A Simulation-Driven Parametric Building Envelope Façade Design Using Generative AI and Virtual Reality in the Early Design Phase

David Stephen Panya[1], Taehoon Kim[2], Geunjae Kim [3], Jungmin Park[4], Gaeun Park[5], Seungyeon Choo[6]
[1,2,3,4,5,6]School of Architecture, Kyungpook National University, Republic of Korea
[1,2,3,4,5,6]{david.panya@gmail.com|thlouiskim@gmail.com|clack92@knu.ac.kr| zktm4935@knu.ac.kr| gaeun2868@naver.com| choo@knu.ac.kr}

Recent advances in generative AI have significantly impacted architectural design, enabling the exploration of complex tasks such as site layout planning, interior design, and exterior design. While architects recognize the potential of generative AI, personal barriers often hinder its widespread adoption in the field. Understanding the principles and applications of generative AI is crucial to overcoming these challenges and improving both the sustainable and functional aspects of design outcomes.
This study aims to enhance design productivity by digitizing early-stage processes, such as Bubble Diagrams, into graph-structured datasets and developing a Generative Design algorithm. The algorithm automates the creation of space layouts by quantifying design elements like spatial adjacency and environmental factors, defining building mass outlines, and generating floor plans complete with walls and doors.
Additionally, the paper integrates AI-generated floor plans with parametric design tools to optimize building performance during the early design phase. This process involves generating 3D geometry from spatial layouts, organizing them into multi-level floor plans, and using Rhino and Grasshopper to create building envelope facades. The facades are then simulated with Honeybee to evaluate performance, producing multiple design iterations. These iterations are visualized in a virtual reality (VR) environment, where a variant manager enables real-time interaction and analysis of various parametric building envelope designs.
By leveraging these tools, architects can explore complex forms, resulting in more sustainable, contextually relevant designs that enhance user experiences.

Keywords: *Generative AI, Parametric Building Design, Data-Driven Simulation, Virtual Reality.*

INTRODUCTION

According to the United Nations Environment Program, buildings account for approximately 36% of global energy consumption and contribute around 37% of greenhouse gas emissions attributable to human activities (Min et al., 2022). Early-stage building design plays a critical role in determining the ultimate performance of buildings. Given the significant environmental footprint of the built environment,

it is imperative to implement robust strategies in the initial design phases to accurately predict the impacts of various design decisions on energy use and sustainability outcomes.

The integration of advanced technologies such as generative AI and virtual reality (VR) within the architectural design process presents promising opportunities to improve decision-making, optimize energy efficiency, and minimize environmental impacts. These tools enable architects and designers to rapidly explore a broad spectrum of design alternatives, facilitating more informed choices that balance sustainability goals with functional and aesthetic requirements. Simulation-driven approaches during early design stages provide a foundation for ensuring that the final building meets user comfort needs, energy performance targets, and global emissions reduction commitments.

This research proposes a comprehensive workflow that synthesizes AI-driven generative design, computational algorithmic design, performance simulation, and immersive VR visualization. Starting with the generation of residential floor plan spatial layouts based on a robust graph-structured dataset, the methodology employs Dynamo within BIM software to create initial floor plans and corresponding BIM models. These are then exported to Rhino via Rhino.Inside to develop detailed building envelopes. Grasshopper algorithms perform simulations of building performance and occupant comfort. The resulting building envelopes and simulation data are subsequently imported into VR environments, allowing stakeholders to experience and evaluate multiple design iterations interactively and immersively. This integrated approach enhances the architectural design process by enabling real-time performance analysis and visualization, ultimately promoting sustainable design outcomes.

BACKGROUND AND RELATED RESEARCH

Building Envelope Design

The building envelope fundamentally influences energy efficiency, construction cost, and overall building performance, particularly during the early design phases. Environmental factors such as climate conditions exert strong control over envelope strategies and effectiveness.

In Oceanic climates, optimizing window-to-wall ratios and leveraging thermal mass effects are key drivers for reducing energy consumption (Leonidaki et al., 2014). Embedding climate-responsive strategies early in design enables envelopes to adapt to local environmental conditions, improving overall energy performance.

