MODERN TOOLS FOR DIGITAL VISUALIZATION OF BUILT ENVIRONMENTS

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Abstract: *This paper investigates the role of digital visualization tools in improving the design and construction processes within the Architecture, Engineering and Construction (AEC) industry. It examines a spectrum of advanced technologies such as Building Information Modeling (BIM), Computer-Aided Design (CAD), 3D Modeling and Geographic Information Systems (GIS), along with immersive technologies like Virtual and Augmented Reality (VR/AR). These tools can be used separately or jointly in order to provide detailed visual representations and interactive simulations of built environments. Such representations and simulations can then support stakeholders with information needed for improved decision making and project efficiency. Having in mind different use cases of tools for digital visualization, the paper presents various technologies and specific tools used in urban planning, architecture design and development of built environments. The aim is to emphasize the impact of these digital tools in visualizing and shaping future built environments, at the same time encouraging their wider adoption in the industry.*

Keywords: *digital visualization, building information modeling (BIM), Virtual and Augmented Reality (VR and AR), Geographic Information Systems (GIS)*

1. INTRODUCTION

The Architecture, Engineering and Construction (AEC) field is of vast importance for shaping our physical and social environment. This is partially done through the design, engineering and construction of built environments. These environments include all spaces made by humans, including spaces intended for people to live in, work in and interact within. Built environments represent significant support to processes of urban planning and community development while promoting sustainability (Manzoor et al., 2021).

The concept of the built environment within the AEC sector does not include only construction. It represents a full integration of buildings and spaces that empowers interactions between human activities and the natural environment. Through different quality parameters, these environments directly impact public health, productivity and social connectivity in the real world (Manzoor et al., 2021). It is important to understand that improving the efficiency, aesthetic appeal and sustainability of built environments is highly important for advancing societal well-being. These improvements can be powered by innovative tools, methodologies and technology.

Recent years have seen a revolutionary adoption of digital tools in the AEC industry. In this way it is fostering significant advancements in the visualization and modeling of built environments. Technologies such as Building Information Modeling (BIM), 3D modeling, Computer-Aided Design (CAD) and augmented and virtual reality (AR/VR) are central to this transformation, enabling precise simulation and analysis of design and construction options (Wang et al., 2019). These digital tools facilitate better decision-making and project outcomes by providing a multi dimensional view of architectural projects and simulating their real-world performance.

The critical role of tools for digital visualization in the AEC field is enabling a shift towards more integrated and efficient practices. AEC professionals can improve their project accuracy, optimize resources and lower the costs by incorporating these technologies into standard workflows. Additionally, digital tools significantly contribute to the resilience and adaptability of built environments which enables more responsive design and construction strategies that align with emerging urban needs and real world conditions (Almusaed, 2023).

This paper aims to provide an overview of current techniques, technologies and tools for digital visualization of built environments.

2. LITERATURE REVIEW

The rapid advancement of digital technologies significantly impacts the Architecture, Engineering and Construction (AEC) sector, especially in digital visualization of built environments. This literature review explores various technologies for digital visualization, categorizes the types of tools used and details specific existing tools, highlighting their key features and primary use cases.

2.1. Digital Visualization technologies in Built Environments

Literature mentions several technologies used in the process of digital visualization. Each of the techniques supports digital visualization of built environments in one or several aspects. There are five emphasized approaches to digital visualization that are mentioned by respected authors:

- Building Information Modeling (BIM)
- Virtual and Augmented Reality (VR/AR)
- 3D Modeling
- Geographic Information Systems (GIS)
- Computer-Aided Design (CAD)

Table 1 shows the brief summary of these five technologies together with description, example of existing tools, as well as areas of potential application. In the following sections, each of the presented technologies is described and presented.

