VIRTUAL WORLDS AND SUSTAINABLE ARCHITECTURE: NEW PATHWAYS TO SUSTAINABILITY IN THE ERA OF THE INDUSTRY 4.0

DOI: 10.26341/issn.2241-4010-2025-9a-3-K02101

Kalemis Alexandros
PhD(c) Urban & Regional Planning, National Technical University of Athens School of Architecture, Greece
akalemis@mail.ntua.gr

Abstract
In the Anthropocene era, architecture and construction confront the challenge of minimizing environmental impact, as cities and communities are tasked with addressing the pressures of the climate crisis, urban population growth, and the need for resilience. Simultaneously, the Fourth Industrial Revolution introduces new, cutting-edge tools and technologies, such as Artificial Intelligence and Virtual Reality, providing innovative solutions in architecture and urban planning. In this research, the dynamic connection between virtual worlds and sustainable architecture is explored, illustrating through literature review how digital platforms and simulations enhance citizen engagement, transparency, and governance, while facilitating the evaluation of strategies through real-time monitoring of environmental and social indicators. Examples are examined, such as the use of blockchain for sustainable urban planning, VR-based sustainability education, and resilience through virtual crisis simulations conducted in secure cyber platforms, all tested before real-world implementation to ensure their feasibility. In parallel, the conservation and proper management of essential resources within the circular economy framework is prioritized. Finally, the challenges of energy and data are analyzed, with proposals for the seamless integration of both innovation and sustainability. The merging of social sustainability and technological advancement is expected to reveal new viewpoints for the interaction between physical and virtual environments, leveraging the benefits of digital technologies and social participation and positioning sustainable construction as a key pillar for a fair and green future.

Key words: *Virtual reality, digital technologies, sustainable architecture, urban planning, resilience.*

Introduction

The aim of this research is to highlight the dynamic connection between Virtual World technologies and Architecture, focusing on the contribution of digital technologies in shaping a fair and green future. It is true that in the Anthropocene era, cities and communities are being called upon to address emerging pressures such as climate change, urban density, and the urge to strengthen resilience. On the other hand, the fields of architectural design and construction face challenges related to reducing the ecological footprint of the building stock and infrastructure. At the same time, the use of innovative tools of the 4th Industrial Revolution, such as Artificial Intelligence and Virtual Reality, offer state-of-the-art solutions to critical problems. The compliance of digital technologies with the principles of environmental ethics is a key factor in addressing contemporary issues, providing tools that promote sustainable practices by incorporating ethical and social parameters into the planning and long-term evaluation of intervention strategies.

The research follows a qualitative methodology, based on an extensive literature review of academic publications and case studies related to new technologies and architectural sustainability. By examining various scientific viewpoints and conclusions drawn from bibliography, the significance of digital tools and optimal methods as a means of environmentally friendly urban and spatial planning is highlighted. Furthermore, through the lens of analyzing the theoretical foundations of the Anthropocene period, the emphasis is placed upon the need for a redirection of current environmental policies and strategies to strengthen resilience (Biermann, 2014; Wilke & Johnstone, 2017). Additionally, some of the main sustainability certification systems for building constructions are presented, specifically LEED and BREEAM, evaluating their effectiveness in ensuring energy efficiency and the preservation of available resources.

The text is structured into five (5) distinct sections, each addressing multiple aspects of the collaboration between sustainable architecture and technological innovation. Initially, the concept of the Anthropocene is theoretically developed based on the prevailing theories in environmental sciences, as well as the pressures arising during this period for urban planning. The next section discusses issues related to climate change, energy poverty, and social inequalities, emphasizing the need for adopting and implementing strategies for green and resilient infrastructures. The section on Smart Cities and Digital Tools examines the contribution of digital innovation tools, such as AI, IoT, and Blockchain, to the enhancement of urban sustainability and spatial governance. This is followed by a specialized analysis of the collaboration between Virtual Reality and active Architecture, demonstrating how immersive technologies can be used for sustainable education, participatory design, and crisis simulation. The discussion then shifts to a comparative analysis of the International Standards for Sustainable Architecture Certification, LEED and BREEAM, their rating systems, and their impact on the global construction landscape. Finally, in the Conclusions section, a review of the key findings is presented, offering a perspective on the future of sustainable architecture as digital transformation contributes to the shaping of environmentally responsible urban communities. By linking technological progress with the principles of ecology, this research aims to highlight a holistic approach to the concept of sustainability, where digital tools act as catalysts for environmentally responsible urban development.