Effective early-stage collaboration among architects, engineers, and energy consultants is vital. Identifying critical design variables such as glazing type, shading devices, and insulation thickness during conceptual design supports alignment of energy targets with structural feasibility. This interdisciplinary approach embeds sustainability considerations from project inception.

Accordingly, deploying energy simulation and decision-support tools early in the design process facilitates the assessment of multiple design scenarios. Since the conceptual design phase is when major alternatives are explored and pivotal decisions made, it significantly influences building performance outcomes. For instance, selecting an optimal building form and orientation alone can reduce energy consumption by 30–40% without additional construction costs (Wang et al.).

AI based Generative Design

The integration of generative AI into the early stages of building envelope and façade design offers significant potential to improve accuracy, efficiency, and creativity. These technologies

streamline the design process and enable architects to explore a broad range of alternatives while maintaining precision and performance criteria. This section examines how generative AI contributes to improving façade design accuracy and workflow effectiveness.

Generative AI has become a powerful tool in architectural design, allowing rapid generation of multiple design options that address both aesthetic and functional requirements. In this research, generative AI is employed in two key areas:

1. The generation of building spatial layouts
2. The optimization of spatial configurations based on predefined parameters

(Nauata et al. 2020) demonstrated the potential of generative AI in spatial layout generation through a graph-constrained generative adversarial network (GAN). In this approach, both the generator and discriminator employ relational architectures, embedding architectural constraints directly into a graph structure. The system produces house layouts by generating axis-aligned bounding boxes representing rooms, offering enhanced spatial logic and control.

(Park et al. 2024) addressed challenges in AI-driven layout generation by developing a domain-specific training dataset for architectural applications. Their method extracted spatial relationship diagrams from raster-based floor plans and converted them into vector-based data. Using web-crawled data, they compiled a dataset of 10,000 samples, categorized into 21 room types and three spatial relationship classes. When evaluated with the YOLO model, the system achieved a 99% detection rate, 85% mean average precision, and 74.2% mean intersection over union (MIoU), demonstrating strong performance in recognizing spatial configurations.

Generative AI is a transformative tool for early-stage architectural design, enhancing the speed, accuracy, and adaptability of layout and envelope generation. By enabling automated, data-driven design iteration, it supports high-quality outcomes that align with functional requirements and environmental performance goals.

Simulation Driven Virtual reality

Simulation-driven virtual reality (VR) is reshaping architectural design by offering immersive, interactive environments that enhance creativity, collaboration, and informed decision-making. When integrated with simulation tools, VR enables real-time design evaluation, facilitating a more dynamic and iterative design process from concept development to final visualization.

VR empowers architects to interact with their designs in real-time, providing immediate feedback for iterative refinement—particularly valuable in early design phases where rapid prototyping is essential. Its integration with Building Information Modeling (BIM) enhances this process further by enabling proactive clash detection. While traditional BIM workflows often identify conflicts retrospectively, coupling VR with machine learning allows for predictive identification and resolution of design issues, reducing costly revisions and improving workflow efficiency (Shehadeh et al., 2025).

Additionally, VR-enhanced BIM supports detailed design development by offering comprehensive, immersive visualizations of architectural and engineering components. This foster improved interdisciplinary collaboration, aligning design intent across teams (Natephra et al., 2017).

Simulation-driven VR also supports performance-based design by integrating environmental simulations directly into the immersive environment. Real-time visualization of metrics such as daylighting, energy efficiency, and thermal comfort enables architects to make data-informed decisions early in the design process.

Several studies highlight the practical application of VR in sustainable building design. (Lai et al. 2022) presented a VRML-based virtual system applied to a real-world energy-saving demonstration project, which achieved notable reductions in energy consumption. Similarly, (Lie et al. 2021) explored an online VR platform for green building design, enabling remote users to collaboratively engage in the creation of energy-efficient architecture.

The integration of simulation-driven VR into architectural workflows offers substantial advantages for sustainable design. By providing immersive platforms for analyzing building performance, VR equips architects with the tools to make more informed, sustainable choices. The literature emphasizes the importance of combining VR with BIM and simulation technologies and highlights the need for further research and real-world implementation to fully leverage their potential.

