World Journal of Engineering and Technology, 2023, 11, 976-988
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

The Application and Prospects of Digital Visualization in Urban Public Building Space Design

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How to cite this paper: Liang, P. and Sharudin, S.A. (2023) The Application and Prospects of Digital Visualization in Urban Public Building Space Design. *World Journal of Engineering and Technology*, **11**, 976-988.
https://doi.org/10.4236/wjet.2023.114064

Received: July 13, 2023
Accepted: November 27, 2023
Published: November 30, 2023

Abstract

With the development and innovation of digital information technology, digital visualization plays an increasingly important role in the design of urban public building spaces. This paper explores the application of digital visualization technology in the design of urban public building spaces and looks ahead to future trends. Firstly, it analyzes the challenges in the design of urban public building spaces, including extensive professional involvement, complex functional layout requirements, rational emergency evacuation routes, multidimensional analysis of architectural spatial environments, and appropriate selection of decorative materials. Next, it introduces the applications of digital visualization technology in showcasing visual design and expression, optimizing spatial functional layouts, enhancing the rationality of evacuation routes, analyzing dynamic environmental impacts and energy consumption, and improving the effectiveness of material selection in the design of urban public building spaces. Lastly, it discusses the prospects of extended reality (XR) technology, interactive design using data platforms, and AI technology in the design of public building spaces. It is hoped that this paper provides inspiration and reference for the deeper application of digital information technology in the field of architecture.

Keywords

Digital Visualization, Urban Public Building, Space Design, Application

1. Introduction

In modern urban life, public buildings play a significant role, encompassing various aspects of people's social activities. Urban public buildings include office buildings, hotels, commercial complexes, museums, stadiums, libraries, hospitals, and more. Therefore, the spatial design of urban public buildings holds great importance for work, life, and the urban environment in modern society. With the development of society and the continuous improvement of people's quality of life, the spatial functional requirements for urban public buildings are also increasing. The spatial design of public buildings is highly flexible, and architects need to achieve a combination and application of economy, artistry, and other aspects based on user needs, striving to create a safe, comfortable, and fully functional architectural environment [1]. Public buildings belong to the realm of public services and generally adopt large-scale spatial design. The same space involves multiple disciplines such as architecture, structure, mechanical and electrical systems, and interior decoration, making the expression of spatial design more complex.

The development of digital visualization has brought about more convenient working methods and collaboration approaches in the spatial design of urban public buildings. Digital visualization technology is a technique that utilizes computer information technology to convert parameters into three-dimensional graphics, allowing for the presentation of three-dimensional graphics and specific ideas [2]. Introducing digital visualization technology into the spatial design of urban public buildings can assist designers in expressing spatial design effects more accurately. It helps construction engineers and on-site construction workers better understand the intended design expression, clarify the spatial geometric relationships of building components and equipment layout, and improve project progress and engineering quality. Furthermore, the visualization of architectural design greatly aids in the preliminary work and component production of Industrialized Building System (IBS) projects in Malaysia [3].

2. The Challenges of Urban Public Building Space Design

2.1. Wide Range of Professional Involvement

The in-depth design of public buildings involves multiple professional fields, including civil engineering design, mechanical and electrical design, interior design, landscape design, and more. Each professional field is further subdivided into different specialties. For example, civil engineering can be divided into architectural and structural directions, while mechanical and electrical engineering can be divided into plumbing, electrical, HVAC (heating, ventilation, and air conditioning), and other directions. Each specialty requires specialized designers to carry out engineering design. When multiple specialties are involved in the same space, designers are responsible for their respective tasks within their own specialty during the design phase. However, clashes or overlaps between different disciplines may occur during the construction phase. Taking civil engineering and mechanical and electrical engineering as examples, clashes between MEP (mechanical, electrical, plumbing) pipelines and civil components, or conflicts between HVAC ducts and MEP cable trays can occur. **Figure 1** and **Figure 2** show that collision between pipe and beam, and collision between spray and air duct. This poses a challenge to the collaborative work between designers in related specialties. Specifically, the collaboration between MEP in-depth design and civil engineering in-depth design includes coordination of reserved spaces and embedded items, ensuring equipment loads are accommodated, and coordinating the operational conditions of mechanical and electrical equipment [4]. This is also one of the important reasons why technical disclosure and drawing review must be carried out before project construction.