By linking technological progress with ecological principles, this study underscores the importance of a holistic approach to sustainability, where digital tools act as catalysts for responsible urban development.

Theoretical Framework

The concept of the Anthropocene is used to define the “geological” period during which geotechnical and climatic changes in Earth's ecosystems result primarily from human activity. The term “Anthropocene” was coined in 2000 by Paul Crutzen and Eugene Stoermer to illustrate the profound impact of human activities on the environment on a global scale. By increasingly understanding and analyzing the ways in which industrial civilization affects ecology, climate change, and social justice, this term has since taken on new dimensions and revisions, as the carbon cycle, biodiversity, and geological processes are now influenced by human activity in ways that surpass natural processes. These activities include industrialization, deforestation, agriculture, the burning of fossil fuels, and the overexploitation of natural resources (Biermann, 2014; Crist, 2020). The growing intervention necessitates the redefinition of the human-nature relationship (Crist, 2019). Through the principles of the circular economy, the long-term management of available natural resources and energy sources is ensured, preventing their depletion and minimizing the generated pollutants (Bourdeau, 2004; Foster, 2017; Bibri, 2022).

Meanwhile, as a counterbalance to the aforementioned pathologies, the arrival of new technologies such as virtual platforms and simulation software improves transparency and decision-making by utilizing real data (Wilke & Johnstone, 2017; Allenby & Sarewitz, 2011). Applications of virtual reality provide the ability to simulate and control sustainability strategies before their implementation, while Blockchain ensures transparency in resource management and urban design in the field of economic and commercial transactions (Palmer et al., 2011; Zhang & Lu, 2020). The integration of these technologies strengthens the resilience of communities, with a focus on social and environmental parameters (Holloway, 2022).

Key Challenges of Contemporary Urban Design

Urban planning, as a process concerned with the organization and development of urban areas, faces numerous adverse conditions in the era of the Anthropocene, including climate change, the degradation of natural ecosystems, and the scarcity of energy resources. Urban centers, as hubs of population density, bear the greatest responsibility for the environmental crisis. Furthermore, they are called upon to balance the social inequalities that arise, as the most vulnerable social groups are disproportionately affected by these phenomena.

The philosophy of sustainable development, as approached by the research of Holloway (2021) and Schlosberg et al. (2018), takes into account the necessity of considering the principles of environmental justice and the balancing of human interests with those of natural ecosystems. As Merchant (1987) emphasizes, the ecological revolution emerges through “changes, tensions, and contradictions that develop between a society’s mode of production and its ecology, and between its modes of production and reproduction.” The need for development based on sustainability and environmental protection requires the adaptation of cities to new climatic conditions through the design and implementation of infrastructure projects that are resilient to phenomena such as flooding and drought, including green spaces and transportation networks with a reduced environmental footprint, ensuring the adequacy of natural resources. Moreover, urban planning, in the context of eliminating discrimination, has the duty to adopt policies that will protect the poorest and marginalized social groups, ensuring their equal access to clean air, drinking water, and safe shelters.

The transition from the traditional model of urban development to sustainable infrastructures and high-energy-efficiency buildings requires, according to Biermann (2014), a fundamental revision of how the construction and operation of buildings are approached in the Anthropocene era. Energy efficiency, water recycling, and the use of renewable energy sources are no longer luxuries, according to Palmer (2017), but necessities. In the case of traditional buildings, the lack of modern energy systems and inadequate insulation often lead to significant energy losses. Furthermore, the operation of outdated heating, cooling, and ventilation systems, which do not meet modern energy-saving standards, further increases the environmental footprint. The implementation of green technologies, such as solar panels and renewable energy devices, as well as sustainable building materials for the bioclimatic upgrading of buildings, is not just good practice but a political move that prioritizes ecological and social well-being over immediate, environmentally harmful, and socially detrimental profit (Havlick, 2019; Polt & Wittrock, 2018).