METHODOLOGY

This research introduces an integrated design methodology that combines AI, generative algorithms, performance simulations, and VR to optimize architectural design with a focus on sustainable building envelopes. The process begins with AI-generated 2D spatial layouts, which are transformed into 3D models in BIM software like Revit using generative algorithms. The building envelope is refined through parametric modeling in Rhino and Grasshopper. Performance metrics such as daylighting, thermal comfort, and energy use are analyzed using Ladybug and Honeybee. Finally, the design is visualized in VR using Unreal Engine, enabling immersive evaluation and stakeholder collaboration. This workflow streamlines early-stage design, enhances energy performance, and supports data-driven decision-making.
is illustrated in Figure 1.

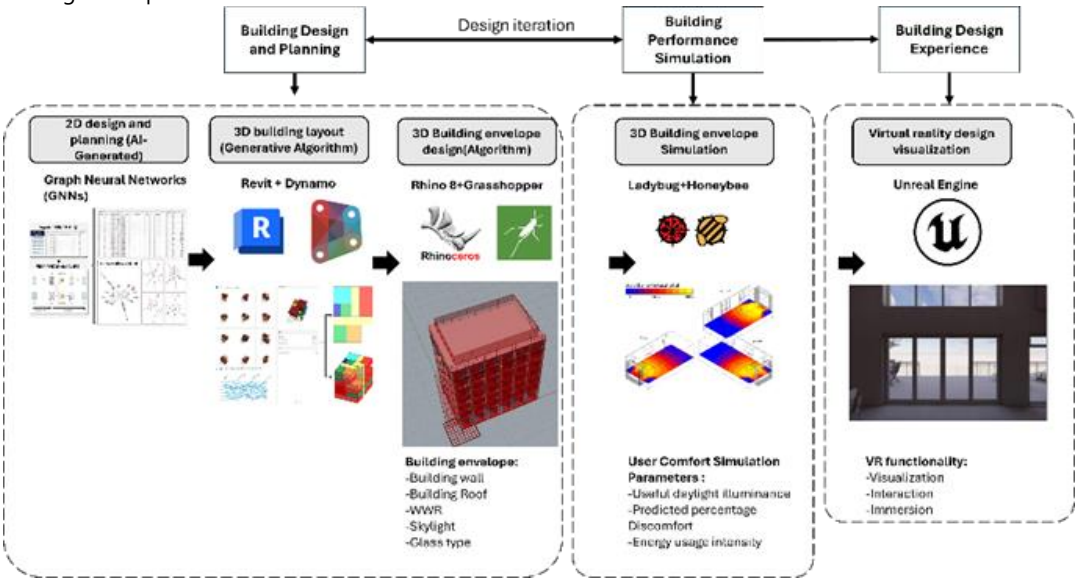

Figure 1
AI-Driven Building Design Workflow: From Planning to Virtual Experience

2D Floor Plan Generation

The first phase focuses on 2D design and planning using AI-generated models. Spatial requirements are input into an AI-driven system that produces optimized 2D spatial layouts and architectural bubble diagrams.

This study introduces a conditional generative framework based on Stochastic Differential Equations (SDEs) to synthesize architectural bubble diagrams. Architectural layouts are converted into graph representations, where nodes correspond to spatial elements (e.g., rooms) and edges represent spatial relationships. Each node carries a feature matrix with categorical (e.g., room type) and continuous (e.g., aspect ratio) data, while the adjacency matrix encodes connectivity. Categorical variables are treated as scalars rather than one-hot vectors to simplify modeling. This abstraction enables diffusion-based generation and recovery processes.

Training involves two stages: noise injection and denoising. Gaussian noise is progressively added to the feature and adjacency matrices via a forward SDE, distorting data into noise priors. Drift and diffusion coefficients govern this transformation, implemented through Variance Preserving SDE (VPSDE) and Variance Exploding SDE (VESDE) configurations for stability and expressiveness. The denoising phase reverses this process using neural score functions that estimate gradients of the data distribution, gradually restoring the original data. Time embedding with sinusoidal encoding integrates temporal context into learning.

To enable conditional generation, partial user inputs such as specified nodes or edges—are integrated into the pipeline. Noise sampled from a standard normal distribution is combined with these conditions and fed into trained score models, which iteratively generate complete diagrams via reverse SDE. An annealed Langevin dynamics corrector refines outputs to better align with target distributions, particularly useful in complex, high-dimensional cases.