2.2. Complex Functional Layout Requirements

Urban public buildings belong to the realm of public services, and their spatial functionality needs to meet the requirements of different user groups. For example, in the design of the project for the Nishan Hotel, there are requirements not only for the comprehensive facilities within the space but also for the emphasis

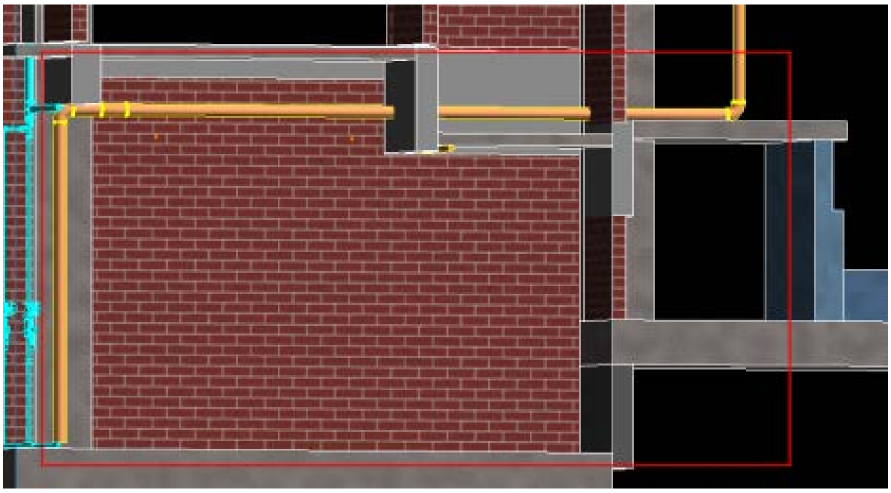

Figure 1. Collision between pipe and beam.

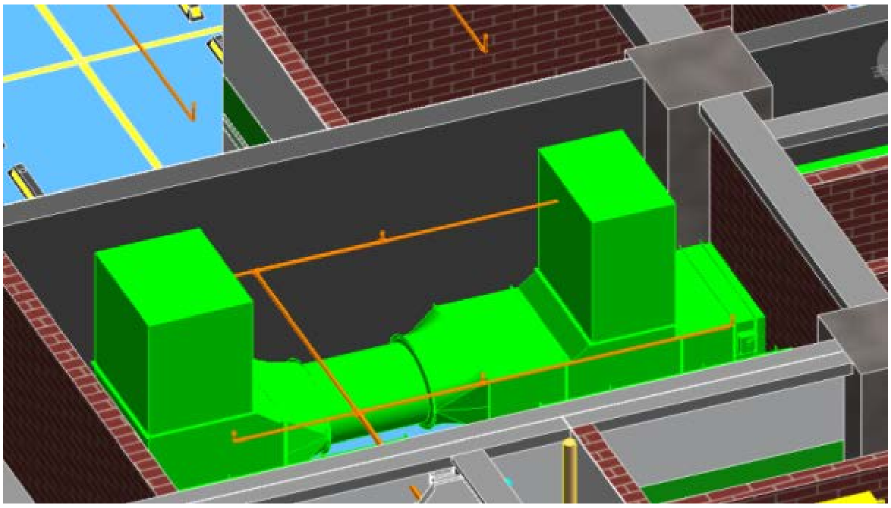

Figure 2. Collision between spray and air duct.

on space creation, functional layout, and flow design [5]. To cater to different functional service needs, designers need to divide the overall architectural space into multiple functional zones. In the case of hotel buildings, the architectural space is divided into areas such as the lobby, dining area, multifunctional conference area, and guest rooms. In addition to hotels, commercial complexes prioritize the principle of providing users with convenient and high-quality services throughout the entire process, ensuring that the users' various commercial activity needs are met [6]. In summary, in the design of public building spaces, designers face complex functional requirements. They need to consider spatial functionality and design from multiple perspectives. Typically, designers simulate layouts through the creation of small-scale physical models, although there are certain limitations.