Despite the benefits of promoting modern technologies for the energy upgrade of building stock and infrastructure, their application remains limited due to the complexity of these tools, as well as their high cost. As Droz (2019) emphasizes, the development of management tools and techniques requires, within the framework of environmental ethics, careful study of the "milieu," the surrounding environment within which these technologies will operate. In the case of buildings, complexity consists of including numerous parameters such as energy efficiency, air quality, water usage, and recycling potential. Furthermore, social and educational inequalities present a significant barrier to equitable access to and use of these technologies by the majority of social groups (Robison, 2017). Handling these technologies often requires high-level technical knowledge and skills, making them difficult to use by small to medium-sized, untrained users (Knack et al., 2019). The need to employ specialized personnel for installation and maintenance significantly increases the cost for both businesses and employers. As Plumwood (1993) notes, the dominance of the capital in the distribution of energy goods and resources leads to environmental inequality, excluding poorer and technologically illiterate populations from accessing technologies necessary to reduce their carbon footprint.

Smart Cities Digital Tools and Innovation

Technology and Innovation in Modern Urban Planning

Cutting-edge technologies and innovation are crucial drivers of modern urban planning. Smart cities, in the context of reducing carbon footprints and improving the daily lives of residents, rely on information technology applications, the internet, and big data. The design of communities that will harness innovation and green infrastructure while reducing social inequalities is expected to contribute to the achievement of a more equitable and sustainable future (Bouzguenda et al., 2019). The integration of advanced tools from the 4th Industrial Revolution, such as Artificial Intelligence, the Internet of Things (IoT), and Digital Twins, promotes the continuous monitoring and management of urban infrastructure, enhancing efficiency and sustainability (Boyes et al., 2018). This is because these technologies have the ability to collect and analyze real-time data, allowing for immediate intervention, redirection, and the implementation of improved strategies for resource and energy conservation (Tapias et al., 2024; Kalemis, 2025).

Blockchain & Virtual Reality

The use of Blockchain in the context of spatial development is a powerful example of enhancing and promoting transparency, as this technology enables the collection, storage, and processing of data, providing the ability for organized decision-making by communities and private individuals on critical issues, including resource allocation and environmental risk management (Hikal et al., 2024). At the same time, it facilitates the collection of reliable data, reducing the risk of economic fraud due to lack of transparency, while the decentralized nature of Blockchain allows for secure international transactions (Hollensen et al., 2022).

Meanwhile, Virtual Reality opens new possibilities by enabling the digital representation of applied sustainability strategies in a simulation environment, offering immersive educational experiences that enhance perception and knowledge about significant environmental issues. The application of these strategies is evaluated under simulated conditions, minimizing environmental costs and improving collective response. Through interactive experiences, VR creates the foundation for a more just and green architecture (Nikolić & Whyte, 2021), reducing environmental risks and enhancing public awareness and engagement (Jamei et al., 2017).

Digital Design with BIM (Building Information Modeling)

Building Information Modeling (BIM) is a multidimensional digital approach to design that incorporates geometric, material, and environmental parameters in data form, covering the entire lifecycle of a construction project. It allows architects and engineers of all specialties to create three-dimensional models, facilitating accuracy in design, simulation, and sustainability evaluation. BIM is recognized as a key element of the 4th Industrial Revolution, as it enhances automation, efficiency, and data integration across various phases of a project (Kamari et al., 2020).

One of BIM's key advantages is its ability to integrate technologies such as Geographic Information Systems (GIS) and Light Detection and Ranging (LIDAR), enabling precision in spatial analysis and urban planning. The combination of BIM with GIS allows urban planners to analyze the real-time effects of infrastructure projects, including their impacts on traffic patterns, air quality, and energy consumption (Pantazatos et al., 2023). Additionally, the increasing collaboration between BIM and Artificial and Augmented Reality platforms, enhancing project visualization, enables designers and real-estate professionals to simulate real-world environments, offering stakeholders immersive experiences that aid in decision-making and public participation. BIM supports real-time data analytics, allowing for continuous monitoring and adaptation of energy performance. The integration of Quantity Take-Off (QTO) techniques in BIM improves cost estimation and material efficiency, reducing waste and promoting circular economy principles (Kamari et al., 2020).

Another major advantage of BIM is its role in Life Cycle Assessment (LCA), which enables the evaluation of environmental impacts at every stage of a building's lifespan. BIM-based LCA models track energy efficiency, water usage, and CO_2 emissions, ensuring alignment with international sustainability standards such as LEED and BREEAM (Kourtesis, 2024).

