energy efficiency of every network component and promote sustainable metaverse development. First, we examine the sustainability, efficiency, and energy consumption of energy-intensive technology in the Metaverse. Next, we present significant developments in energy efficiency and their integration into the Metaverse, with an emphasis on networking and computation. We propose a case study of energy conservation in the Metaverse using stochastic resource allocation and semantic communication. Lastly, we highlight the crucial issues facing the sustainable growth of the Metaverse, suggesting possible future research avenues for the Metaverse's green transformation.

As information technology has advanced, the idea of the metaverse has progressively come into our awareness. A virtual environment with real-world integration and interaction is called the Metaverse. In order to realise the deep incorporation of the aviation and tourism industries, the aviation Metaverse combines a number of growing techniques to create an immersive aviation virtual interaction platform. It also uses media, digital, and virtual elements to bring people immersive and scene-based experiences [5]. In this article, the technical framework of the aviation Metaverse is designed from four perspectives: data, application, basic technology, and market. The ecological framework of the aviation Metaverse is designed from three perspectives: application, technology, and market.

The idea of the Metaverse has garnered a great deal of interest lately. An exhaustive synopsis of the Metaverse is given in this article. First, a presentation of the Metaverse's development state is made [6]. We provide information on the number of publications linked to the Metaverse, along with an overview of the policies of different nations, businesses, and organisations that are pertinent to the Metaverse. The following traits of the Metaverse are recognised: 1) Hyper-spatiotemporality; 2) Sociality; and 3) Convergence of several technologies. We break down the Metaverse's technological architecture into five dimensions to account for its multitechnology convergence. We consider the Metaverse to be a virtual social world when discussing its sociality. In relation to the attribute of hyper-spatio-temporality, we present the Metaverse as an interactive, open, and immersive three-dimensional virtual environment that transcends temporal and spatial limitations in the physical world. There is also discussion of the Metaverse's difficulties.

3. Research Methodology

Building theory from the metaverse's primary aspects is crucial to determining the metaverse's function and efficacy in architectural design. The objective is to provide a solid empirical foundation for architectural design based on the metaverse. Three stages of the metaverse architecture will be analysed, with each stage being contrasted to the traditional architectural methods. These stages comprise place attributes, design techniques, and technologies. This method aids in identifying the existing architectural design bottlenecks, which can be resolved by obtaining information from metaverse applications.

On the other hand, expert knowledge from other disciplines, including user interface, content, character, and game design, may need to be integrated into 3D modelling for the metaverse, which may require new skills and a different viewpoint. Game engines are employed to build the metaverse's spaces in order to accomplish this.

AI is becoming so ubiquitous that it is even having an impact on the architectural sector. AI is used to address a variety of architectural issues, including pattern recognition in architectural drawings, early-stage design, space planning, automatic generation of new designs, dynamic optimisation of architectural designs, crowdsourced design, digital fabrication, and form-finding optimisation.

Physical laws impose constraints on real-space design. Virtual design methods, however, are not the same as real-space design processes. Moreover, because the metaverse is still in its prior phases of growth, neither industry nor academia can agree on how best to organise it. However, there have been some initiatives made to address this issue. For example, certain scholars built layered metaverse techniques. Furthermore, digital game design techniques can be applied as the most metaverse-like environment, and 3D modelling algorithmic approaches can be used as a methodology for the easy creation of flexible visualisations.

4. Results and Discussion

Table.4.1. Energy Efficiency Evaluation using Machine Learning Models in Digital Architecture

Model	**Accuracy**	**Precision**	**Recall**	**F1 Score**
Random forest	0.92	0.91	0.93	0.92
Gradient boosting	0.89	0.87	0.91	0.89
SVM	0.88	0.85	0.90	0.87
Neural network	0.95	0.94	0.96	0.95
K-nearest neighbours	0.84	0.83	0.86	0.84