2.3. Reasonable Emergency Evacuation Routes

Public building spaces often gather many people, and their layouts are generally complex and diverse, including multiple floors, winding corridors, and separated areas. In the event of an emergency, such as a fire, it can lead to significant loss of life and property. Decorative materials and electrical appliances within public buildings are potential fire hazards. Additionally, as the number of combustible materials increases with higher floors, it poses challenges for firefighting efforts and creates significant safety risks. During a sudden fire, elevators become unusable, resulting in many people being trapped in the public building space. Due to the general lack of familiarity with evacuation routes and the spread of smoke, overcrowding and stampede accidents can occur, making evacuation more difficult and complicating firefighting and rescue efforts [7]. Therefore, in the design of architectural plans, the importance of safety evacuation design must be emphasized. However, the design of evacuation routes in two-dimensional plans generally relies on the experience of the designer and does not allow for first-person perspective spatial simulations and optimized designs.

2.4. Multi-Dimensional Analysis of Architectural Spatial Environments

Energy efficiency and emissions reduction in buildings are among the important measures recommended for promoting an environmentally friendly society. Currently, China is vigorously promoting the concept of "green buildings." Green building design emphasizes environmentally friendly practices throughout the entire life cycle of a building, including planning, design, construction, renovation, use, and even demolition [8]. Given the public service nature of public buildings, they undoubtedly place greater emphasis on green and environmentally friendly designs. They play a demonstrative role in reducing energy consumption and carbon emissions in the construction industry. Currently, the government has established relevant regulations and mandatory requirements for green and energy-efficient designs of public buildings. Designers need to consider building environmental analysis from the conceptual design stage. Although public building spatial environments can be assessed and analyzed based on five dimensions: surrounding safety and durability, health and comfort, convenience of life, resource conservation, and environmental suitability [9], traditional design approaches cannot quantitatively analyze these dimensions. Designers must consider how to conduct environmental analysis of public building spaces through appropriate technical means and data. This aspect was often overlooked in previous architectural designs but has become particularly important now.

2.5. Appropriate Selection of Decorative Materials

Decorative works in public building construction can be divided into three parts based on the space: ceiling decoration, wall decoration, and floor decoration. There is a wide variety of building decorative materials in terms of types and styles. To accurately convey the chosen decorative materials, interior designers often provide material specifications and construction details in the drawings. Additionally, they need to create graphic legends to illustrate key construction nodes. However, due to the limitations of two-dimensional CAD floor plans, the actual effects of the materials cannot be fully demonstrated. Therefore, clients and contractors often require designers to provide visual renderings. Unfortunately, because of the different types and qualities of building materials, designers cannot comprehensively and effectively specify the required material standards and models on the drawings. This can result in contractors purchasing decorative materials that do not meet the designer's requirements in terms of quality and appearance [10]. To select suitable decorative materials, contractors often need to order numerous material samples in advance and set up a dedicated display area on the construction site. The final selection is made in collaboration with the designer and the client, which can be time-consuming and labor-intensive.

3. Application of Data Visualization

3.1. Display of Visual Design and Expression

Architectural space design can be divided into three stages: conceptual design, construction design, and completion design. BIM (Building Information Modeling) technology is utilized to create three-dimensional visual models of the building, which permeate through all three stages of architectural space design. During the conceptual design stage, where many clients may not have architectural expertise, designers use BIM software like Revit to transform design sketches into conceptual models. This allows for an intuitive presentation of the design concept, greatly facilitating the client's understanding of the proposed solutions. It also helps designers grasp the overall architectural style and provide viable options for the subsequent construction design stage. During the construction design stage, BIM models are used to integrate various disciplines such as architecture, structure, mechanical and electrical systems, and interior decoration. By creating three-dimensional views and animated effects, construction personnel can visually examine the expression of each discipline within the architectural space. This helps avoid clashes and conflicts between different disciplines, guiding the construction process and improving quality, reducing costs, and saving time [11].

During the completion design stage, the construction model serves as the foundation for integrating with a visual operations and maintenance management platform. By combining elevator systems, heating systems, cooling systems, water supply systems, security systems, parking systems, etc., with big data visualization, the control and management of the building's spatial environment can be visualized. This enhances the capabilities of post-operation and maintenance management [12]. **Figure 3** and **Figure 4** show that civil model and electromechanical model.