Table 1: Technologies used in Digital visualization of built environments

Technology	Description	Example tools	Application
Building Information Modeling (BIM)	Digital representation of physical and functional characteristics	Autodesk Revit, BIM 360	Lifecycle management, collaboration
Virtual and Augmented Reality (VR/AR)	Immersive technologies overlaying or creating digital environments	VR headsets, AR apps, Unity, Unreal Engine	Design validation, client presentations, training
3D Modeling	Creation of detailed three-dimensional models and their visual renderings	SketchUp, 3D Studio Max, Blender, Lumion	Architectural visualization, marketing
Geographic Information Systems (GIS)	Integration and analysis of spatial and geographic data	QGIS, Esri ArcGIS	Urban planning, site analysis
Computer-Aided Design (CAD)	Utilization of computer systems to assist in the creation, modification, analysis, or optimization of a design	AutoCAD, TurboCAD	Drafting detailed engineering plans, precision modeling

2.1.1. Building Information Modeling (BIM)

BIM provides a collaborative framework for the lifecycle management of buildings. It emphasizes physical and functional characteristics (Sacks et al., 2018). Building Information Modeling (BIM) does not only provide simple visualization, but it also enables holistic management of architectural and construction projects by enabling information management. BIM integrates all relevant project data into one digital model that is improved through time. By creating such a model, it facilitates collaboration among project stakeholders. BIM's capacity to manage not only graphics but also data concerning the lifecycle of a building makes it invaluable for large-scale projects (Ding, 2014). Propelled by the advancements in the field of information technology, improved BIM solutions are arising. One of such improvements is the recent integration of cloud-based technologies with BIM which has enhanced its accessibility and collaborative potential (Zhao & Taib, 2022).

2.1.2. Virtual and Augmented Reality (VR/AR)

Virtual Reality (VR) and Augmented Reality (AR), together with other similar immersive technologies, are commonly referred to as Extensive Reality (XR) (Balakrishnan & Hameed, 2021). These technologies are used for interactive presentations and simulations. They allow stakeholders to experience built environments in immersive ways, facilitating better design validation and training (Milovanovic et al., 2017).

Virtual Reality in built environments offers an immersive experience that is unparalleled by other visualization tools. VR allows stakeholders to step into a virtual representation of a proposed space, understanding and interacting with the design in a way that traditional methods cannot match. According to (Ehab et al., 2023), VR significantly enhances client engagement and approval processes, as clients can visualize and “experience” a building or space before it is realized. Moreover, VR's role in architecture, engineering and construction highlights its potential to not only improve design understanding but also construction support, operations and management support and training (Delgado et al., 2020).

Augmented Reality overlays digital information onto the physical world. This way it offers dynamic insights and enhancements to real-time views of a project site. AR tools have been particularly transformative in site management and maintenance. For example, AR can superimpose a building’s digital blueprints over its construction site to guide placement and installation processes accurately, reducing errors and speeding up the construction timeline (Gerger et al., 2023). There are many other use cases of AR in digital visualization of built environments. One of important utilizations of AR that should be emphasized is the possibility to visualize the 3D models of part of the building directly on the field in real-time (Schiavi et al., 2022).

2.1.3. 3D Modeling

3D modeling is a technique in computer graphics for creating a three-dimensional digital representation of any object or surface (Concept Art Empire, 2018). An essential tool in various industries, including architecture, engineering and construction (AEC), 3D modeling facilitates the visualization, simulation and analysis of designs. The process involves constructing an object using dedicated software that creates a virtual three-dimensional model through layers of meshes or polygons, textures and digital sculpting (Cory & Bozell, 2001). Essential for visualizing design impacts before construction, 3D Modeling assists in decision-making and marketing by enabling visualization of design impacts before construction (Lopez et al., 2018; Sinha et al., 2008).

In regards to the built environment, 3D modeling serves multiple roles in enhancing the design process. One of the roles is in architectural visualization which empowers architects to create realistic and detailed presentations of projects. These models make it easier to understand complex architectural concepts and the spatial dynamics of a building. In the construction field, 3D models are used for simulation of the processes which is crucial for minimizing construction delays and optimizing resource allocation (Centofanti et al., 2014). 3D modeling is also frequently used in interior design. Interior designers are using 3D modeling to draft layouts and visualize interior spaces. Additionally, 3D modeling is utilized in the process of urban planning for visualization of entire urban landscapes. This technique is especially important in the preservation of cultural heritage, as it allows for the digital recreation of historical sites (Marques et al., 2017).

2.1.4. Geographic Information Systems (GIS)

Geographic Information Systems (GIS) are frameworks for gathering, managing and analyzing data rooted in the science of geography (ESRI, 2018). GIS integrates many types of data. It analyzes spatial location and organizes layers of information into visualizations using maps and 3D scenes. With this unique capability, GIS reveals deeper insights into data, such as patterns, relationships and situations helping users make smarter decisions.