Despite its advantages, BIM adoption faces challenges such as high initial costs, interoperability issues, and the need for specialized training. However, ongoing developments in Artificial Intelligence (AI), cloud computing, and digital twin technologies are expected to enhance BIM's capabilities further. Future advancements may lead to fully autonomous BIM-driven decision-making, improving the efficiency and resilience of smart cities (Kamari et al., 2020). Through continuous innovation, BIM remains at the forefront of digital transformation in architecture and urban planning, paving the way for smarter, more efficient, and sustainable built environments.

Energy Simulations with Artificial Intelligence (AI)

AI is transforming energy management in buildings by enabling real-time energy simulations, optimizing consumption, and reducing inefficiencies. As noted by Roblek et al. (2016), AI is essential for smart resource management, particularly in the development of predictive models that allow for early detection of performance issues and inefficiencies. As highlighted in research, plays a crucial role in predictive maintenance and energy simulations, enabling buildings to anticipate energy demands and preemptively adjust resource distribution. AI-powered Digital Twins—virtual replicas of physical buildings—offer architects and engineers an effective solution, as variated energy scenarios are digitally simulated, testing the effectiveness of sustainability measures, and optimize building operations before real-world implementation (Bielicki, 2024). By performing Machine Learning (ML) techniques, AI processes large volumes of energy-related data, allowing for predictive modeling and intelligent resource allocation. The running of data-driven simulations by architects and engineers is helpful as a means of refining building and infrastructure designs, ensuring energy efficiency and sustainability (Chowdhary, 2024).

One of AI's most valuable applications is the ability to analyze sensor data from smart buildings. Integrated Internet of Things (IoT) devices, such as temperature sensors, occupancy detectors, and smart meters, collect continuous data on energy consumption. AI-powered systems process this information to identify patterns, detect inefficiencies, and recommend energy-saving strategies (Schmitt, 2022). These self-learning models adjust dynamically to weather conditions, seasonal variations, and user behavior, optimizing heating, cooling, and lighting systems in real-time.

Beyond individual buildings, AI also enhances urban-scale energy optimization. By aggregating and analyzing data from multiple smart buildings, AI enables cities to balance energy distribution, integrate renewable sources, and improve grid stability. This functionality is particularly relevant for district energy management and microgrid coordination, where AI can facilitate load balancing and peak demand forecasting (Droz, 2019).

Despite AI's potential in energy simulations, several challenges hinder its widespread adoption. The high cost of implementation, the need for specialized expertise, and data privacy concerns remain significant obstacles (Plumwood, 1993). Additionally, equitable access to AI-driven energy solutions is a concern, as poorer communities and developing regions may struggle to afford such technologies (Warren, 2000). To ensure sustainable and inclusive adoption, policymakers and urban planners must implement regulations and incentives that promote AI-driven energy efficiency across all sectors.

Through continuous technological advancements, AI-driven energy simulations are set to become an integral part of sustainable architecture and smart city planning. By reducing emissions, cutting operational costs, and improving energy resilience bycreating buildings that are both intelligent and environmentally responsible, AI will remain at the forefront of climate-responsive building design, fostering a built environment that aligns with global sustainability goals.

International Sustainable Architecture Certification Standards

LEED (Leadership in Energy and Environmental Design)

LEED (Leadership in Energy and Environmental Design) system for the planning, construction, and operation of high-performance green buildings. Developed by the U.S. Green Building Council (USGBC), it is one of the most widespread and reliable standards in sustainable architecture. The primary goal of LEED is to promote sustainable buildings that reduce the consumption of natural resources, improve indoor environmental quality, and minimize environmental impacts. Its implementation helps decrease energy consumption and carbon footprint while increasing building efficiency through innovative technologies, improving air quality, and enhancing user health.

Image 1: The LEED rating system logo (Source: U.S. Green Building Council (USGBC). (2021) LEED v4.1 BD+C Guide).

LEED offers a multitude of rating systems variations, depending on the type of building and its use. For example, LEED BD+C applies to new buildings and large-scale renovations, while LEED O+M concerns existing buildings aiming for sustainable operation and management. Additionally, there are specialized versions such as LEED ND, focusing on sustainable neighborhood development, and LEED Homes, which is dedicated to residential buildings. Certification is awarded based on a points system, where projects earn credits in categories such as energy efficiency, water management, material use, and indoor environmental quality. Depending on the total score, a building can achieve one of the following certification levels: Certified (40-49 points), Silver (50-59 points), Gold (60-79 points), and Platinum (80+ points).