3.2. Optimizing Space Functionality Layout

The spatial layout and functional characteristics of public buildings vary depending on their service purposes. Common combinations of spatial layouts in public buildings include parallel space arrangement, serial space arrangement, atrium-style space arrangement, and open-plan space arrangement [13]. Digital visualization technology can assist designers in spatial planning and functional layout design, overcoming the limitations of traditional physical models in space layout. By creating a 3D building model and arranging corresponding facility models using BIM software, designers can use lightweight tools for interior walkthroughs, allowing them to immerse themselves in a detailed understanding of the internal structure and layout of the building from a first-person perspective. **Figure 5** shows architectural visualization for spatial exploration. This helps

Figure 3. Civil model.

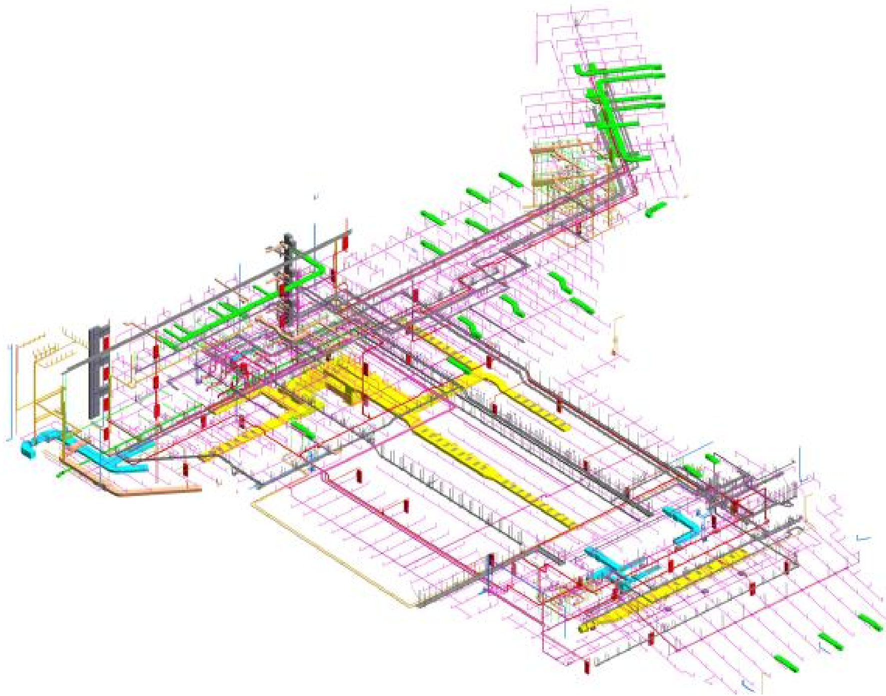

Figure 4. Electromechanical model.

Figure 5. Visual space exploration.

designers evaluate different spatial layout options based on functional requirements and find the best layout through visual analysis. Additionally, designers should fully utilize BIM technology for visual analysis to improve spatial efficiency, functionality, and user experience, ensuring the rationality of the design solutions [14].

3.3. Enhancing the Rationality of Evacuation Routes

The design of evacuation routes in public buildings has always been a key consideration for designers. By using digital visualization technology to assist in the design of evacuation routes in architectural spaces and combining it with relevant simulation software to analyze the horizontal and vertical evacuation of large public buildings using 3D models, designers can calculate evacuation time and evacuation areas. Effective evacuation guidance and layout can improve the efficiency of personnel evacuation and ensure their safety [15]. For example, Haotian Zheng *et al.* [16] used Revit software to create a 1:1 scale BIM model and then used Pathfinder software to determine the most efficient evacuation channels. Following the "worst-case principle," they assumed that the nearby area was the location of a fire. They used Pyrosim software to determine conditions such as smoke diffusion, visibility, carbon monoxide concentration, and temperature at each stairwell during a fire. **Figure 6** shows software conducting visualized fire simulation analysis. They compared the evacuation results of the planned routes with the original conditions. Based on the simulation results, they proposed optimization suggestions such as adding broadcast guidance, signage, and widening staircases, which significantly improved evacuation efficiency.