3D GIS extends these capabilities by adding a third dimension, elevation, to the datasets. This allows for a more realistic and comprehensive representation of physical spaces. 3D GIS is particularly valuable in urban planning and natural resource management, where three-dimensional data provides a more accurate representation of the world (Abdul-Rahman & Pilouk, 2007).

GIS and 3D GIS integrate spatial data for urban planning and large-scale project management to provide a comprehensive analysis of geographic impacts on building designs (Batty et al., 1999; Gebur, 2021; Scholten et al., 2013). These technologies are commonly used in combination with other digital visualization techniques such as BIM and Heritage BIM for the purpose of site analysis and virtual reconstructions in heritage preservation (Dore & Murphy, 2012). GIS tools are not just about mapping and geographic analysis but rather they utilize the synthesis of various data layers, including environmental and economic datasets, to create a holistic view of the landscape and facilitate smarter decision making in the fields of urban planning, environmental and network and infrastructure management. Advanced GIS platforms provide capabilities for analyzing spatial relationships and patterns, which are crucial for urban planning and the management of natural resources (Scott & Janikas, 2009).

2.1.5. Computer-Aided Design (CAD)

Computer-Aided Design (CAD) has a crucial role in the field of digital visualization, particularly in the AEC industry (Aouad et al., 2013). CAD systems support precision and efficiency required in designing complex structures and components. These tools allow architects and engineers to create, modify, analyze and optimize their designs with a high level of accuracy. In that way compliance with specified standards and functional requirements can be ensured. The implementation of CAD not only speeds up the design process but also reduces errors through automated calculations and enhanced visualization capabilities. For instance, advancements in CAD technology have enabled the integration of simulation features that predict real-world performance, providing insights into mechanical stress, airflow and thermal properties. Such integrative capabilities ensure that the designs are not only feasible but also optimized for performance and cost-efficiency before the physical construction begins and additionally support more efficient education (Ibrahim & Rahimian, 2010).

2.2. Existing Tools and Their Applications

This section offers a comprehensive overview of contemporary digital visualization tools, highlighting their key features and primary use cases. Additionally, it delves into their significance within various industries and explores emerging trends in the field of digital visualization. In the group of CAD tools, Autodesk AutoCAD (Autodesk, 2024) undoubtedly holds the greatest significance. It is essential for drafting detailed 2D and 3D drawings and widely utilized across engineering disciplines. Additionally, this tool is extensively employed in data preparation for the construction of virtual reality models (Whyte et al., 2000). TurboCAD (TurboCAD, 2023) offers powerful 2D and 3D CAD capabilities with an economical price point, making it a viable option for smaller firms or individuals needing detailed architectural and mechanical design tools. In a study by (Nariman, 2016), TurboCAD is used for evaluation of e-learning systems for CAD drawing courses. On the other side, SolidWorks is primarily used in mechanical engineering and provides CAD and CAE capabilities, enabling designers to simulate physical behaviors, such as kinematics, dynamics, stress, deflection, vibration, temperatures, or fluid flow. Its advanced features and intuitive interface make it an ideal tool for creating highly detailed and accurate 3D models of architectural structures, infrastructure and landscapes (Sommer et al., 2023). Fusion 360 facilitates the visualization of the built environment by providing architects and urban planners with a comprehensive platform to design, simulate and iterate on architectural structures, infrastructure and landscapes in a collaborative, cloud-based environment (Fusion 360, 2024).

Revit software revolutionizes the visualization of the built environment by offering architects and designers advanced tools for creating detailed 3D models, facilitating collaborative design processes and enhancing project coordination and communication within the architecture, engineering and construction industries. (Tytarenko et al.,2023) used Revit in their study to model a historical heritage site with a high level of detail. BIM 360 is another BIM based solution enabling stakeholders to access and analyze project data, coordinate design changes and visualize construction progress in real-time, thereby enhancing project transparency and efficiency throughout the entire lifecycle of a building project (BIM 360, 2024).

In the group of 3D modeling, there are several versatile tools which provide features for visualizing the built environment. Industry leaders include but are not limited to SketchUp, Lumion, Blender, Unity, Unreal Enginde, Adobe Dimension. All of these tools provide architects and urban planners with a highly usable platform for creation and manipulation of 3D models. Their usage enables efficient research of spatial relationships, design concepts and architectural elements within various urban contexts. As a tool with capabilities comparable to AutoCAD and serving as its competitor, research by (De Yong et al., 2020) revealed that SketchUp is primarily utilized for 3D modeling purposes. In the manner of 3D mapping, one of the commonly used software solutions is Cesium, specialized tool for creating 3D globes and maps from geospatial data, Cesium is instrumental in projects that require real-time visualization of large-scale environments. It's particularly useful for integrating various datasets into a cohesive 3D visualization platform (Cesium, 2024).