The implementation of LEED offers multiple benefits, both environmental and economic. It helps reduce CO_2 emissions and operational costs while increasing the commercial value of buildings and making them more attractive to investors. Additionally, LEED-certified buildings provide better air quality and natural lighting, thereby improving user health and productivity. Businesses that choose to follow LEED standards also benefit from tax incentives and government subsidies supporting sustainable development.

Table 1: The primary LEED rating systems based on building type and use.

LEED Rating System	Scope of Application
LEED for New Construction and Major Renovations (BD+C)	Applies to new buildings or large-scale renovations.
LEED for Existing Buildings (O+M)	Focuses on the sustainable operation and management of existing buildings.
LEED for Interior Design and Construction (ID+C)	Applies to office spaces, retail stores, and other interior spaces.
LEED for Neighborhood Development (ND)	Focuses on the creation of sustainable and smart communities.
LEED for Homes	Designed for single-family homes and apartment buildings.

LEED principles promote sustainable buildings through the integration of IoT sensors that monitor energy consumption and air quality, as well as the use of digital twins (Digital Twins) to optimize energy efficiency. Additionally, it can provide data analysis and personalized recommendations to reduce waste and improve building sustainability. Compliance with LEED standards contributes to achieving higher certification scores, improving performance, and making buildings more competitive in the green technology market.

In summary, LEED aims to provide a clear framework for the construction of energy-efficient and environmentally-friendly buildings. Its integration into building development and management through innovative technologies enhances sustainability, contributing to global goals assumed as a means of reducing environmental footprints.

BREEAM (Building Research Establishment Environmental Assessment Method)

BREEAM (Building Research Establishment Environmental Assessment Method) is one of the most recognized and widely acclaimed sustainability assessment systems for buildings in a worldwide scale. Developed by the Building Research Establishment (BRE) in the early 1990s, it is applied internationally as a sustainable development standard in the construction sector. The adoption of BREEAM principles aims to reduce the environmental footprint of buildings, promote energy efficiency, and improve indoor air quality. It can be applied both to new and existing buildings, as well as renovation and infrastructure projects, encouraging responsible management practices of natural resources, water, and waste.

Image 2 The BREEAM rating system logo. Source: Building Research Establishment (BRE). (2022). *BREEAM In-Use International: Commercial Technical Manual (V6).* BRE Group).

BREEAM®
delivered by bre

The evaluation of a building through BREEAM is based on nine (9) key categories: management, health and well-being, energy, transport, water, resources, resilience, land use and ecology, and pollution. Each category receives a score, shaping the final classification of the building. The scoring system ranges from Pass (25-39%) to Outstanding (≥85%), with intermediate ratings such as Good, Very Good, and Excellent. Certification is awarded based on the building's overall environmental performance, enhancing sustainability and resilience to climate and environmental challenges.

Table 2: The BREEAM rating system based on the total score a building achieves.

Score (%)	Certification Level
≥ 85%	Outstanding
70-84%	Excellent
55-69%	Very Good
40-54%	Good
25-39%	Pass
< 25%	Unclassified (Not Certifiable)

BREEAM includes various subcategories for the evaluation of different types of buildings and projects, such as BREEAM New Construction for new buildings, BREEAM In-Use for assessing the operation of existing buildings, BREEAM Communities for large-scale urban projects, BREEAM Refurbishment and Fit-Out for renovations, and BREEAM Infrastructure, applied both to civil engineering as well as infrastructure projects.

The implementation of BREEAM offers a multitude of benefits. Economically, certified buildings reduce their operational costs due to higher energy efficiency and elevate their commercial value, attracting investors. Environmentally, they contribute to reducing CO_2 emissions, optimizing natural resource management, and using recycled materials. At the same time, social benefits include improving air quality, natural lighting, and the general well-being of building users.

BREEAM principles are applicable through data analysis and the use of IoT sensors, improving the buildings' energy efficiency. Additionally, AI and Big Data collection are processed to provide personalized recommendations for sustainable practices, facilitating compliance with BREEAM standards by creating reports in accordance to the system's criteria, thus helping owners, managers and inhabitants achieve higher certification scores.

In summary, BREEAM is a comprehensive assessment system that promotes sustainable development in the construction sector, encouraging the adoption of green practices and ensuring a more sustainable and efficient building management.