A Graph Multi-Head Attention (GMH) mechanism enhances the model's capacity to capture structural details by applying multi-head graph neural network attention, weighting node interactions by spatial and temporal context. Experiments revealed that the sequence of generating node features and adjacency matrices affects output fidelity, with consistent generation across time steps improving quality.

The dataset consists of over 4,500 building samples, split 80/20 for training and testing. Samples encode spatial attributes such as space type, window variations, and connectivity. Model evaluation uses graph statistics—Maximum Mean Discrepancy (MMD), node degree, orbit frequencies—and neural metrics including F1 scores for Precision-Recall and Density-Coverage, providing a comprehensive assessment of structural and attribute accuracy.

The framework supports evaluation under random and additive conditioning. Random conditioning removes parts of the graph to test reconstruction capabilities, while additive conditioning simulates known room types or connections. Ablation studies confirm the effectiveness of key components like the annealed Langevin corrector and reverse-time sampling, validating their role in enhancing generation quality and stability.

The AI model outputs structured CSV data detailing each space and its connectivity, enabling straightforward integration into architectural workflows. Visualization of generated bubble diagrams uses a graphical interface that differentiates input and output: red lines and square nodes denote user-defined elements, while black lines and circular nodes represent AI-generated spaces and connections as seen in Figure 2.

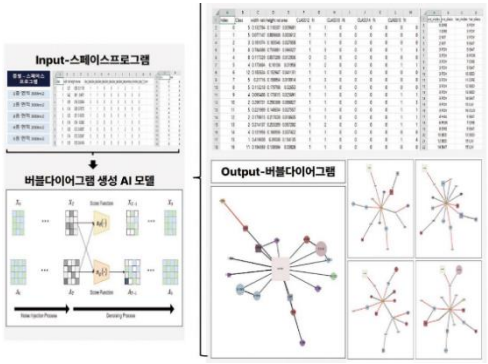

Figure 2
2D floor Plan Generation using AIBIM SpaceMaker

3D Building Layout Generation

The methodology advances into 3D building layout generation using generative algorithms integrated within Building Information Modeling (BIM) environments such as Revit, complemented by parametric design tools like Dynamo. AI-driven algorithms transform 2D spatial diagrams into 3D building layouts, enabling rapid exploration of diverse spatial configurations. This approach facilitates flexible design iteration while ensuring compliance with architectural and functional criteria. By automating the creation of layout alternatives based on predefined design rules, generative algorithms enhance design efficiency as seen in figure 3.

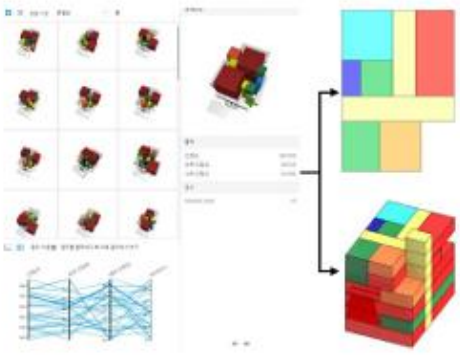

Figure 3
3D Building generated layout using AIBIM SpaceMaker

AIBIM-SpaceMaker (Layout) exemplifies such a tool, automatically generating floor plan alternatives during the early planning phase to alleviate repetitive tasks for designers. The tool accepts AI-generated neighborhood living facility bubble diagrams (in Excel format) and AIBIM_Design-produced building shape IFC files as input data.

The process begins with executing a GenerativeDesign algorithm, which leverages external and internal adjacency parameters to produce multiple floor plan layout options. Architects then evaluate these alternatives to select the layout best aligned with spatial relationships and design intents.

Upon selection, the system generates corresponding Revit elements that embody the proposed design, as illustrated in Figure 3. Certain spaces within the layout remain editable by architects, allowing for tailored refinements. To streamline interior planning, interior walls are created via Dynamo Player, effectively bridging conceptual design and detailed architectural development.

In parallel, this study proposes an algorithmic method for analyzing spatial connectivity within the Revit environment using Dynamo. The methodology unfolds over four stages, aimed at identifying and visualizing both direct and indirect spatial relationships derived from architectural geometry and openings.