As an open-source GIS tool, QGIS supports spatial data analysis and visualization, crucial for environmental impact assessments and infrastructure planning. It is valued for its adaptability to various plugins and extensive data handling capacities (QGIS, 2024). It allows urban planners, geographers, and researchers to incorporate diverse datasets such as land use, transportation networks, and environmental factors to create comprehensive visualizations that inform decision-making processes and facilitate sustainable urban development strategies. On the other hand, as an enterprise software, ArcGIS provides robust GIS capabilities for comprehensive geographic data analysis that assists in site selection and urban planning. Additionally, ArcGIS offers seamless integration with other Esri products, making it a comprehensive solution for organizations requiring advanced geospatial analysis and mapping capabilities (Babayeva, 2013).

Navisworks is a powerful software solution commonly utilized in the construction industry for facilitating coordination, collaboration, simulation and visualization of complex building projects through its advanced 3D model review and analysis capabilities (Navisworks, 2024). Dialux is a vital tool in architecture and construction, enabling architects and engineers to design and assess lighting solutions for buildings and outdoor spaces, ensuring well-lit and visually pleasing environments while meeting industry standards (Dialux, 2024).

Table 2: Existing tools for Digital Visualization of built environments

Tool	Type	Key Features	Primary Use Cases
AutoCAD	CAD	Precision 2D and 3D drawing, customizable, extensive tools	Detailed engineering plans, architectural drafting
Revit	BIM	Integrated BIM capabilities, multi-disciplinary support	Pre-construction modeling, cost estimation
SketchUp	3D Modeling	User-friendly interface, extensive plugin ecosystem	Preliminary 3D modeling, visualization
Navisworks	Simulation	Clash detection, 3D coordination, project review	Project integration management
QGIS	GIS	Open-source, data analysis, customizable	Environmental impact assessments, urban planning
Cesium	3D Mapping	Real-time 3D visualization, geospatial data integration	Large-scale project visualization, simulations
ArcGIS	GIS	Comprehensive spatial analysis, data management	Site selection, comprehensive urban planning
BIM 360	Collaborative BIM	Cloud-based, real-time data sharing, project tracking	Document management, stakeholder collaboration
Dialux	Analysis	Lighting design simulation, standards compliance	Lighting design for interiors and exteriors
TurboCAD	CAD	Affordable, versatile 2D and 3D CAD software	Small-scale architectural and mechanical design
SolidWorks	CAD/CAE	3D design, simulation, and analysis capabilities	Product design, mechanical engineering
Fusion 360	CAD/CAM/CAE	Integrated design, manufacturing, and engineering	End-to-end product development, prototyping

Table 2 presents a structured overview of described existing tools for digital visualization of built environments. Other than the name of the tools, it provides information about the tool type, key features and primary use cases of the presented tools.

3. CONCLUSION

While the current advancement of digital visualization tools is promising, several areas require further research. Future studies should focus on enhancing the interoperability of these tools to ensure seamless data exchange and integration across different platforms and software systems. The accessibility and usability of advanced tools like VR and AR should also be addressed. Additionally, investigating long-term impacts of digital visualization tools on project lifecycle management, maintenance and operation could provide insights into their limitations.

Developing more intuitive and user-friendly interfaces is of vast importance for wide use of these tools. Along with the focus on usability and intuitiveness, improved training programs could also support democratization of the use of such tools. These improvements could make them more accessible to a broader range of stakeholders. Lastly, investigating the sustainability aspects of these tools and their role in promoting environmentally friendly design practices would align with global sustainability goals and enhance the societal value of the AEC industry.

Digital visualization tools continue to evolve and they become more integrated into the AEC industries. The possibilities for transformation of how projects are designed, managed and executed are emerging with the features and potential those tools are bringing. Embracing these technologies while addressing the existing challenges and exploring new research tracks will undoubtedly pave the way for more innovative, efficient and sustainable architecture, engineering and construction practices.

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