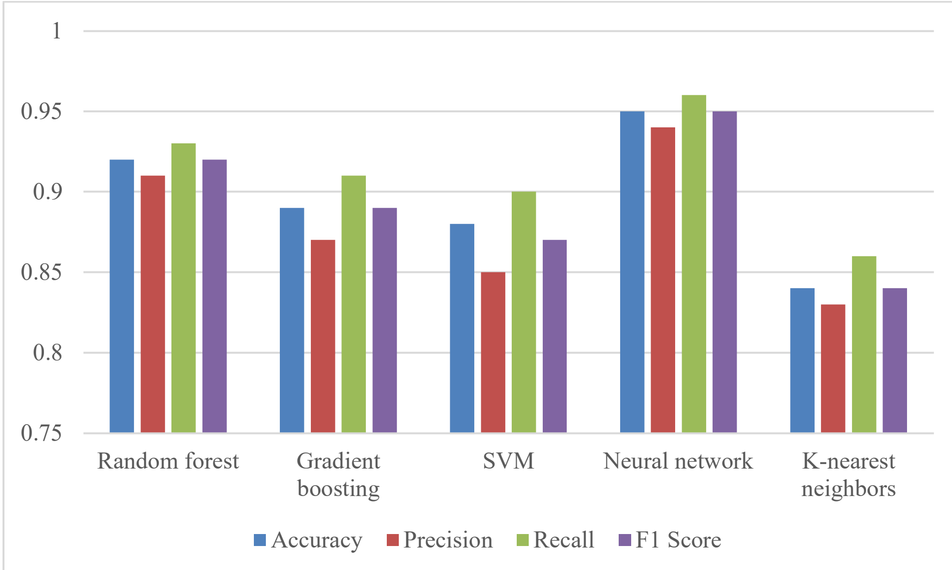

Figure 1. Energy Efficiency Evaluation using Machine Learning

Table.4.2 Resource Optimization Impact in Construction Ecology Using Regression Models

Model	**R-Squared**	**MAE**	**RMSE**
Linear regression	0.78	15.2	20.5
Lasso regression	0.81	13.8	19.1
Ridge regression	0.83	13.5	18.6
Decision tree regression	0.86	12.0	17.0
Random forest regression	0.89	11.2	16.3

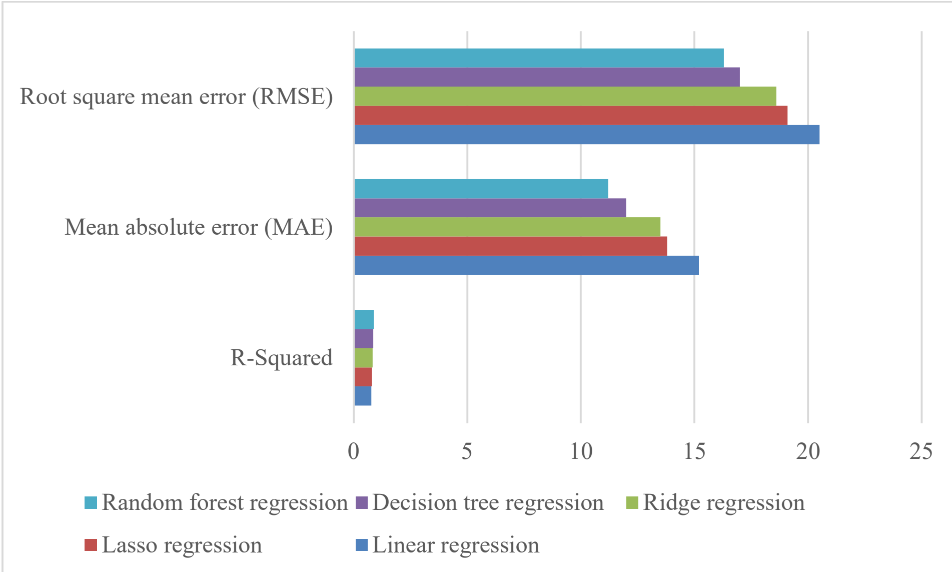

Figure 2. Resource Optimization Impact in Construction Ecology Using Regression Models

Table.4.3 Carbon Footprint Reduction Assessment using Classification Models

Model	Accuracy	True Positive Rate	False Positive Rate
Logistic regression	0.82	0.80	0.18
Random Forest	0.86	0.84	0.15
Decision Tree	0.90	0.88	0.12
Gradient Boosting	0.91	0.89	0.11
Neural network	0.94	0.92	0.09