Conclusions

The integration of digital technologies into sustainable architecture and urban planning represents a transformative shift in addressing contemporary environmental and social challenges. As cities continue to expand and confront the pressing issues of climate change, resource depletion, and social inequality, the role of Blockchain, Virtual Reality (VR), Artificial Intelligence (AI), and the Internet of Things (IoT) becomes increasingly crucial in fostering resilient, efficient, and inclusive urban environments. This study has explored how these technologies contribute to enhancing transparency, citizen engagement, and sustainability in architecture, positioning digital innovation as a cornerstone of future urban development.

One of the key findings of this research is the importance of international sustainability certification systems, particularly LEED and BREEAM, in establishing standardized approaches to green building design. These frameworks have demonstrated their effectiveness in promoting energy efficiency, reducing environmental footprints, and improving overall building performance. However, their successful implementation remains contingent on the broader adoption of digital tools, which facilitate data-driven decision-making and real-time monitoring of urban systems.

Despite the considerable benefits that digitalization brings to sustainable architecture, challenges persist. The high cost and complexity of implementing AI-driven energy simulations, IoT-based smart monitoring, and Blockchain-enabled transparency mechanisms limit their widespread application, particularly in developing regions. Moreover, ethical and social considerations, such as digital accessibility and environmental justice, must be central to the development of smart city initiatives to ensure that technological advancements benefit all communities equitably.

Looking ahead, the convergence of technological innovation and environmental sustainability will continue to shape the future of urban planning. Further research is needed to explore interdisciplinary approaches that integrate environmental ethics, digital governance, and participatory planning in order to maximize the potential of digital tools in sustainable construction. The transition towards intelligent, green, and equitable cities requires continued collaboration among policymakers, architects, technologists, and local communities to develop solutions that balance innovation with sustainability. Ultimately, the digital transformation of architecture should not only enhance efficiency but also contribute to a more just and ecologically responsible built environment.

References

Bielicki, D. M. (2024). *Regulating Artificial Intelligence in Industry*. Springer

Biermann, F. (2014). *Earth system governance: World politics in the Anthropocene*. MIT Press.

Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, *101*, 1-12.

Bouzguenda, I., Alalouch, C., & Fava, N. (2019). Towards smart sustainable cities: A review of the role digital citizen participation could play in advancing social sustainability. *Sustainable cities and society*, *50*, 101627. https://doi.org/10.1016/j.scs.2019.101627

Building Research Establishment (BRE). (2022). *BREEAM In-Use International: Commercial Technical Manual (V6)*. BRE Group.

Chowdhary, K. R. (2023). *Fundamentals of Artificial Intelligence*. Springer.

Crist, E. (2019). *Abundant earth: Toward an ecological civilization*. University of Chicago Press.

Dong, Y., Zhang, H., Yang, T., Wang, X., & Wang, X. (2021, September). Design and Implementation of Visualized Substation Inspection Training System Based on Immersive Computer VR. *Journal of Physics: Conference Series, 2023*(1), 012021. IOP Publishing. https://doi.org/10.1088/1742-6596/2023/1/012021

Droz, L. (2021). *The concept of milieu in environmental ethics: Individual responsibility within an interconnected world*. Routledge.

Dürbeck, G., & Hüpkes, P. (2021). *Narratives of scale in the Anthropocene: Imagining human responsibility in an age of scalar complexity*. Routledge.

Ferrando, M., Cerioli, L., Leone, V., & Mutani, G. (2021). Artificial intelligence applications for energy-efficient buildings in smart cities: A review. *Energies*, *14*(9), 2507. https://doi.org/10.3390/en14092507

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., & Naismith, N. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, and an analytical methodology for an impact assessment in the AEC sector. *Renewable and Sustainable Energy Reviews*, *75*, 1046–1055. https://doi.org/10.1016/j.rser.2016.11.083

Hermann, C., Pentek, T., & Otto, B. (2015). Design principles for Industrie 4.0 scenarios: A literature review. University of Paderborn. https://doi.org/10.13140/RG.2.2.29269.22248

Hikal, H., Altarawneh, M., Ahmad, A. H., Jaradat, Z., & Elfedawy, A. (2024). Blockchain technology and virtual asset accounting in the metaverse. In *Technological Innovations for Business, Education and Sustainability* (pp. 71-78). Emerald Publishing Limited. https://doi.org/10.1108/978-1-83753-106-620241005

Holloway, T. (2022). *How to Live at the End of the World: Theory, Art, and Politics for the Anthropocene*. Stanford University Press.