First, spaces in a residential floor plan are classified using Revit's room elements. Each space is assigned a unique class number corresponding to its function, enabling color-coded visualization and a structured spatial typology for analysis.

Second, intersecting zones between adjacent spaces are generated by extracting room boundary lines and converting them into polylines. Wall thickness is calculated and applied as offsets to these boundaries to create surface geometries. Intersections of these surfaces define

spatial overlaps between rooms, recorded as lists of intersecting room pairs.

Third, indirect spatial connections mediated by openings such as doors are identified. To optimize computation, door geometries are merged into a single shape. Each intersecting zone is evaluated for overlap with this composite door geometry, and categorized as True (includes door), False (excludes door), or Empty (no overlap).

Fourth, direct spatial connections are isolated by subtracting wall geometries from the intersecting zones. Residual surfaces indicate direct connections—i.e., no intervening walls or openings—thereby distinguishing true physical continuity from mere adjacency.

Outputs include graphical visualizations and structured datasets in CSV/XLSX formats. Connections are weighted, with direct links assigned a value of 1 and indirect links lower weights, supporting advanced analysis and applications such as AI-driven spatial referencing and recommendation systems.

Finally, selected 3D model layouts from the generated designs can be refined further within Revit or exported to other CAD platforms for continued development.

3D Building Envelope Design and Simulation

Following the creation of the 3D layout, the building envelope design is developed using algorithmic tools. The generated models are transferred to software such as Rhinoceros (Rhino) and Grasshopper, where parametric modeling techniques refine the building's exterior design as seen in figure 4.

The focus in this phase is to optimize the façade structure, material choices, and environmental adaptability. Algorithmic modeling enables dynamic adjustments to the envelope design based on site-specific factors such as climate, orientation, and shading requirements, ensuring an efficient and well-adapted building envelope.

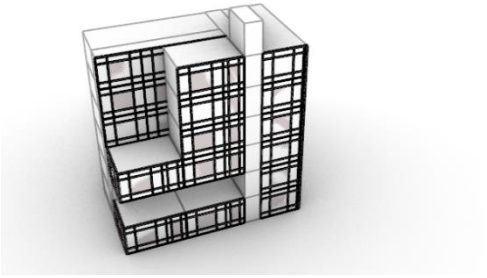

Figure 4
Building envelope façade designed in Rhino using Grasshopper

Once the building envelope is designed, it undergoes 3D performance simulations to evaluate its energy efficiency and sustainability metrics. Simulation tools such as Ladybug and Honeybee are employed to analyze key performance indicators, including daylighting efficiency, thermal comfort, and energy consumption. For instance, Useful Daylight Illuminance (UDI) simulations help assess how natural light is distributed throughout the interior spaces, informing adjustments to optimize daylight access while minimizing energy demand. These simulations provide critical feedback that enhances the environmental performance of the building.

Simulation Driven VR Environment

The final phase integrates virtual reality (VR) visualization to provide an immersive and interactive design experience. Using VR platforms like Unreal Engine, the completed building model, along with its performance data, is visualized in a real-time 3D environment. This step allows stakeholders—including architects, engineers, and clients—to experience the design before construction begins, facilitating better decision-making and collaboration. VR visualization enhances spatial understanding, allowing for refinements in layout, materiality, and user experience through an intuitive, interactive medium.

EXPERIMENT AND RESULTS

Façade Simulation results

The simulation results are visualized through a grid-based spatial distribution of daylight factor values across the analyzed indoor space in figure 5.

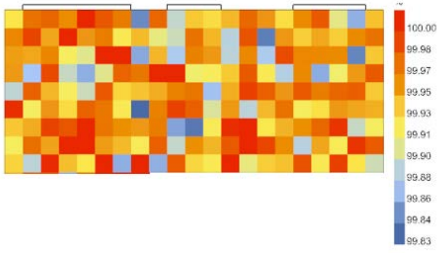

Figure 5
daylight exposure
Façade simulation
in Rhino
Grasshopper

The numerical scale ranges from 99.83% to 100.00%, indicating variations in daylight availability. The higher values (closer to 100%) suggest areas with strong daylight exposure, whereas the lower values (around 99.83%) indicate relatively dimmer zones that might require additional daylighting strategies.