3.4. Analysis of Dynamic Environmental Impacts and Energy Consumption

With the development and application of parametric design analysis software and building performance simulation software, designers can simulate the multidimensional environmental impacts of buildings using corresponding software. This enables visualization, quantification, and analysis of building environmental data, leading to optimized design solutions. Han Fang *et al.* [17] proposed the use of daylight analysis software Dali to model and simulate key functional spaces such as exhibition halls, central halls, and connecting corridors. Through simulation modeling, the design can be optimized to meet the project's daylighting requirements. Xian LiangLiang *et al.* [18] using the teaching building of Xi'an University of Architecture and Technology as an example, employed Rhinoceros modeling and Ladybug + Honeybee for environmental analysis. This

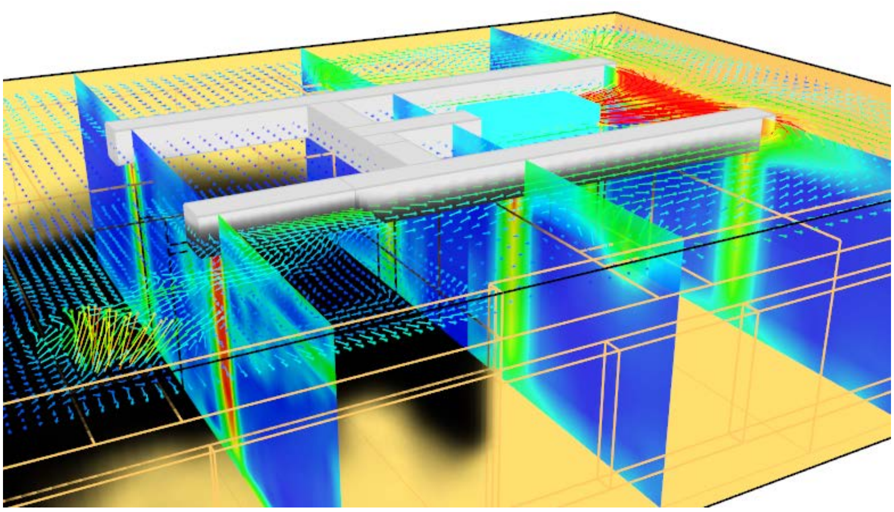

Figure 6. Fire simulation analysis.

approach allows modeling in one software during the design phase and uses connection operators to simulate various physical environments of the building and its site, providing a basis for design decisions. **Table 1** provides an overview of several popular building environmental analysis software and their characteristics.

3.5. Enhancing the Effectiveness of Decorative Material Selection

Due to the limitations of traditional 2D CAD software in meeting the intuitive spatial requirements of interior design, to achieve refinement, rationalization, and efficiency in interior design, it is necessary to enhance the overall operation of architectural projects in terms of material selection, form construction, and cost control. This can be achieved through improving the effectiveness of the benefits and the detailed construction of the architectural project. Digital visualization can assist designers, contractors, and clients in evaluating and selecting different decorative materials and design schemes. Through digital visualization technology, designers can showcase the decorative effects within the architectural space before the decoration stage, simulate different materials and decorative effects, and ensure that the decorative design scheme for public buildings meets the designer's expected goals and satisfies the requirements of all parties involved. **Figure 7** shows architectural visualization for material selection. For example, Bao Xiaoxian. [20] utilized three-dimensional visualization models for decorative design, using BIM technology to create a three-dimensional representation of the connections between different components, including details such as lighting and wall decorations. This allows the designer to have a comprehensive

Table 1. Introduction to various building environment analysis software [19].

Software Name	Main functional purposes	Accuracy
EnergyPlus	Thermal Comfort Simulation and Solar Energy Simulation Analysis	High
Esp-r	Simulation Analysis of Building Thermal Environment	High
Radiance	Light Environment Simulation Analysis	High
Cadna/A	Acoustic Environment Simulation Analysis	High
Ladybug, Honeybee	Simulation Analysis of Sunlight, Orientation, Energy, Thermal radiation, and airflow	Higher
Fluent	Wind Environment Simulation Analysis	Higher
PKPM	Analysis of Structural, Energy-saving, and Green Building Solutions	Higher
Bentley	Energy + carbon, Daylighting, Energy Consumption Simulation Analysis	Higher
Green Building Studio	Analysis of Overall Energy Consumption, Water Resources, and Carbon Emissions of Buildings	Medium
Ecotect	Analysis of Total Energy Consumption of Buildings	Low & Quick

Figure 7. Visualizing material selection.

understanding of the decorative design situation.