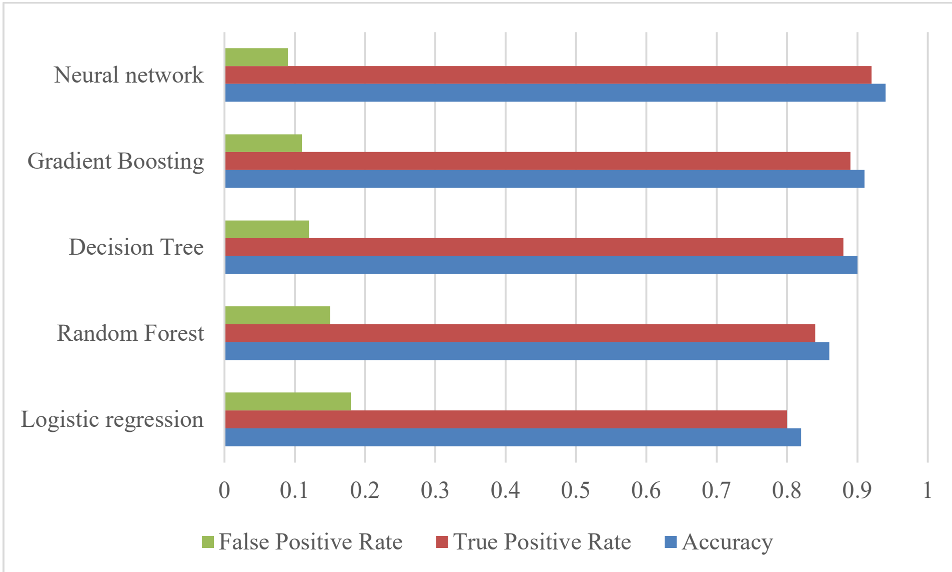

Figure 3. Carbon Footprint Reduction Assessment using Classification Models

Table.4.4 User Experience Metrics in Virtual Environments Using Deep Learning Models

Model	Engagement rate	Learning curve index	Retention rate
CNN	75	0.42	68
RNN	70	0.46	64
Transformer models	78	0.38	71
Autoencoder	80	0.35	74
Generative Adversarial network	73	0.40	66

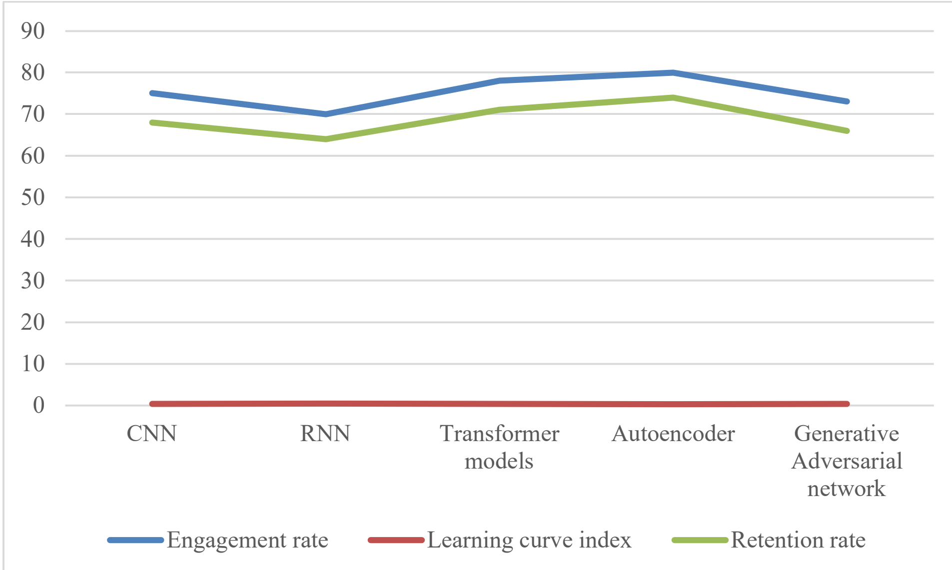

Figure 4. User Experience Metrics in Virtual Environments Using Deep Learning Models