This research employs a performance-driven design methodology focused on optimizing the building envelope to enhance overall building sustainability. Recognizing that the envelope mediates critical thermal and lighting processes, its design is treated as a central factor in achieving sustainable development goals within architecture. The methodology is structured around parametric modeling and environmental simulation to iteratively evaluate and improve envelope performance.

Parametric modeling is conducted using Rhino and Grasshopper, enabling flexible manipulation of envelope components such as glazing ratios, shading devices, material configurations, and geometric forms. These models are integrated with environmental simulation tools specifically Ladybug and Honeybee which interface with analysis engines such as EnergyPlus and OpenStudio for energy performance simulations, and Radiance and Daysim for daylight analysis. This workflow allows for quantitative evaluation of how envelope design decisions impact thermal comfort, daylight autonomy, and energy consumption.

Recognizing the building envelope's role as the interface between indoor and outdoor environments, additional parameters such as material properties, insulation levels, and surface geometry are incorporated into the simulation models. The simulation-driven approach supports iterative feedback between design intent and performance outcomes, enabling the optimization of envelope configurations to reduce energy demand, enhance daylight access, and maintain indoor environmental quality.

To align performance metrics with industry standards, sustainability frameworks such as the Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) are used as reference criteria. These frameworks guide the evaluation of envelope-related aspects, including thermal efficiency, daylighting performance, and material sustainability. Their integration into the workflow ensures that design solutions meet established benchmarks and can be computationally validated.

By combining parametric modeling, performance simulation, and recognized sustainability criteria, the methodology facilitates the identification of high-performance envelope solutions and supports evidence-based decision-making throughout the design process.

Simulated VR visualization

A digital architectural workflow where a parametric model created in Rhino and Grasshopper is imported into a Virtual Reality (VR) environment for immersive interaction. This process allows designers to visualize, analyze, and refine architectural concepts dynamically, making VR an integral part of modern architectural design workflows. The left side of the image shows a wireframe-like parametric structure, while the

right side presents a more refined, rendered version of the same model in a virtual space. This transition highlights the evolution from computational design to real-time immersive visualization as seen in figure 6.

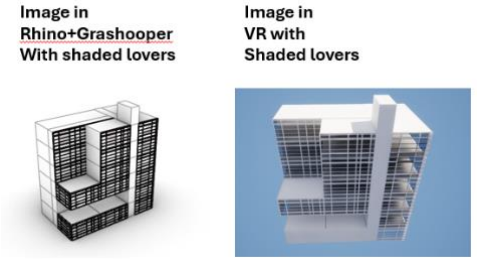

Figure 6
Building envelope façade from Rhino in VR

The parametric design phase in Rhino and Grasshopper enables rule-based geometry generation, where architects set parameters, such as building height, structural grid density, and façade patterns. Algorithmic adjustments allow rapid exploration of multiple design iterations. This computational approach streamlines the workflow and supports optimization for structural efficiency, daylighting, and sustainability. The wireframe image on the left illustrates an early-stage exploration focused on spatial organization and façade articulation.

Integrating VR into the architectural workflow offers key benefits, including real-time collaboration, immersive decision-making, and iterative refinement. Unlike traditional 2D drawings or static 3D renders, VR allows stakeholders to experience designs as if physically present, improving client understanding and engagement. Architects also use VR sessions to identify design flaws—such as inadequate lighting or inefficient layouts—before finalizing construction documents.

By combining parametric modeling, real-time rendering, and immersive VR, architects can push digital design boundaries. This workflow fosters a more intuitive, efficient, and interactive design process, producing results that are visually compelling and functionally optimized. As VR technology advances, its role in architectural design will expand, offering even greater capabilities for simulation, analysis, and collaboration.

DISCUSSION AND CONCLUSIONS

This research highlights the transformative potential of integrating generative AI, virtual reality (VR), and building performance simulation into the architectural design process. Given that buildings account for a substantial share of global energy use and greenhouse gas emissions, early-stage design decisions are critical to improving energy efficiency and sustainability. By incorporating AI-driven generative models, parametric tools, and simulation-based VR environments, designers can develop more functional, efficient, and sustainable buildings while optimizing spatial configurations and façade performance.