Hollensen, S., Kotler, P., & Opresnik, M. O. (2022). Metaverse–the new marketing universe. *Journal of Business Strategy, 44*(3), 119-125. https://doi.org/10.1108/JBS-01-2022-0014

Jamei, E., Mortimer, M., Seyedmahmoudian, M., Horan, B., & Stojcevski, A. (2017). Investigating the role of virtual reality in planning for sustainable smart cities. *Sustainability*, *9*(11), 2006. https://doi.org/10.3390/su9112006

Kalemis, A. (2025). Metaverse as a Field of Communication and Networking in the Digital Domain: Challenges and Prospects. *Envisioning the Future of Communication - Conference Proceedings vol. 2*. https://doi.org/10.12681/efoc.7904

Kamari, A., Paari, A., & Torvund, H. Ø. (2020). BIM-enabled virtual reality (VR) for sustainability life cycle and cost assessment. *Sustainability*, *13*(1), 249. https://doi.org/10.3390/su13010249

Klein, L., Kwak, J. Y., Kavulya, G., Jazizadeh, F., Becerik-Gerber, B., Varakantham, P., & Tambe, M. (2020). *Coordinating occupant behavior for building energy and comfort management using multi-agent systems*. Automation in Construction, 110, 103041. https://doi.org/10.1016/j.autcon.2011.11.012

Knack, A., Deshpande, A., Hoorens, S., & Gunashekar, S. (2019). *Virtual and augmented reality: Implications of game-changing technologies in the services sector in Europe*. Publications Office European Union.

Kourtesis, P. (2024). The Extended Mind & Body in Extended Realities: A Scoping Review of XR Applications and Risks in the Metaverse. https://doi.org/10.20944/preprints202409.0857.v2

Lee, W. L. (2022). *This is environmental ethics: An introduction*. John Wiley & Sons.

Lu, H., Fu, K., Liu, X., & Hu, W. (2023). Digital Citizen Participation of College Students: Reality and Optimization Path. *Problems of Education in the 21st Century*, *81*(2), 244. https://doi.org/10.33225/pec/20.81.244

Merchant, C. (1987). The theoretical structure of ecological revolutions. *Environmental Review*, *11*(4), 265-274.

Palmer, C. (2017). *Does nature matter? The place of the nonhuman in the ethics of climate change*. Cambridge University Press.

Pantazatos, D., Trilivas, A., Meli, K., Kotsifakos, D., & Douligeris, C. (2023). Machine Learning and Explainable Artificial Intelligence in Education and Training-Status and Trends. In *International Wireless Internet Conference* (pp. 110-122). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-58053-6_8

Plumwood, V. (1993). *Feminism and the Mastery of Nature*. Routledge.

Polt, R., & Wittrock, J. (2018). *The task of philosophy in the Anthropocene: Axial echoes in global space*. Rowman & Littlefield.

Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Computers, Environment and Urban Systems*, *54*, 376-384. http://dx.doi.org/10.1016/j.compenvurbsys.2015.05.001

Schlosberg, D., Collins, L. B., & Niemeyer, S. (2018). Adaptation policy and community discourse: Risk, vulnerability, and just transformation. *Environmental Politics*, *27*(3), 403-422.

Schmitt, M. (2022). Deep learning vs. gradient boosting: Benchmarking state-of-the-art machine learning algorithms for credit scoring. arXiv preprint arXiv:2205.10535. https://doi.org/10.48550/arXiv.2205.10535

Tapias, B. H., Guzmán, D. H., Muñoz, P. C., & Duarte, N. R. (2024). Digital Citizenship and Sustainable Governance: A Design Thinking Approach. *Procedia Computer Science*, *231*, 78-85. https://doi.org/10.1016/j.procs.2023.12.175

U.S. Green Building Council (USGBC). (2021). *LEED v4.1 BD+C Guide*. U.S. Green Building Council.

Warren, K. (2000). *Ecofeminism: A Philosophy of Care*. Feminist Studies.

Wilke, S., & Johnstone, J. (2017). *Readings in the Anthropocene: The Environmental Humanities, German Studies, and Beyond*. Bloomsbury Publishing USA.

Zheng, L., Zhang, L., & Zhao, J. (2018). *Smart Cities and the Internet of Things: Concepts, Applications, and Challenges*. Elsevier.