Table.4.5 Material Lifecycle Analysis in Sustainable Construction Using Clustering Algorithms

Algorithm	**No. of clusters**	**Silhouette score**	**Material recycling rate**
K-means	4	0.72	35
DBSCAN	5	0.75	37
Mean shift	3	0.68	30
Gaussian mixture	4	0.74	36
Hierarchical clustering	4	0.77	38

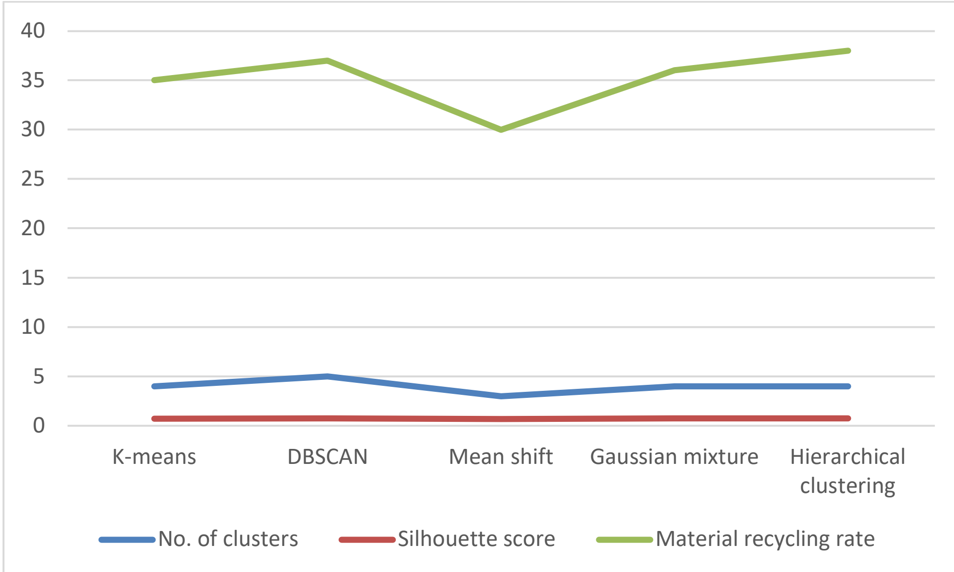

Figure 5. Material Lifecycle Analysis in Sustainable Construction Using Clustering Algorithms

5. Conclusions

Future AEC I6.0 will emphasise human-centered concepts above equipment, marking a dramatic departure from traditional construction processes. This study looked at the social advantages of AEC I6.0, which uses technology to improve human-machine collaboration. It guarantees sustainability, encourages wellbeing, and fosters inclusivity. The IoT, robotics, human intelligence (HI), AI, and conventional building techniques are important elements. Innovative construction methods, enhanced productivity, and higher environmental consciousness have all resulted from this synergy. Smart buildings, digital twins, and AI algorithms are all integrated into AEC I6.0 to satisfy global sustainability targets and minimise environmental effect while improving predictive and efficient construction. Concerns about ethical issues and skill development present challenges that call for generous funding for training and education as well as a focus on stakeholder trust. Additionally, Construction 6.0 emphasises customisation, giving collaborating robots more freedom, transforming the industrial industry, and creating new prospects for those with specialised knowledge. AEC I6.0 ushers in a time of cutting-edge building, commitment to the environment, and human-centered design. It offers potential for efficiency, sustainability, and beneficial effects on society through technology-driven innovation and teamwork. A focus on human-centered concepts and resolving innate problems are necessary to achieve these goals. More study is required to fully understand its implications, establish policies, and devise strategies for leveraging AEC I6.0's potential to develop flexible and environmentally friendly construction techniques. I6.0 has the potential to completely alter several industries. The main worry is job displacement owing to increased automation, even while it offers virtualised, antifragile manufacturing and services emphasising customer-centric approaches, dynamic supply chains, and automation-driven flexibility. To prevent social unrest, future industrial revolutions should place a high priority on creating jobs.

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