The study demonstrates the effectiveness of generative AI in automating and optimizing spatial layout generation through a graph-constrained generative adversarial network (GAN). This approach enables the production of accurate, diverse, and constraint-aware layouts, surpassing traditional methods in precision and speed. The AI-driven generation of 2D spatial plans, followed by their conversion into 3D BIM models, streamlines the workflow, accelerates design iteration, and supports data-informed decision-making.

The integration of VR into the design workflow further enhances stakeholder engagement by offering immersive and interactive evaluation of architectural concepts. Linking VR with BIM and simulation tools enables real-time analysis of key performance metrics such as daylighting, thermal comfort, and energy consumption. This immersive feedback reduces costly revisions and supports more informed, performance-oriented design decisions.

The methodology also emphasizes the value of simulation-driven approaches in evaluating

and refining building envelope design. By using tools such as Rhino, Grasshopper, Ladybug, and Honeybee, designers were able to optimize façade geometry.

Overall, this research demonstrates that the convergence of AI, generative design, and VR-based simulation offers a robust framework for advancing architectural design. These technologies not only improve design efficiency and creativity but also enable a data-driven process that prioritizes sustainability and environmental performance. Future work should explore expanding AI's role in generative design, enhancing VR interactivity, and refining simulation models to further improve energy outcomes and ecological integration. Continued development of these digital workflows will contribute to more intelligent, adaptive, and sustainable architectural practices.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (RS-2024-00349586)

REFERENCES

Lai, Z., Zeng, Q. and Zhou, S. (2022) 'Research on Online Virtual Energy-Saving and Environment-Friendly Building Design and Implementation Based on VRML', *Wireless Communications and Mobile Computing*, 2022(2). doi: 10.1155/2022/5869037

Leonidaki, K., Kyriaki, E., Konstantinidou, C., Giama, E. and Papadopoulos, A. (2014) 'Thermal performance of office building envelopes: the role of window-to-wall ratio and thermal mass in Mediterranean and Oceanic climates', *Journal of Power Technologies*, 94(2), pp. 1–7. Available at: https://papers.itc.pw.edu.pl/index.php/JPT/article/view/550

Lie, Z., Zheng, Q., Zhou, S. and Rauf, H. (2021) 'Virtual energy-saving environmental protection building design and implementation', *International Journal of System Assurance Engineering and Managemen*t, 13(1), pp. 263-272. https://doi.org/10.1007/s13198-021-01387-2

Min, J., Yan, G., Abed, A. M., Elattar, S., Khadimallah, M. A., Jan, A. and Ali, H. E. (2022) The effect of carbon dioxide emissions on the building energy efficiency. *Fuel*, 326, 124842. https://doi.org/10.1016/j.fuel.2022.124842

Natephra, W., Motamedi, A., Fukuda, T. and Yabuki, N. (2017) 'Integrating building information modeling and virtual reality development engines for building indoor lighting design', *Visualization in Engineering*, 5(19). Available at: https://doi.org/10.1186/s40327-017-0058-x

Nauata, N., Chang, K.-H., Cheng, C., Mori, G. and Furukawa, Y. (2020) House-GAN: Relational Generative Adversarial Networks for Graph-Constrained House Layout Generation. https://doi.org/10.1007/978-3-030-58452-8_10

Park, H., Gu, H., Hong, S. and Choo, S. (2024) 'Developing a Robust Training Dataset for AI-Driven Architectural Spatial Layout Generation', *Applied Sciences*, 14(16), 7095. https://doi.org/10.3390/app14167095

Shehadeh, A., Alshboul, O., Taamneh, M. M., Jaradat, A. Q., Alomari, A. H. and Arar, M. (2025) 'Advanced integration of BIM and VR in the built environment: Enhancing sustainability and resilience in urban development', *Heliyon*, 11(4), e42558. https://doi.org/10.1016/j.heliyon.2025.e42558

Wang, W., Zmeureanu, R. and Rivard, H. (2005) 'Applying multi-objective genetic algorithms in green building design optimization', *Building and Environment*, 40(11), pp. 1512–1525. a https://doi.org/10.1016/j.buildenv.2004.11.017