4. The Future of Data Visualization

4.1. Applications of Extended Reality (XR)

With the advancements in computer graphics and simulation technology, virtual reality (VR) technology has been applied in the field of architecture, and extended reality (XR) is the collective term for virtual reality (VR), augmented reality (AR), and mixed reality (MR) [21]. Shenghuan Zhao *et al.* [22] utilized XR technology for interactive visualization of curtain wall window geometry and interior illuminance simulation, comparing and evaluating AR, MR, and VR technologies. The evaluation results showed that MR was the most suitable XR technology for this objective when compared to AR and VR. Designers can use XR technology not only for visualizing and analyzing architectural spaces but also for experiencing and interacting with public building spaces in a more immersive manner. Furthermore, XR technology allows users to immerse themselves in architectural environments during the initial design phase, overlaying virtual content onto real scenes, providing real-time design demonstrations and guidance, and experiencing aspects such as spatial scale, material texture, and lighting effects, thereby providing more accurate feedback and opinions. Sepehr Alizadehsalehi *et al.* [23] state that XR technology immerses users through visual, audio, and potentially olfactory and haptic/tactile cues. Although the strongest demand for these immersive technologies currently comes from the "creative" industries (such as video entertainment and gaming), XR technology has significant potential for improving efficiency and productivity in the architecture, engineering, and construction (AEC) industry.

4.2. The Development of Data Platform Interaction Design

The application of digital visualization in the design of public building spaces will increasingly focus on data-driven design methods. By collecting and analyzing a large amount of building usage data, designers can better understand user behavior and needs, thereby optimizing space design and functional layout [24]. The Digital Building Development White Paper (2022) [25] proposes a fully digitalized collaborative approach, using a unified building data model to efficiently circulate information between different stages, enabling collaborative work among stakeholders. This is achieved through direct information reading or output in proprietary data formats between software systems and data sharing and exchange in neutral data formats. It aims to promote data compatibility and circulation among various professional software, reshape the entire professional design process, and disrupt the traditional document-based design paradigm. Zhang Enjia [26] mentioned three forms of digital innovation application scenarios: spatial interventions in external public spaces, the smartification of urban furniture and buildings, and the virtual scene construction of physical space experiences. The first two forms enhance the experience of physical space through spatial interventions and place-making, while the third form expands the design elements beyond physical space and focuses on the creation of virtual spatial scenes. Zeynep Engin [27] believes that data-driven design and interdisciplinary collaboration have become industry standards, and the new digital design "methodology" permeates every corner of architectural design scenarios. Data has become the most fundamental element as the object of design, and it is restructuring the connections among all knowledge workers from a higher dimension.

4.3. Integration of AI in Architectural Visualization Design

With the introduction of AI technology products in the market and the increasing popularity of AI-powered conversational models like ChatGPT, more and more people are paying attention to the impact of AI on the architecture design industry. Hongyu Li *et al.* [28] analyzed the data transmission process of architectural space models based on semantic networks and architectural spatial structure analysis. The fitting curves of the comprehensive model demonstrated that AI-based intelligent architectural spatial design solutions outperformed traditional architectural design solutions. Shanaka Kristombu Baduge *et al.* [29] highlighted that machine learning (ML) and deep learning (DL) are undoubtedly the core applications of AI, empowered by enhanced computing capabilities and the availability of large-scale generated data. They discussed the use of generative deep learning models for automated architectural design generation, such as floor plan generation, innovative concept design, and interior scene synthesis. While there are currently no fully performance-based AI architectural design tools available, AI-based software tools can assist designers in easily tackling tedious and repetitive tasks when dealing with the complexity of comprehensive public building space design.

5. Conclusion

Urban public buildings have always been an important component of urban architecture. The design of public building spaces involves multiple disciplines, complex spatial layouts, challenges in emergency evacuation route planning, multidimensional analysis of building environments, and the selection of decorative materials. By applying digital visualization technology to the design of public building spaces, it becomes possible to visualize and express designs, optimize spatial functionality and layout, improve the rationality of evacuation routes, analyze dynamic environmental impacts and energy consumption, and enhance the selection of decorative materials. With the development of Extended Reality (XR) technology, interactive design platforms, and AI technology, digital visualization technology will play an even more important role in the design of public building spaces. This will lead to improved design quality and user satisfaction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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